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# A review of behind-the-meter energy storage systems in smart grids

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ABSTRACT

The electric power industry is experiencing a paradigm shift towards a carbon-free smart system boosted by rising energy demand, depreciation of long-lived physical assets, as well as global environmental challenges. Recent advances in information and communications technology, as well as the widespread integration of renewable energy resources to the power distribution system, have introduced new opportunities and challenges for system operators and end-users alike. Energy storage systems (ESSs) can help make the most of the opportunities and mitigate the potential challenges. Hence, the installed capacity of ESSs is rapidly increasing, both in front-of-the-meter and behind-the-meter (BTM), accelerated by recent deep reductions in ESS costs. This work is focused on BTM ESSs installed in end-users ' premises and associated technologies, different billing and pricing policies, as well as their potential capabilities from both the system operators' and end-users' perspectives. Furthermore, a brief but comprehensive overview of optimization solutions for BTM energy management problems and a quick summary of some BTM case studies are provided. Finally, challenges in the realization of BTM systems in today's power system are explored, and potential research areas and progressive solutions for future studies are identified.

## 1. Introduction

With the world's rapid modernization and increased need for electricity, worldwide worries about growing emissions and climate change, energy supply security, as well as rising fuel prices have intensified in recent years [1]. Buildings are one of the greatest energy consumers, accounting for over 40% of total global energy consumption, and have a considerable carbon impact [2]. The literature shows that the deployment of renewable energy sources (RESs) such as rooftop photovoltaics (PVs) to satisfy a portion of buildings' energy demand may relieve network stress and reduce reliance on fossil fuels, lowering costs and emissions [3]. However, the growing installation of RESs makes it challenging to maintain the demand-supply balance in real-time, which has always been addressed with reserve generators. Conventional solutions are no longer capable of withstanding the extra fluctuations caused by intermittent renewables, and there is an urgent need for effective alternatives [4,5].

Energy storage systems (ESSs) controlled with accurate ESS management strategies have emerged as effective solutions against the challenges imposed by RESs in the power system [6]. Early installations are large-scale stationary ESSs installed by utilities, which have had positive effects on improving electricity supply reliability and security [7,8]. Thanks to rapidly dropping costs, smaller ESSs are being installed in the power distribution system to provide on-site services for send-users. Overall, ESSs may be classified into three groups based on their power rating (P) [9,10];

1) large-scale technologies: $P > 100$ MW;
2) medium-scale storage systems: $5 \text{ MW} < P < 100$ MW;
3) small-scale energy storage devices: $P < 5$ MW.

Small-scale ESSs are routinely installed in customers' premises, known as behind-the-meter (BTM) ESSs, typically up to 5 kW/13.5 kWh for residential customers and up to 5 MW/10 MWh for commercial and industrial units [11,12]. Following recent advances in power electronics, considering services that ESSs might be expected to offer, they

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can either store electricity from an on-site generator or the grid, or they can be fed by both [13]. Recently, there has been a dramatic rise in the installed capacity of BTM ESSs with the growth in distributed generators (DGs) [14]. This trend has been accelerated by advancements in ESSs technologies, the adoption of time-variant electricity tariffs, government subsidies and incentives programs, and sophisticated energy optimization systems [15]. For instance, in Germany, more than 40% of rooftop PV systems have been paired with BTM ESSs in recent years [16]. In Australia, the process is speeding towards the goal of 1 million storage devices for residential and small-scale commercial units, by 2025 [17]. In the United States, there was a steady increase in the installed capacity of residential BTM storage systems by 73% per quarter during 2020 [18].

BTM ESS implementation necessitates an accurate and efficient system design as well as the use of relevant technologies. This involves selecting an appropriate energy storage type, tailoring power electronics to the system specifications, and installing smart meters to monitor and control power flows. To assign roles to a BTM ESS, policies and regulations prevailing in its host network need to be fully investigated, as well as end-user expectations, which are heavily influenced by the type of metering system and tariffs used to calculate customers' bills. To get the best results and to ensure efficient and optimal system operation, accurate ESS management strategies should be implemented. To do so, system designers must have a solid grasp of the challenges associated with implementing BTM devices, BTM ESS optimization techniques, and results from implemented case studies. To the best of the authors' knowledge, although numerous review works on storage technologies have been published, there is no review on behind-the-meter small-scale ESSs in the literature that provides all this information.

In this work, an effort has been made to thoroughly study BTM ESS in terms of the following areas: BTM system configurations and their associated technologies, economic impacts of different metering and pricing schemes, potential applications of BTM ESSs for both utilities and end-users, optimization strategies and their use in BTM ESS problems, worldwide implemented BTM case studies, BTM storage systems implementation challenges, and potential areas for future studies. The remainder of this paper is organized as follows. Section 2 delves into the BTM technologies and system components. Section 3 investigates the billing and pricing strategies and their impacts on billing costs for ESS owners. Section 4 provides a thorough review of different potential applications of BTM ESS for both end-users and utilities. Section 5 investigates optimization solutions utilized for BTM ESSs energy management problems. Section 6 is dedicated to reviewing a number of implemented case studies worldwide. Section 7 explores potential challenges in the deployment of BTM ESSs in smart grids. Section 8 highlights potential areas for future investigations to enhance the efficiency of BTM ESSs in future smart grids and finally, section 9 concludes the paper. The presented work complements the existing literature by providing valuable insights into the potential value of BTM ESSs for future smart grids.

## 2. Technologies

BTM ESS technologies have been introduced to enable end-users to satisfy their energy demands even in the event of a power outage. Customers can produce energy by installing either fuel-based or renewable generators on their premises. They can also equip themselves with BTM ESSs to increase energy resilience, particularly in the case of weather-dependent renewable generators [13]. In areas with time-variant tariffs, a BTM ESS can help users to reduce their billing costs by enabling them to store energy during low-price periods for use during high-price hours. Nowadays, the most common BTM installation, particularly for buildings, is PV plus ESS [14]. Therefore the focus of this study is on such an installation, although other types of generators, such as small/medium-scale hydro turbines, wind turbines, and diesel generators, as well as hybrid systems containing several of these technologies can be considered for BTM installations. From here on after, the term BTM system/resource in this work refers to a BTM PV plus ESS. However, for more information [19], discusses the use of other potential distributed energy technologies at various levels. For illustration, the implementation of a PV plus BTM storage system in Fig. 1 introduces a range of components and operational modes, which are detailed in the subsections below.

### 2.1. Distributed photovoltaic systems

PV systems are one of the most often used DG sources due to their simplicity of installation. They absorb light (photons) and convert it directly into electricity in DC form through solar cells. A PV module is formed when solar cells are connected together to increase the output voltage and/or current. PV systems usually consist of an array of PV modules, deployed either to supply a single user or feed electricity to the grid [20]. They offer a range of advantages to the system operator, including reduced environmental pollution and power losses, increased generation capacity, and network expansion deferral. However, the network may be challenged by the uncontrolled and extensive penetration of PV systems [1].

The global installed capacity of distributed PV systems has expanded substantially over the last decade, initiated by supportive financial policies, but now the trend has accelerated as the cost of PV systems has reduced. Currently, PV generators account for over a quarter of the total 2800 GW renewable energy capacity installed worldwide [21]. Solar cell efficiency and manufacturing advancements as well as economies of scale are the key drivers of PV system cost reduction. China is the world leader in PV installation capacity, with 27 GW of distributed PV installed by 2020, bringing its total installed capacity to 205.2 GW. The United States with 76 GW of cumulative installed PV systems, comes in second place followed by Japan with approximately 63 GW of installed capacity. Germany and India are the fourth and fifth countries on the list, with about 50 GW and 38 GW, respectively [22].

Currently, one of the main challenges that hinders the widespread installation of PV systems for small/medium-scale applications is their high costs and long payback period [23]. Therefore, it is necessary to establish appropriate supportive policies and subsidies to develop the industry. Supporting policies, such as those offered in Japan since 1994, have shown to be effective in the spread of PV systems [24], as has the end-user payment scheme set up by the Italian and German governments for each kWh of self-consumed PV electricity [25]. Another example is the Chinese government's subsidy for solar-generated electricity, initiated in 2013 [26]. Additionally, many countries have put in place support packages for PV installations, such as Ireland, which offers a subsidy of €2,400 to end-users who install rooftop PV arrays and BTM batteries in their premises [27].

### 2.2. Small-scale energy storage systems

The ability to increase the share of the total RES production directly consumed by on-site demand (self-consumption) for RES owners (prosumers) and improve the resilience of the power supply for utilities, is the key value proposition that led to the widespread deployment of BTM ESSs [15]. Currently, the BTM ESS market is dominated by lithium-ion (Li-ion) batteries, nevertheless, lead-acid (Pb-acid) battery, flow battery, and ultra-capacitor (UC) technologies have also been deployed to some extent. Meanwhile, hydrogen ESSs (HESSs) [28], and mechanical ESSs, in particular flywheel ESSs (FESSs), are also gaining attraction for BTM applications considering their ability to provide an uninterruptible power supply [13]. Table 1 compares these technologies in terms of their technical parameters. It should be noted that the HESS specifications in Table 1 refer to the entire system, including the water electrolyzer, storage tank, and fuel cell (FC).

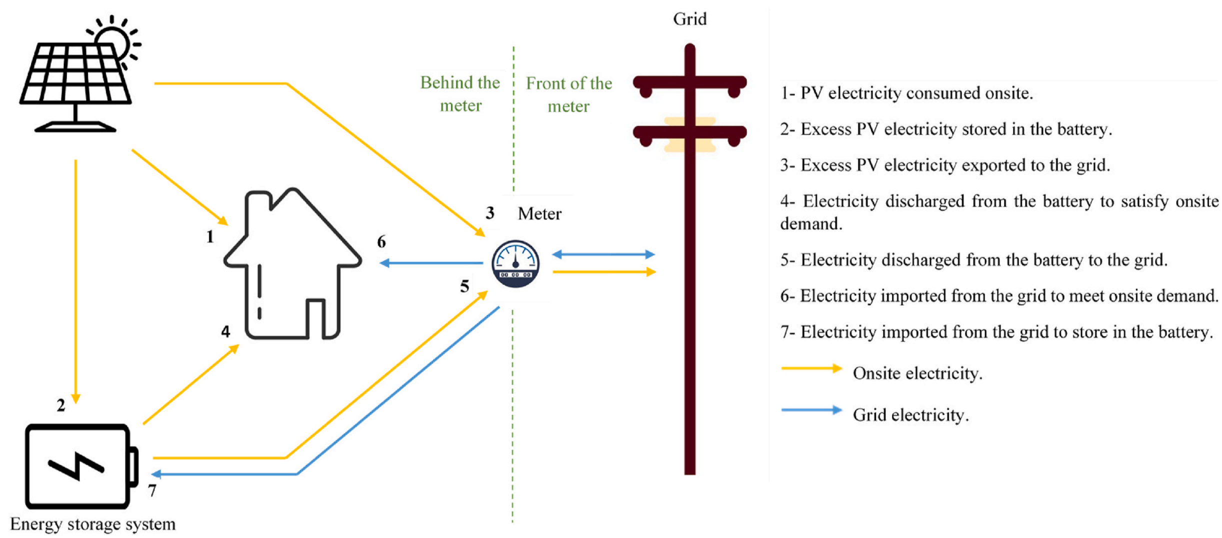


**Fig. 1.** A schematic diagram of a behind-the-meter energy system.

**Table 1**
ESSs technical parameters [7,21–42].

| Technology | Power density (kW/m$^3$) | Energy density (kWh/m$^3$) | Specific power (W/kg) | Specific energy (Wh/kg) | Power rating (MW) | Efficiency (%) | Cycling times (cycles) | Service life (years) |
|---|---|---|---|---|---|---|---|---|
| Pb-acid | 10–400 | 25–90 | 10–200 | 30–80 | 0–20 | 70–90 | 500–1000 | 5–15 |
| Li-ion | 50–800 | 90–500 | 500–2000 | 100–200 | 0–0.1 | 85–90 | 1000–10000 | 5–15 |
| VRFB | 2.5–33.5 | 10–33 | 80–150 | 30–50 | 0.03–3 | 75–85 | >12000 | 5–10 |
| UC | 15–4500 | 1–35 | 500–5000 | 2.5–15 | 0–0.3 | 75–95 | >100000 | 10–12 |
| HESS | 1–300 | 25–770 | 5–50 | 200–1200 | 0–50 | 30–45 | >1000 | 3–10 |
| FESS | 40–2000 | 0.25–424 | 1000 | 100–130 | 0–2 | 85–90 | 105–107 | >20 |

### 2.2.1. *Batteries*

Batteries are classified into two types: 1) disposable batteries that cannot be recharged, and 2) rechargeable batteries that can be recharged and used after discharge. Normally, rechargeable batteries are deployed for power system applications, among which the three most common technologies used for BTM installations are discussed below.

*2.2.1.1. Lead-acid batteries.* Lead-acid batteries are the oldest type of rechargeable batteries that can deliver excellent pulsed power, making them a potential technology for BTM applications [9]. Pb-acid batteries have been used in a variety of applications, ranging from small-scale to large-scale applications in the power system [29]. However, whether flooded or valve-regulated, they release hydrogen and oxygen during charging via water electrolysis, which raises safety concerns, necessitating their installation outside of buildings [30]. But, despite their ability to operate in the range of −5 to 40 °C, they have poor low-temperature performance, making them a less desirable option for cold climates [31]. Moreover, the sulfuric acid and lead used to form the electrolyte and the anode respectively are toxic and have a relatively limited cycle life. Besides, periodic water maintenance, sulfation of the plates, low specific energy, and limited depth of discharge, have been significant barriers to the introduction of Pb-acid batteries for BTM systems [29].

*2.2.1.2. Lithium-ion batteries.* The most commonly used battery technology for BTM applications is the Li-ion battery. Li-ion batteries outperform Pb-acid batteries in terms of energy density, depth of discharge, and round-trip efficiency. This means that with the same physical size as a Pb-acid battery, more energy can be stored in a Li-ion battery; thus it can supply more appliances for a longer period. However, they are still an expensive technology relative to Pb-acid batteries [9]. Also, the requirement for cobalt to manufacture the cathode puts a strain upon limited cobalt sources as the usage of Li-ion batteries for energy storage systems increases [32]. They are also vulnerable to high temperatures and catch fire easily, so a battery management system is needed to prevent overcurrent, overheating, and overvoltage. Nonetheless, they can operate normally in the range of −30 and 60° Celsius [33]. Apart from being widely used in energy storage for both BTM and front-of-the-meter systems, Li-ion battery technology is the most popular choice for portable electronics and electric vehicles (EVs) [34].

*2.2.1.3. Flow batteries.* Chemical reactions between electrolytes, just like in conventional batteries, form the foundation for charge and discharge cycles of flow batteries, also known as redox flow batteries (RFBs). Instead of storing energy in solid-state electrodes as in conventional batteries, energy in RFBs is converted to chemical potential and stored in two separate liquid electrolyte solutions in external tanks, the size of which defines the battery's capacity [35]. Vanadium redox, zinc-bromine, and polysulfide bromide are the three main types of flow batteries now in use, among which the vanadium redox flow battery (VRFB) is the most common and mature technology [36]. VRFBs have a fast response time, high efficiency, and long cycle-life that can provide high storage capacity, making them ideal for industrial BTM ESSs [37]. They may also be charged and discharged simultaneously and be used to minimize voltage and frequency fluctuations and provide load-levelling services [38]. Because of the significant advantages that VRFBs have over chemical batteries, this technology is ideal for grid-scale applications such as voltage and frequency regulation services, distribution power quality, load shifting, and power output smoothing for large-scale renewable energy systems [39]. However, VRFB's complicated structure, the need for an external power supply to power the pumps, and expensive fluids that are also toxic and corrosive are what restrict its widespread adoption for BTM technology [37].

#### 2.2.2. Ultra-capacitors

Ultra-capacitors are ESSs that fall somewhere between conventional capacitors and batteries, with the ability to offer 100–1000 times more capacitance per unit volume than conventional capacitors [40]. Instead of chemical reactions, UCs store energy in the electrostatic field of an electrochemical double layer, allowing them to be cycled millions of times and to have a much longer lifespan than batteries [41]. UCs energy efficiency is up to 95% and they have a higher power density than batteries [42]. However, they suffer from low energy density due to the limited surface area of the electrode [43]. Moreover, because of high internal resistance, this technology requires a continuous low current to keep its charge. Otherwise, UCs lose their charge significantly compared to batteries, known as the self-discharge characteristic. However, considering their ability to deliver quick but small bursts of energy, UCs have been recently deployed in hybrid BTM ESSs for voltage regulation and PV output voltage smoothing [28].

#### 2.2.3. Hydrogen storage

Hydrogen, like electricity, is a carrier of energy and is not itself a primary source of energy. An important advantage of hydrogen is that it can be stored for a long time, unlike electricity, which makes this technology ideal for remote areas that need energy all year around [44]. Hydrogen is currently produced using a variety of sources, such as diesel fuel, gasoline, coal, natural gas, biomass, and water electrolysis. The most promising idea that emits no pollution is to use RESs power to electrolyze water using electrolyzers and split it into oxygen and hydrogen, which is known as green hydrogen [45]. This process releases oxygen dissolved in water, which may be released into the atmosphere or stored for industrial processes or medical uses. The other output is hydrogen, which, depending on the conditions and requirements, can be stored as compressed gas, cryogenic liquid, or as a solid in a metal hydride [46]. The three primary water electrolysis technologies introduced so far are solid oxide electrolysis, alkaline, and polymer electrolyte membrane (PEM) [47,48]. Stored hydrogen can be used on-site, or it can be transported over long distances via transmission lines or truck tankers to generate electricity using FCs, supply thermal demand, or power FC electric vehicles. In case of electricity generation, stored hydrogen can be used along with the oxygen present in air in FCs, from which the sole emission is water which can be reused and electrolyzed again to produce more hydrogen [49].

There are five widely commercially available FC technologies, each with its own set of specifications that make it suitable for specific applications: PEM, alkaline (AFC), phosphoric acid (PAFC), molten carbonate (MCFC), and solid oxide (SOFC) [47]. Overall, the PEM technology is the most suitable for BTM applications, due to its smaller size, higher power density, and dynamic characteristics [50]. For example, the slowest and fastest technologies in terms of the start-up time are SOFC (60 min), and PEM (less than 1 min). However, using PEM FCs for BTM electricity storage purposes is still in development, and it is considered an expensive solution due to its expensive catalyst, and water and heat management. Moreover, hydrogen itself is a colorless, odorless, and highly combustible element, which means it requires adequate ventilation and leak detection to ensure the reliability of hydrogen systems [46].

#### 2.2.4. Flywheels

FESS works based on the principle of converting electrical energy into kinetic energy and vice versa [10]. During charging, the electric energy in a motor is converted into rotational kinetic energy, which causes a mechanically coupled flywheel to rotate. With increased electrical energy input to the system, the rotational speed of the flywheel rises, increasing the mechanical energy stored. To minimize friction and energy loss in modern FESs, a pump is used to vacuum the system and magnetic gears are implemented to support rolling elements, allowing energy to be stored for a long time with a very low self-discharge rate when compared to other ESS technologies [51]. The process is reversed in the discharge mode, with the spinning flywheel providing kinetic energy to the generator, which in turn delivers power to the output, reducing the rotational speed of the flywheel and therefore the mechanical energy stored in the system [52].

FESSs have a longer lifespan, higher specific power, and can offer higher output power and energy capacity compared to batteries. Furthermore, because they don't contain toxic chemicals, they have a considerably lower environmental impact than other ESS technologies [52]. However, this technology can have high risk since it contains rolling elements with extremely high speeds, and in the case of a failure, explosion of its vacuum chamber may cause serious harm to bystanders. Also, the size of a FESS's mechanical component determines its storage capacity, putting extra constraints on its design and making it less flexible than batteries, as well as taking up more space [53]. Frequency and voltage control, and load levelling for the power system, pulsed power applications for the military, uninterruptible power supply for critical loads, and large-scale ESSs are the most common applications of FESS [52].

Table 2 compares the suitability of the aforementioned ESS technologies for BTM on-site services based on the characteristics discussed.

### 2.3. Power electronics

Power electronics is an integral part of smart grids that are primarily employed to convert and control electrical power from one form into another using AC-to-AC (e.g. wind to grid conversion), AC-to-DC (grid to battery), DC-to-DC (PV to battery), and DC-to-AC (battery/PV to grid) converters for industrial, commercial, and residential applications [55]. In addition to converting electrical energy, they ensure operational security by directly enhancing the reliability and resilience of smart grids through the provision of a range of important services for end-users and utilities. For instance, appropriate power electronics and controller design enable BTM ESSs to offer both reactive and active power simultaneously, independently, and very quickly [56]. The potential scope for their development is very significant as BTM ESSs are expected to become one of the most critical components of modern future power systems.

In BTM ESSs, due to limited storage capacity and bi-directional power flow during charging/discharging, efficiency must be maximized using fast response, high-efficiency power converters to interface ESSs with the electrical grid. Overall, the network structure and power conditioning system are designed based on the owners' desired applications and expectations from their ESS. An illustrative BTM system configuration and associated power converters for a PV system are shown in Fig. 2 [57–59].

#### 2.3.1. DC coupled energy storage system

In this configuration, the ESS is connected on the PV side using a DC-DC ESS converter [28]. Moving from left to right in Fig. 2: first, the PV output is sent into the DC-DC PV converter, which changes the PV output voltage to match the DC link voltage level. At this stage, based on the decision of a power management system, the PV converter's output may be delivered to the ESS converter to charge the ESS, or it can be routed to the PV inverter to be consumed on-site or fed into the grid. In this configuration, the co-located PV and ESS are connected on the same DC link and share the same DC-AC inverter to feed the on-site load or the grid. However, using three separate power converters and multiple power conversions deteriorate the overall energy efficiency [57]. Therefore, a hybrid PV inverter plus charge controller is introduced for BTM applications, which eliminates the need for DC-DC conversion between the PV array and the ESS. Therefore, the ESS can be directly charged from the PV array, and both the PV and ESS assets are connected to the grid using a single multimode inverter [58]. It should be mentioned that multimode inverters are significantly more expensive than traditional inverters. Moreover, since the entire system is reliant on a single multimode inverter; 1) if the inverter fails, the entire system

**Table 2**
Suitability of different ESS technologies for various BTM applications [54].

| Technology | Demand-supply balance | Smoothing RESs' output | Uninterruptible power supply | Load levelling & energy time shift | Peak shaving | Voltage & frequency regulation | Electric service reliability | Electric service power quality |
|---|---|---|---|---|---|---|---|---|
| Pb-acid | HP | HP | HP | HP | HP | HP | P | HP |
| Li-ion | HP | HP | HP | HP | HP | P | HP | HP |
| VRFB | HP | P | P | P | P | HP | P | P |
| UC | NS | MR | NS | NS | NS | HP | P | P |
| HESS | MR | MR | P | P | P | NS | MR | NS |
| FESS | P | P | P | MR | HP | HP | P | P |

HP: highly promising, P: promising, MR: more research required, NS: not suitable.

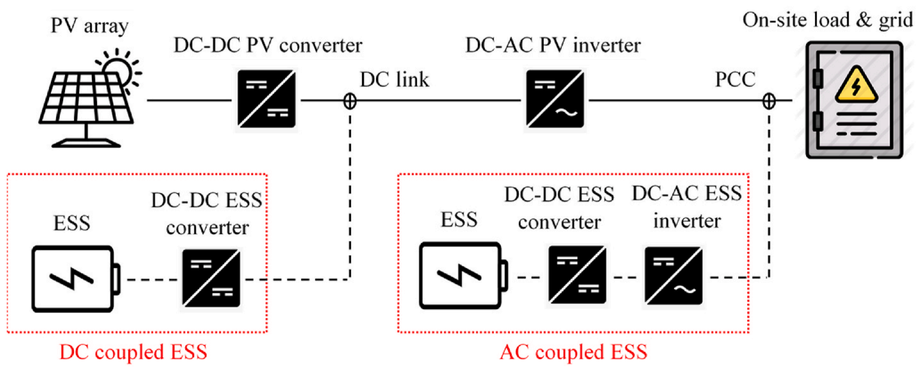


**Fig. 2.** Schematic diagram of a BTM PV plus ESS. ESS connection point can either be at the DC-link or the point of common coupling (PCC).

fails, 2) the total power from the PV and the ESS delivered to the load is limited by the multimode inverter capacity.

#### 2.3.2. AC coupled energy storage system

In this configuration, the ESS is connected to the AC side of the system through a DC-AC inverter. This means that the BTM system capacity is no longer limited by a single inverter thus the system can supply more power to the load/grid from both the PV and the ESS at the same time using separate power electronics [57]. However, this arrangement is more expensive than the DC coupled system since an additional ESS inverter is required to convert the ESS DC output to AC output within an acceptable voltage range suitable for appliances or the grid. To avoid having to install two different converters, a two-stage multimode power converter may be the best option. The first stage is responsible for stabilizing the battery voltage regardless of the state of charge, while the second stage is responsible for delivering sinusoidal voltage and meeting the needs of AC loads [60]. Otherwise, according to Fig. 2, a DC-DC converter plus a DC-AC inverter need to be installed to regulate the battery voltage that affects the systems' overall efficiency. Nevertheless, the AC coupled configuration is immune to the probable failure that may occur in the DC coupled one [57]. In case of failure in the ESS inverter, if the sun is still shining, loads are supplied by the PV system through the PV interactive inverter. On the other hand, when choosing a PV interactive inverter, it is typically assumed that the PV system would seldom run at full power. As a result, to save money, an interactive inverter with a lower capacity than the PV nominal power is chosen, which prevents the option of using 100% of the power provided by the PV system. This is not the case when a multimode inverter is utilized to link the PV array to the load/grid [59].

In both cases, DC coupled and AC coupled, the power backup service can be offered by the BTM ESS to system owners. For this purpose, protective relays must be put between the system and the main grid to enable AC loads to be supplied either by the ESS or the main grid via offering a new neutral earth connection [57]. However, utilizing intelligent power electronics eliminates the need for protection relays and can provide similar functionality while also lowering costs.

### 2.4. Smart meter

A smart meter (SM) is an advanced measurement device that monitors real-time power consumption and records this data at predetermined intervals. One of their great advantages is that the device's architecture and interface can be customized to offer a range of services [61]. SMs monitor the power by sensing frequency, voltage, current, and phase angle, and communicate data in the form of a set of parameters including data timestamps, meter unique ID number, and electric energy import/export values. They can be programmed to control household appliances as well as equipment owned by commercial and/or industrial customers. The implementation of SMs allows measurement of the energy from the main grid, on-site generators, or ESSs separately and accurate billing. Using SMs, it is also possible to set power consumption thresholds and have loads automatically disconnected in the event of overloading [61].

Utilities worldwide have considered the widespread use of SMs in energy planning and are investing heavily to equip customers with such technology. In the European Union, Sweden and Finland are among the pioneers, having already equipped more than 80% of their customers with SMs. Other notable examples are Ireland and Italy, where all existing electricity meters are being upgraded with SMs to enable accurate billing via time-of-use pricing [62,63]. In North America, almost all customers are equipped with modern smart meters, the same as those in Canada and Australia [64].

SMs, however, present several challenges. For instance, in many countries, the lack of proper infrastructure to synchronize SMs with existing equipment continues to be an obstacle to their adoption. Another significant challenge is the selection and design of a stable as well as precise communication system [65]. Communication systems must be chosen based on their installation and maintenance costs, available communication infrastructure, transmittable range, bandwidth, and most significantly, security features. Table 3 lists the features of several communication technologies presented so far.

**Table 3**
Summary of the widespread communication technologies for SM applications [47–50].

| Standard | Technology | Communication style | Frequency (MHz) | Bit rate (Mbps) | Max coverage (km) | Challenges |
|---|---|---|---|---|---|---|
| ***Wireless*** | | | | | | |
| Cellular | 4G | Symmetrical | 800–1900 | $\leq$ 20 | 50 | Costly spectrum fees |
| | 5G | Symmetrical | 25000–39000 | 50–1000 | 0.3 | Costly spectrum fees, short-range, not widespread |
| | GSM | Symmetrical | 900–1800 | $\leq$ 0.009 | 35 | Low bit rate |
| | GPRS | Symmetrical | 800–1900 | 0.032–0.048 | 10 | Low bit rate |
| | SigFox | Asymmetrical | 433/868/915 | 0.0001 | 40 | Limited bi-directional communication capacity, low bit rate |
| IEEE 802.11 | Wi-Fi | Symmetrical | 2400/5800 | $\leq$ 54 | 0.25 | Short range |
| | Enhanced Wi-Fi | Symmetrical | 2400 | $\leq$ 54 | 0.25 | Short range |
| | IEEE 802.11n | Symmetrical | 2400 | $\leq$ 600 | 0.25 | Short range |
| IEEE 802.15 | ZigBee | Symmetrical | 868/915/2400 | 0.02/0.04/0.1/0.25 | 0.1 | Low bit rate, short-range |
| | 6LoWPAN | Symmetrical | 2400 | 0.25 | 0.1 | Low bit rate, short-range |
| | Bluetooth | Symmetrical | 2400 | $\leq$ 0.25 | 0.01 | Low bit rate, short-range |
| IEEE 802.16 | WiMAX | Symmetrical | 2500–5800 | $\leq$ 100 | 60 | Not widespread |
| Satellite | LoRa | Symmetrical | 169/433/868/915 | $\leq$ 0.25 | 20 | Low bit rate, not ideal for continuous and real-time monitoring |
| ***Wired*** | | | | | | |
| NB-PLC | PRIME | Symmetrical | $\leq$ 0.5 | $\leq$ 0.5 | 150 | High signal attenuation, noisy channel environment |
| | G3-PLC | Symmetrical | $\leq$ 0.5 | $\leq$ 0.5 | 150 | High signal attenuation, noisy channel environment |
| BB-PLC | HD-PLC | Symmetrical | $\leq$ 30 | $\leq$ 240 | 5 | High signal attenuation, noisy channel environment |
| DSL | ADSL | Asymmetrical | 0.025–1 | 1.5 (upload)<br>7 (download) | 5.4 | Distance-sensitive, wiring quality dependent. |
| | HDSL | Symmetrical | 0.025–1 | 1.5–2 | 3.6 | Distance-sensitive, wiring quality dependent. |
| | VDSL | Asymmetrical | 0.025–1 | 1.5–2.3 (upload)<br>13–52 (download) | 1.3 | Highly distance-sensitive, wiring quality dependent. |

## 3. Electricity billing systems

The decrease in grid-dependency of customers on the demand side, along with the inability of conventional energy tariffs to reflect real electricity costs, has challenged network operators in recouping the full costs of electricity generation and delivery. Besides, the increased rate of PV self-consumption has enabled prosumers to reduce their grid consumption and thus the network operator's income. This is a serious issue, known as the Death Spiral, which operators are increasingly confronted with as the costs of PV and ESSs reduce [66]. As a result, the electricity price rises to compensate for the decreased profits, but this price increase becomes a double incentive for customers to implement more BTM PV plus ESS to reduce reliance on the utility [15]. This trend again raises energy prices, which will ultimately be unfair to those who do not own PV plus ESS.

### 3.1. Metering and billing

To address the aforementioned issues in networks with distributed resources, two primary metering methods, net metering and net billing, have been introduced, allowing utilities to charge prosumers in two different ways.

#### 3.1.1. Net metering

Net energy metering (NEM), or net metering, is the most common metering mechanism in networks with DG penetration [67]. Under NEM, prosumers can send their excess electricity to the grid and gain credit in kilowatt-hours. At the end of a billing period, users are billed given their import from the grid minus the energy exported to the grid, which is generally measured by a smart meter. With a relatively similar structure, Gross metering is defined in which prosumers' energy import and export are measured by two separate power meters [68]. In this case, the cost of electricity is set to be the same for both energy import and export, and customers' billing formulation is the same as that for NEM. So, as discussed in Ref. [69], the utility can be thought of as a virtual energy storage system that stores prosumers' excess output to be used at a later time. Besides, prosumers will no longer need to install an ESS because whenever they require energy, they can import the same amount of energy/credit as they have saved by sending their surplus production to the grid; this of course reduces their costs but increases the grid costs [70]. Ideally, this concept may enable prosumers to use the energy they have stored in the grid at any time. However, given the grid in its present form, electricity cannot be stored on a large scale for an extended period and must generally be consumed as soon as it is generated. Therefore, sending a large amount of energy from prosumers to the grid can disrupt the system's safe operation and impose serious challenges such as transmission line congestion, demand-supply imbalances, and an increase in power losses and costs [71,72]. In order to alleviate these issues, many regions are implementing non-intrusive demand-side management programs by introducing variable tariffs based on the rate of energy import/export from/to the grid. This is known as Net billing as described below.

#### 3.1.2. Net billing

In net billing, the energy imported and energy exported are not given the same credit; instead, the values are measured and priced separately using different smart meters. In net billing, an export meter measures the energy fed to the grid and usually sets the sale rate cheaper than the retail electricity tariff. Similarly, a separate meter measures energy imported from the grid, which is then added to the bill based on predetermined retail tariffs. Finally, customers must pay the difference between the cost of electricity purchased from the grid and the revenue obtained through selling energy to the grid at the end of a billing period [68]. Unlike in NEM, customers who are subject to net billing typically tend to pair their on-site generators with ESSs to increase the rate of self-consumption and thus reduce billing costs. This is particularly true of PV systems, in which generation is not usually synchronized with customers' demand and storing it for later use is more profitable than selling it to the grid [73]. Besides, net billing allows utilities to indirectly control BTM resources to some extent, and implement demand-side management programs by manipulating electricity sell and purchase rates.

From what has been discussed above, whether for net metering or net billing, the purchase and sale prices of electricity have a significant impact on customers' willingness to install BTM resources. Hence, the following subsection gives a detailed overview of different tariff designs.

### 3.2. Retail tariff design

The prices at which customers purchase/sell electricity from/to the grid are known as retail tariffs. From the customers' perspective, the profitability of BTM systems is greatly affected by the design of retail tariffs. From the utility's point of view, optimum retail tariff design will help incorporate demand-side management programs to increase overall system efficiency and improve the utility's cost-revenue balance [15].

#### 3.2.1. Volumetric energy rates

The volumetric pricing scheme is a common mechanism designed to charge customers for their electricity usage in kilowatt-hours. It can be seen on bills of all end-users and accounts for the vast majority of households' electricity costs [74]. Billing for commercial and industrial users is somewhat different, as they may also be charged based on the rate at which they consume electricity at a single point in time, known as demand charges [70]. Different types of volumetric tariffs are discussed below.

*3.2.1.1. Time-invariant energy rates.* Time-invariant, also named flat-rate mechanisms, are the most common volumetric pricing system applied to residential and commercial customers. Under a flat-rate tariff, the electricity price remains constant regardless of the time of consumption, which makes it easy for users to understand the electricity price, as well as brings simplicity and ease of implementation for utilities [75]. On the other hand, this scheme is not ideal for PV plus ESS owners since they are subject to a fixed price and would not benefit from potential arbitrage activities (purchasing more energy when the energy use is usually low (off-peak hours), storing it, and selling it back to the grid at higher prices when the electricity use is the highest (on-peak hours)) [76].

*3.2.1.2. Time-of-use (ToU) rates.* In this case, energy consumption is subjected to different rates predetermined for different periods [70]. ToU rates are set based on the variable conditions of the grid and its associated costs, resulting in a considerably higher price for electricity during on-peak hours compared to off-peak hours. During on-peak intervals, utilities must increase their capacity to meet the additional demand; thus the real-time cost of supplying electricity increases and is compensated for by increasing the ToU rates. Therefore, customers, whether they have BTM PV plus ESS or not, tend to reduce their grid consumption in response to higher electricity rates, thus resulting in an overall reduction in total final consumption [77]. In general, ToU rates encourage customers to add more BTM PV plus ESS capacity to meet a portion of their demand and reduce their reliance on the power system.

*3.2.1.3. Incline block tariffs.* In this pricing scheme, the electricity price is divided into several blocks. It begins from the first block, which is the cheapest, and progresses to the next block when the customer purchases more energy over the billing period, resulting in a higher tariff applying to their consumption. This process continues automatically as energy consumption grows until the billing cycle ends, at which point the process is reset and it begins again from the first block for the new billing cycle [78]. The implementation of this pricing scheme can encourage end-users to raise the rate of PV self-consumption by installing ESSs, allowing them to reduce their network purchases and pay lower electricity costs.

*3.2.1.4. Critical peak pricing (CPP).* The power grid may come under pressure during on-peak periods, due to increased customer demand, raising overall system costs. Under the CPP scheme, prices are generally set significantly higher than normal during critical peak intervals, encouraging end-users to reduce their consumption thereby reducing pressure on the generation side [70]. In this system, end-users are informed in advance that certain days of the year are designated as critical days, and the electricity price may increase up to 6 times compared to normal periods [76]. In this way, CPP provides operators with a strong instrument to control consumption behavior, so that offering high prices for critical intervals would cause customers to shift their demand to cheaper periods and relieve pressure on the power system. The timing of CPP has a direct impact on customers' decisions to install BTM PV plus ESS. For example, if critical periods are set outside of PV generation hours, the use of ESSs would be a viable cost-cutting solution for customers.

*3.2.1.5. Real-time pricing.* In this system, rates are set in real-time, and energy consumers are billed based on their real-time usage and energy tariffs [79]. Due to the greater price volatility under this scheme, end-users are more inclined to minimize their reliance on the main grid by installing BTM ESSs, which allow them to store excess energy generation for later use, as well as earn credits from energy arbitrage activities. However, since real-time pricing has yet to be widely adopted in the residential and commercial sectors, there is little data and experience on its effect on the economy and efficiency of PV/ESS. One application of such a pricing system might be in the realization of a peer-to-peer (P2P) energy trading mechanism in smart grids, briefly discussed in section 8.3. In this model, prosumers as price makers and consumers as price takers may trade energy together to optimize their return thanks to BTM ESSs and the real-time pricing mechanism [80].

#### 3.2.2. Demand charges

Demand charges are introduced for a certain period during a billing cycle, known as on-peak hours, during which every extra kW of power used above a maximum threshold set by the utility will incur a demand charge [70]. Under this pricing scheme, two customers with the same amount of energy consumed from the grid over a billing period may receive different bills due to their different usage patterns [81]. For prosumers, the installation of an ESS provides the opportunity to store excess PV for later use, especially to cover their demand during peak hours. Hence, it is expected that implementing demand charges along with conventional volumetric tariffs may increase the effectiveness and thus the attractiveness of BTM PV plus ESS. For example, in Ref. [82] it is shown that the introduction of demand charges has resulted in more bill savings for PV plus ESS owners than those who only have PV.

#### 3.2.3. Sell rate design

The sell rate (also known as feed-in tariff) has a pivotal impact on the efficiency and economics of BTM PV plus ESS. Under Gross/net metering, for example, the sell rate is set equal to the retail electricity prices, so prosumers have no reason to install ESS and incur installation and maintenance costs, unless utilities impose limits on authorized hours and the amount of energy sold to the grid [69]. On the other hand, in net billing systems, the PV feed-in tariff is lower than volumetric retail prices. Therefore, as previously explained, PV self-consumption would be much more economical than exporting electricity to the grid, encouraging the use of ESS paired with PV [25]. Furthermore, as with volumetric retail tariffs, sales rates can be set dynamically and be variable over time to control the rate of energy export to the grid by encouraging or discouraging exports taking into account the network's demand-supply balance [83].

## 4. Applications

So far, behind-the-meter ESSs have offered many services ranging from energy-based services for power system utilities and end-users to non-energy benefits for their host network, as seen in Fig. 3.

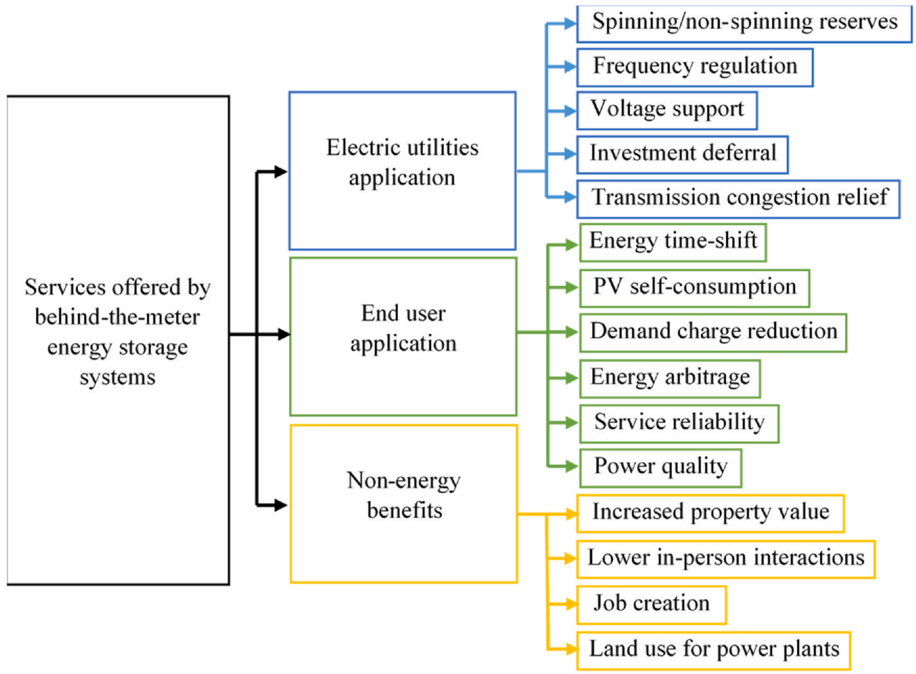


**Fig. 3.** Potential services offered by BTM ESSs.

### 4.1. Electric utilities application

BTM ESSs have been identified as an asset to ensure the safe and smooth operation of power systems via providing several options for utilities, listed as follows.

#### 4.1.1. Spinning reserve and non-spinning reserves

The power system should always be protected against excessive fluctuations in frequency and power flow, even when the largest power generator goes down. Historically, it's been accomplished using a reserve capacity in the generation units, which increases costs and affects energy efficiency [65]. However, under aggregation platforms, a large number of BTM ESSs can act as a single entity and be considered as a reserve capacity to provide energy for the network as required [84,85].

#### 4.1.2. Frequency regulation

In AC systems, power transmission frequency from generators to end-users must be kept at the synchronous frequency, 50 Hz for Europe and Asia, 60 Hz for South and North America [86]. The power system frequency is directly influenced by the equilibrium between demand and supply, and when that balance is achieved, the frequency is therefore stable. In conventional power systems, frequency regulation is attained by adjusting the rotational speed of synchronous generators, driven by steam turbines, gas turbines, or hydro turbines, by turbine governors in response to deviations from nominal synchronous speed, taking into account changes in the network demand on a second-by-second basis. The growing number of RESs raises the rate of fluctuations in the power generation side, making it even more challenging to maintain the demand-supply balance in microgrids [1]. BTM ESSs have become a more appealing option for frequency services because of their lower cost compared to load-following power plants, due to faster response times, and more flexibility when compared to fuel-based generators [85–87].

#### 4.1.3. Voltage support

The voltage level, like the frequency regulation, must be stabilized at the allowable range to ensure efficient and reliable operation of the power system. To do this, the grid operator controls the reactance across the entire network, using an ancillary service called voltage regulation [14]. To date, generators able to provide reactive power have been used to control the level of reactance in the power system. But reactive power can only be transmitted over short distances, so users located far from centralized generators experience voltage drops. This issue has been alleviated by installing BTM storage units in customers' premises where ESSs may act as a load or a generator in case of overvoltage or undervoltage, respectively [88,89].

#### 4.1.4. Network investment deferral

With the increased demand for electricity, more investments in power generation, transmission, and distribution sectors are unavoidable for utilities. To this end, the introduction of BTM ESSs to low/medium voltage networks, considering the services they may offer to both utilities and users, can defer or even reduce the investment costs to a great extent [90].

#### 4.1.5. Transmission congestion relief

Congestion in electricity transmission lines is one of the grid's challenges especially during peak hours when due to transmission constraints the transmission lines are not sufficient to transfer the power and support all requests [71]. Utilities aim to address this issue by introducing dynamic tariffs to encourage end-users to participate in demand-side management programs, but since the full implementation of these programs is not guaranteed, the problem continues to cost utilities and consumers alike. Utilities may subsidize the installation of BTM ESSs to use the accumulated storage capacity to store energy and release it during peak hours for local demand, thereby reducing congestion levels on power transmission lines [91].

### 4.2. End-user application

Power system customers with or without PV can implement BTM ESSs to have better control over their energy usage and avoid possible costs associated with poor power quality and reliability. Besides, they may benefit from their ESSs via energy arbitrage or entering into a contract with a utility or a third-party aggregator for grid ancillary services [91,92]. In the latter scenario, the aggregator may group individual ESSs and enable the utility to exploit the potential services offered by the aggregated ESSs as a large capacity single entity [93,94].

#### 4.2.1. Energy time-shift

The simplest but most cost-effective strategy in networks with variable tariffs is to transfer grid demand to hours when electricity rates are lowest, as much as possible. ESS owners can purchase and store energy during off-peak/low-price hours to use later during on-peak/high-price periods to fulfill their needs [15,95].

#### 4.2.2. Self-consumption of on-site renewable generation

Pairing PV systems with ESS enables prosumers to store excess PV generation for later use, particularly during the middle of the day when PV output exceeds household demand. This will reduce end-user reliance on the grid and save money on bills, depending on the retail tariff structure. This is an especially useful solution for remote microgrids with limited access to the main grid [28,87].

#### 4.2.3. Demand charge reduction

Currently, demand charges account for 40–50% of commercial and industrial customers' bills. The implementation of these tariffs on the residential sector in some areas has heightened interest in small-scale ESSs. Similar to energy shifting strategies, ESS owners can store energy and use it later for peak-shaving, saving them a lot on their bills [15,73,76,82,95].

#### 4.2.4. Energy arbitrage

In networks with a significant gap between power tariffs at different intervals, BTM ESS owners can purchase and store electricity during low-price hours to sell it back to the grid at a later time when electricity is more expensive. However, because of the high cost of ESSs and unavoidable power losses associated with charging/discharging, energy arbitrage alone is not very profitable and is usually offered combined with other services (stacking ESS revenues) [95–98].

#### 4.2.5. Electric service reliability

During a power outage, BTM ESSs may supply the on-site load for a certain period, depending on the installed capacity. This is particularly critical in regions where natural disasters such as lightning, flooding, and earthquakes pose a high risk of power outages. Currently, most hospitals, data centers, military installations, and emergency services use BTM resources to ensure an uninterrupted power supply for their operation [99,100].

#### 4.2.6. Electric service power quality

Installed BTM ESSs may provide protection for on-site equipment against potential damages by poor power quality from the grid. Examples include transient high-frequency deviations and voltage fluctuations which can be effectively addressed by designing advanced ESS management systems using modern power electronics [101,102].

### 4.3. Non-energy benefits

BTM ESSs can offer a range of advantages outside of energy markets. Although it is impossible to quantify their impacts in detail, some of them are mentioned below.

#### 4.3.1. Increased property values

BTM ESSs will increase the value of the property in which they are installed by reducing reliance on the grid and thereby saving money on energy bills. Like other advanced technologies, this is an advantage and can be effective in the marketability of properties [103].

#### 4.3.2. Avoided collection, termination, and reconnections

Electric utilities always incur high costs for non-paying customers. Usually, a procedure must be followed to disconnect and/or reconnect those customers from/to the network, which requires utilities to bear associated costs. In the United States, for example, the costs associated with the termination and reconnection are estimated at $1.85 per customer per year [104]. Customers with BTM ESSs will have reduced billing costs thus it will decrease the number of ratepayers who are unable to pay their bills.

#### 4.3.3. More job opportunities

The use of BTM ESSs has the potential to create a significant number of job opportunities in a variety of fields, including manufacturing, marketing, sales, installation, and maintenance of the equipment. It also opens up investment opportunities in the technology industry, which may result in hiring a large number of experts and researchers to make progress in the area of BTM resources [105].

#### 4.3.4. Better land use and fewer emissions

Ideally, the installation of an adequate number of BTM ESSs and implementation of a smart virtual power plant (VPP) eliminates the need to build gas-fired peaking power plants by utilities, which means reduced power plant land usage. Meanwhile, the advent of BTM systems necessitates the allocation of land to construct a plant for the manufacturing of equipment, but they are less land-intensive and also provide significantly more added value than peaking power plants. Furthermore, by reducing the need for new fuel-based generators and facilitating the integration of RESs into low/medium voltage power systems, environmentally friendly BTM resources may be effective solutions to air pollution in metropolitans [9,13,15,96,103].

## 5. Approaches to optimizing the operation of BTM ESSs

Optimizing the energy efficiency of BTM ESSs entails optimizing the operational strategy for BTM resources for a given BTM available capacity while taking into account host system characteristics. But, deciding on which optimization method serves the best for a given BTM energy management problem is always a challenging process. It necessitates a thorough understanding of mathematical modeling of system components and their interactions, as well as familiarity with feasible solution search spaces, variables, and optimization algorithms. Overall, an algorithm should be chosen based on a problem's search space and its dimensions, defined by the problem formulation and its constraints. In many cases, either due to lack of time or sufficient background information about different methods, researchers choose one algorithm that works well with one problem and implement that to solve all other problems. So, they may not produce optimal solutions that might be found using alternative approaches. Therefore, in this section, an effort has been made to provide a brief overview of different optimization methods, and their application to the scheduling of BTM PV plus ESS in smart grids.

Optimization can be defined as an attempt to find the best solution from a set of available feasible solutions to a problem. In terms of the number of objective functions and optimization criteria, there are two types of optimization problems: (1) single-objective optimization problems, and (2) multi-objective optimization problems [106]. The former is implemented when the purpose of solving a problem is to improve a single performance index whose minimum or maximum fully reflects the quality of the results obtained. On the other hand, in some cases, a decision-making problem may have several dimensions/objectives that need to be optimized, so-called multi-objective optimization problems [107]. In BTM projects, for example, minimizing end-users billing costs and enhancing grid reliability and thereby increasing utility revenue must be accomplished simultaneously. Multi-objective optimization leads to finding the best feasible solutions (Pareto front) that are not dominated by other possible solutions in the search space, which enables decision-makers to achieve a range of optimal feasible solutions each of which can be selected based on utilities' priorities [78].

Given the literature, the optimization methods can be categorized from three different perspectives [108,109]. First, centralized solutions versus distributed methods. The former refers to a situation in which a central unit makes decisions and those decisions are passed down from top to bottom, just like the way load dispatch centers control traditional power grids [110]. The latter is a scenario in which the decision-making authority is distributed among all players, with each participant eventually contributing to the systems' overall optimality by making the best feasible decision [89]. Second, they can be classified into two groups depending on the problem-solving approach: single-stage and multi-stage. For example, in single-stage, a battery charge/discharge schedule for a day is optimized at the start of the day [111]. This process can be broken down into 24 steps, one for each hour, and instead of solving the problem all at once, the optimization can be performed separately for each hour [79]. The third viewpoint divides the problem in terms of whether the problem inputs are deterministic or stochastic. If the problem data contains uncertainty, it will be a stochastic optimization method that aims to maximize the expected outcome [87]. On the other hand, it is a deterministic problem if the inputs are already available without any uncertainties [111].

In the following subsections, the presented optimization methods are reviewed and classified taking into account decision policies based on which they are implemented. The overview of the methods is presented in Fig. 4.

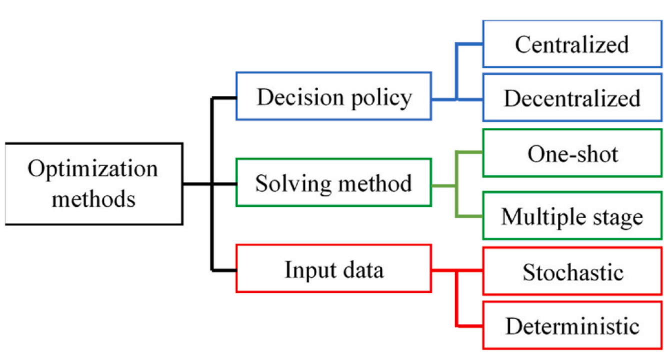


**Fig. 4.** Classification of optimization methods.

### 5.1. Centralized strategies

In this method, orders are issued from top to bottom, the most common type of which is the direct load control agreement, in which customers allow utilities to control some equipment in exchange for payment [112]. The problem formulation is categorized into the following groups based on the structure of the energy management system.

#### 5.1.1. Linear programming (LP)

In LP, unlike non-linear programming (NLP), the objective function and problem constraints are formulated linearly, and inputs are deterministic [113]. An LP problem can be solved using one of these three approaches: the graphical method, the algebraic method, or the simplex method. In general, the first two methods are being used for problems with a maximum of two target variables, but the simplex method may be used for problems with a large number of optimization variables due to its high speed [107]. Many well-known tools, including LINGI & LINDO, STORM, TORA, LINPROG, and WINSQB handle LP problems using the simplex method. Authors in Ref. [114] presented an optimal sizing strategy for BTM resources using an LP method. Since the inputs to LP problems are deterministic, the impacts of the stochastic behavior of PV generators, end-users, and energy prices on optimization problems cannot be investigated.

#### 5.1.2. Heuristic/metaheuristic optimization

Heuristic methods may solve problems faster than classical methods and offer an approximate solution when classical methods fail to provide an exact solution [107]. There is always a trade-off in heuristics between computing speed, solution optimality, feasibility, completeness, and accuracy. A heuristic optimization is typically successful on a range of problems, although it may not result in the best solution, especially when dealing with real-time BTM problems with a huge amount of uncertainties [115]. For such intractable problems, metaheuristic optimization techniques have been established. Genetic algorithms (GAs) are of the most well-known metaheuristic methods. GAs are population-based algorithms, which search through a search space to find the optimal value for their objective function [116]. Authors in Ref. [117] optimized charge/discharge schedules for commercial BTM ESSs using a GA algorithm. Another well-known algorithm is the particle swarm optimization (PSO) algorithm, which is an iterative algorithm that seeks to improve the quality of feasible particles/solutions to the problem with each iteration, ultimately arriving at the local/global optimal solution [118]. The work presented in Ref. [119] employs the PSO algorithm to solve the EVs' fast-charging problem via optimizing the power flow from BTM installations. Heuristic and metaheuristic algorithms are also widely used for integer linear optimization[1] (ILP) and mixed-integer linear programming[2] (MILP) problems. For example, in Ref. [76] a problem is formulated as a MILP and solved using heuristic methods. Reviewing the literature, heuristic and metaheuristic algorithms have also been deployed for mixed-integer non-linear programming[3] (MINLP) problems. In Refs. [120,121], using MINLP programing, energy management controllers are proposed to minimize customers' billing costs while offering grid services.

#### 5.1.3. Convex optimization

The problem of convex optimization is to find the minimum value of a convex objective function (or the maximum of a concave function) from a convex set taking into account constraints defined as convex functions [122]. The most important advantage of convex programming is that each local optimal point is also a global optimal point, meaning that if any optimization algorithm finds a locally optimal point, it will be a global optimal point as well. Convex problems are more general than LP problems, but they share many of the same desirable properties. If a problem is formulated as a convex optimization problem, thanks to the recent advancements in optimization and computation, the solution is as straightforward as LP [123]. Some solution approaches include Lagrange multiple methods, conic programming, least squares, and geometric optimization [124]. The BTM energy management problem in Ref. [125] is formulated as a convex problem.

#### 5.1.4. Dynamic programming (DP)

In DP, the problem is broken down into phases and solved one by one. This approach is used when problem parameters are time-correlated and change over time [107]. In this case, the problem cannot be optimized at one shot but must be solved by taking into account the effect of changes on each interval's decisions [126]. For example, the Markov decision-making process has been heavily used in the literature to solve dynamic programming problems in which the goal is to find a strategy to maximize the reward for the actions taken at each step [127]. In Refs. [126–128], authors used dynamic programming for the BTM batteries scheduling problem.

#### 5.1.5. Stochastic optimization

In stochastic optimization problems, objective functions and constraints are formulated in such a way as to capture the effects of uncertainties in inputs on the optimization result. In stochastic

[1] It is similar to linear optimization problems, with the exception that all or some of the variables are integers in the problem.

[2] It will be a MILP problem if certain variables are expressed as integers and the rest are expressed at non-integers.

[3] Similar to MILP except that some constraints of the objective function itself are non-linear.

optimization problems, uncertainty is combined in the model programming and the goal is to find a policy that is feasible to all (or nearly all) data samples while also maximizing the model's expected efficiency [129]. In this case, the problem is represented by a set of probabilistic scenarios (a scenario tree) that represents the potential steps at each time. So, it may suffer from the curse of dimensionality when the problem is formulated as a multi-stage stochastic optimization problem. To overcome this challenge, two-stage stochastic programming methods are applied in which; 1) first the decisions in each step are taken based on available data and not based on future observations, and 2) the decisions are updated once the random event happens [130]. So far, several powerful methods for stochastic problems have been proposed in the literature, among which Lyapunov optimization, Markov Decision Processes (MDP), and model predictive control (MPC) are widely used methods for BTM ESS optimization problems. Authors in Refs. [131, 132] use MPC to solve the BTM battery scheduling problem to provide both energy and ancillary services for a microgrid. In Ref. [133], a Lyapunov optimization method is deployed to obtain the optimal strategy for residential BTM resources.

### 5.2. Decentralized strategies

The use of centralized optimization approaches creates privacy and data protection concerns, as these systems rely on comprehensive information on end-users usage habits [109]. Decentralized strategies are introduced as an alternative that does not infringe on the user's privacy and comfort, in which individual users make their own decisions to maximize their performance, which ultimately leads to system performance optimization [134]. One example of decentralized control strategies is the implementation of different electricity tariffs, which by offering economic incentives, encourages customers to comply with a utilities' desired plan. While time-variant pricing has long been employed by utilities, recent studies show that using them alone is insufficient, and their ability to manage the demand-side is limited [135]. Hence, game-theoretic strategies, inspired by applied mathematics that provides tools for analyzing the situations of game parties and their mutual decisions are proposed [136].

The focus of game-theoretic strategies is a game scenario, which represents a model of an interactive situation among rational players [137]. The concept of game theory is that one player's efficiency depends on the strategy implemented by the other players. This game determines the identity of the players, the existing preferences and strategies, and how these strategies affect the outcome of the players. The concept of game theory is widely deployed for BTM energy management problems, due to its capacity to deliver distributed self-optimizing and self-organizing solutions to problems with conflicting objective functions [109]. When defining a game, the player setting can be multiple utilities – multiple customers, single utility – multiple customers, and/or single utility – single customer. Game-theoretic methods can be divided into two types based on the interaction model between players; 1) cooperative games, in which players have reached a contractual agreement [138], 2) non-cooperative games, including players with no binding agreement among themselves [139].

In cooperative games, players communicate with each other and act as a super-entity for mutual interest, like what happens in VPP programs via the collaboration of a network of BTM ESSs. Works in Ref. [140], employed such a strategy to obtain an optimal operation strategy for BTM resources to minimize billing costs and payback period for battery storage as well as offer regulatory services. They've shown that customer collaboration brings opportunities for cost reduction and efficient system operation. A similar management strategy is proposed in Ref. [141], where a coalition and the cooperative game are introduced to a group of residential prosumers to increase the rate of PV self-consumption. In these cases, when the players reach their optimal point, they are no longer willing to change their strategy, so the system reaches a state of equilibrium, known as the Nash Equilibrium. This is the point at which no player (assuming the rest don't change their game) gains more profit by changing their strategy.

Non-cooperative games look at the effects of decisions made by a self-interested group of rational players who have no ties to one another on a system's overall performance [107]. However, in some cases, a collaboration between players may occur for self-enforcing reasons. Since complete coordination and cooperation among end-users and utilities is nearly impossible, non-cooperative games have been widely utilized to address the energy management problem in microgrids with BTM resources. In Ref. [142], an aggregative game is developed for a group of self-interested end-users to modify the network demand curve via optimizing the operation of BTM batteries. Authors in Ref. [143], used a stochastic differential game-based battery scheduling model for smart houses with un/controllable loads and EVs. In these studies, players maintain their strategies after reaching the equilibrium point.

An overview of optimization studies carried out in the literature, using the aforementioned methods has been listed in Table 4. Gaps and challenges associated are further discussed in section 7.

## 6. Case studies

The integration of distributed ESSs into low/medium voltage power systems has been accelerated by large investments in transferring a portion of power generation capacity to the power distribution system close to end-users, particularly using roof-top PV arrays. As a result, the traditional power sector has experienced a paradigm shift in terms of energy management strategies. Behind-the-meter ESSs are relatively new elements in the distribution network, however, their advantages have established them as a viable option for both end-users and grid utilities [15]. Hence, distributed ESSs have seen a 605 MW rise in installed capacity worldwide in recent years, with a significant share of residential BTM units [146]. The capacity of BTM ESSs is projected to continue to expand, with the installed power capacity expected to reach 20 GW by the year 2025, Fig. 5.

The key drivers of BTM resources deployment include increased end-users interest in self-consumption and energy supply security, power quality and reliability, as well as dynamic pricing schemes that help them to offset their billing costs [7,73,77,81,103]. The variety of services and opportunities offered by BTM ESSs to both customers and utilities have led to plenty of energy projects, from small-scale to large-scale, across the world. This trend is expected to accelerate as associated costs are expected to fall further, making BTM technologies more accessible to customers, Fig. 6. BTM ESSs are being deployed in many regions, examples include Australia, Netherlands, Japan, the United Kingdom, and the United States.

### 6.1. Australia

Due to its great solar potential, Australia is one of the countries that has invested a lot in BTM PV plus ESS projects to shift away from fuel-based power plants. For example, the artificial power plant project implemented by the Australian Gas Light company (AGL) in Adelaide, using over 1,000 residential and commercial small-scale BTM systems [149]. The AGL operates based on a cloud-based management system that enables ESSs to communicate with each other, creating an integrated system that can function like a 5 MW power plant. This project tries to reduce billing costs for ESS owners while still providing regulation services and reserve capacity for the local microgrid. Another example is the $25 million worth 36 MW residential BTM ESS project funded by the Australian Capital Territory government under the Next Generation Energy Storage program [150]. This project is aimed to equip households in the territory with BTM ESS to help them reduce billing costs by storing the PV excess generation for later use and energy backup during a power outage.

**Table 4**
A summary of a few papers with their main optimization technique and objective.

| Ref. | Solver | Category | Optimization objectives | Impacts of optimization | Year of pub. |
|---|---|---|---|---|---|
| [44] | Hybrid chaotic search/ harmony search/simulated annealing algorithm | Metaheuristic | To obtain the optimal size of distributed energy resources aiming to maximize the efficiency and reliability of a hybrid system for remote areas. | A 7% reduction in the levelized costs of electricity production by an optimal combination of a wind turbine, battery storage, and power electronics. | 2018 |
| [144] | Harmony search algorithm | Heuristic | To optimize the operation for an on-site hybrid renewable generator and hydrogen storage system to minimize the operating cost of a microgrid. | The optimized hydrogen system reduced the amount of energy purchased from the grid, resulting in a 9.6% reduction in daily costs of electricity supply. | 2018 |
| [68] | Gurobi | NLP | Optimizing the size of a grid-tied PV system to maximize the net present value of the BTM project and minimize the electricity costs for Croatian households. | The PV payback period is reduced to less than 10 years under the current Croatian net metering system. | 2021 |
| [78] | Multi-objective wind-driven optimization algorithm & multi-objective genetic algorithm | Stochastic | To minimize the operation cost, emissions, and to maximize the efficiency of renewable resources in a hybrid system. | The system operating cost and pollution emission are reduced by around 25%, and 15%, respectively. The availability of RES is maximized by approximately 20%. | 2021 |
| [93] | Linny-R software | LP | To optimally schedule BTM resources to minimize the total costs of electricity while satisfying local loads taking into account the possibility of energy arbitrage with the grid. | The total system costs are reduced by 12.8% compared with a system without distributed ESSs. | 2018 |
| [95] | Pyomo optimization modeling language | MINLP | To minimize the billing costs for customers. | The annual billing cost is reduced by 9.6%, from $702,600 to $634,600. | 2017 |
| [87] | Gurobi | Stochastic | To obtain the optimal schedule for a BTM ESS aiming to maximize the rate of PV self-consumption while offering frequency services. | 300% and 25% higher revenue from ESS compared to solely using ESS for self-consumption or frequency control, respectively. | 2019 |
| [98] | Gurobi | Convex | To minimize billing costs for BTM ESS owners under ToU and demand charge tariffs. | 46–64% reduction in mean peak net demand, 25–49% reduction in mean net demand fluctuations, and 24–39% increase in PV self-consumption compared to the case without BTM ESS. | 2017 |
| [100] | Gurobi | MILP | To minimize the facilities' total operation cost and enhance the power supply resilience. | The PV system capable of meeting 80% of the system peak demand, paired with a small ESS can serve all critical loads almost 100% of the time in case of a short-duration power outage. | 2021 |
| [101] | – | Game-theoretic strategy | To maximize cost savings taking into account real-time price signals broadcasted by utilities. | *Analytical results are provided depending on the use of ESS with various operational priorities.* | 2020 |
| [88] | cvx_toolbox | Convex | To improve power quality through providing voltage regulation and to offer demand charge reduction. | 30% improvement in battery degradation, reduction in the network peak load value from 137.8 kW to 37.8 kW. | 2019 |
| [90] | GLPK | MILP | To schedule charge/discharge for ESS to minimize the peak load and maximize the revenue from the ESS. | Over ten years, an increase in the ESS power rating from 1 MW to 10 MW resulted in a 17%–200% increase in revenue from ESS. | 2019 |
| [110] | Dual-simplex | LP | To minimize billing costs for BTM ESS owners. | A considerable decrease in peak power demand, resulting in a reduced demand charge. | 2016 |
| [111] | Branch and bound algorithm | MINLP | To minimize the payback period via optimizing the design of a BTM PV plus ESS system and scheduling the operation of the ESS. | A 38.5% reduction in utility bills. | 2019 |
| [117] | GA | Metaheuristic | To obtain the optimal size for BTM ESS to maximize the ESS net present value. | A 20% increase in the ESS net present value. | 2019 |
| [118] | Hybrid GA-PSO | Metaheuristic | To obtain the optimal site and size for distributed energy resources and to schedule the charge/ discharge for EV batteries. | A 54% reduction in daily power loss, a 41% reduction in voltage fluctuation in sensitive buses, and a 58% decrease in daily energy supply costs. | 2017 |
| [119] | PSO | Metaheuristic | To optimize the operation of BTM PV plus ESS aiming to support EV fast charging. | Efficient operation of the ESS through optimizing its SOC limits based on the PV, load, and prices forecasts. | 2017 |
| [113] | Linprog() | LP | To minimize the energy costs through the optimal dispatch of resources and ESS. | A 4.8% reduction in energy costs over three days. | 2013 |
| [120] | Pyomo optimization modeling language | MINLP | To find an optimal schedule for BTM ESSs that minimizes the energy costs while improving the power factor. | About $1000 saving in energy costs. Moreover, the ESS maintains a power factor over 0.9 in the case of high PV penetration. | 2018 |
| [121] | KNITRO in GAMS | MINLP | To optimize the charge/discharge for BTM ESSs to ensure the safe operation of the system under uncertainties. | The optimal sized ESS could minimize the impact of real-time imbalances imposed by onsite renewables and loads. | 2018 |
| [122] | – | Convex | To facilitate the penetration rate of distributed PV generators into smart grids by providing high observability of PV generation. | Possibility of monitoring home consumption and rooftop PV production independently with 42.24% and 31.67% less mean squared error, respectively, as compared to conventional supervised learning-based techniques. | 2018 |
| [125] | Alternating direction method of multipliers | Convex | To minimize the energy cost for smart homes via enabling peer-to-peer transactions between individuals. | Almost 23% reduction in users' peak load and the overall energy cost of the system. | 2021 |
| [126] | – | Dynamic | To obtain the optimal size of BTM ESS to reduce billing costs. | *Analytical results are provided depending on the use of ESS with various operational priorities.* | 2017 |

(*continued on next page*)

**Table 4** (*continued*)

| Ref. | Solver | Category | Optimization objectives | Impacts of optimization | Year of pub. |
|---|---|---|---|---|---|
| [127] | Markov decision process | Dynamic | To minimize the data prediction error required for accurate energy management for households with BTM PV plus ESS resources. | 5% reduction in electrical costs for smart homes, on average. | 2019 |
| [128] | – | Dynamic | To minimize long-term electricity costs under uncertainties associated with RESs and electricity prices. | *Analytical results are provided depending on the use of ESS with various operational priorities.* | 2020 |
| [130] | CPLEX Barrier algorithm | Stochastic | To optimize the resiliency of power supply for households with BTM PV plus ESS | The installation of PV plus ESS for power backup services can add up to 4% to annual electricity costs for customers, although this option is still about 25% less expensive than installing a diesel generator. | 2020 |
| [131] | Model predictive control | Stochastic | To optimize the dispatch of resources and schedule the operation of ESS to minimize the battery degradation and provide grid services. | Lower ESS SOC variations, resulting in lower battery cycling and a longer battery life cycle. Grid prices following on-site consumption, resulting in lower energy costs. | 2019 |
| [132] | Model predictive control | Stochastic | To reduce billing costs for commercial users. | More than 20% saving in billing costs on average, for input data with a range of uncertainties. | 2020 |
| [133] | Lyapunov optimization | Stochastic | To maximize the potential revenue from energy arbitrage as well as reduce the rate of battery degradation. | *Analytical results are provided depending on the use of ESS with various operational priorities.* | 2019 |
| [134] | Hybrid GA-PSO | Non-cooperative game-theoretic strategy | To obtain optimal charge/discharge schedules for EV that satisfies the needs of both customers and grid operator. | A 71% reduction in network load demand profile, 68% reduction in peak-valley difference, and 2.4% reduction in electricity costs. | 2021 |
| [136] | MATLAB optimization toolbox | Non-cooperative game theoretic strategy | To minimize the network peak load demand and the billing costs for BTM ESS owners. | More than 7% reduction in each household billing cost, 9% and 11% reduction in network peak demand and total system electricity costs, respectively. | 2019 |
| [137] | Interior point method | Non-cooperative game theoretic strategy | To minimize the total electricity cost for households with EVs. | $1.48 saving on EV owners' bills, and 21% reduction in the peak-valley difference in demand profile. | 2014 |
| [138] | Iterative linear optimization method | cooperative game-theoretic strategy | To minimize the energy cost for cooperative prosumers with BTM ESS. | *Analytical results are provided depending on the use of ESS with various operational priorities.* | 2019 |
| [140] | – | cooperative game-theoretic strategy | To maximize energy efficiency by improving the rate of BTM self-consumption. | 34% and 43% increase in individual agents' annual savings under flat tariff and time-variant tariffs, respectively. | 2021 |
| [141] | – | cooperative game-theoretic strategy | To maximize the energy efficiency and system balance under different pricing schemes with stochastic PV output. | A 0.9% reduction in total energy costs for 50 households taking into account uncertainties in load and PV generation forecasts. | 2015 |
| [142] | – | Non-cooperative game-theoretic strategy | To improve system demand profile through applying price signals as well as to minimize costs for BTM ESS owners by scheduling the battery operation taking into account electricity prices. | The operation of ESS for customers is optimized and the system is reached the Nash equilibrium state that ensures the maximum payoff for ESS owners. | 2014 |
| [143] | Inverse regression algorithm. | Non-cooperative game-theoretic strategy | To maximize the profit for EV owners and satisfy the needs of utilities via a demand-side management program. | The optimized model reduced the microgrid energy costs by 12.8% while improving the operating of EVs' batteries, resulting in longer-lasting batteries. | 2019 |
| [145] | – | LP | To maximize the amount of return on investment through optimizing the design of BTM PV plus ESS and scheduling the operation of ESS. | 58% and 62% reduction in peak electricity demand and demand charges, respectively. | 2020 |

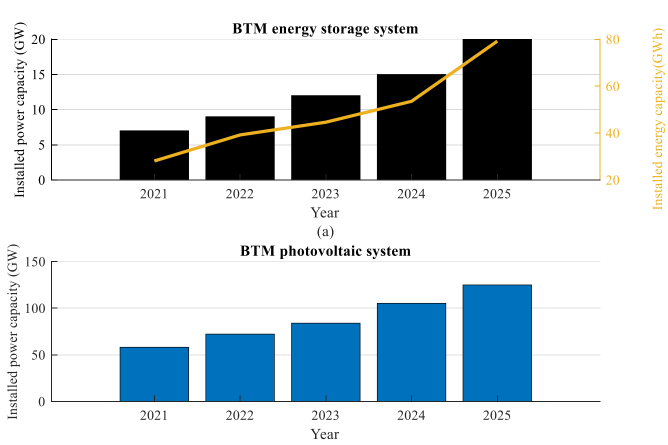


**Fig. 5.** Estimated capacity of installed BTM systems worldwide [146,147]. *(a) BTM ESSs; (b) BTM PV systems.*

### 6.2. Netherlands

Dutch utilities have realized a VPP project, known as CrowdNett, by implementing a network of interconnected residential BTM ESSs, which are also used to increase the rate of self-consumption for prosumers [93]. Like the AGL, here, in addition to the services provided for ESS owners, the accumulated storage capacity is also used for ancillary services and electricity markets, yielding benefits for utilities. To encourage households, they are paid financial compensation at around €500 a year to allow the storage capacity to be used for frequency regulatory services and reserve markets. Plans are underway to integrate the CrowdNett into Germany's and Belgium's power grids.

### 6.3. Japan

Japan has not been able to completely compensate for the loss of power capacity after the Fukushima Daiichi disaster led to the shutdown of a large portion of the country's nuclear generating capacity in 2011 [151]. Hence, Japanese company ENERES in collaboration with

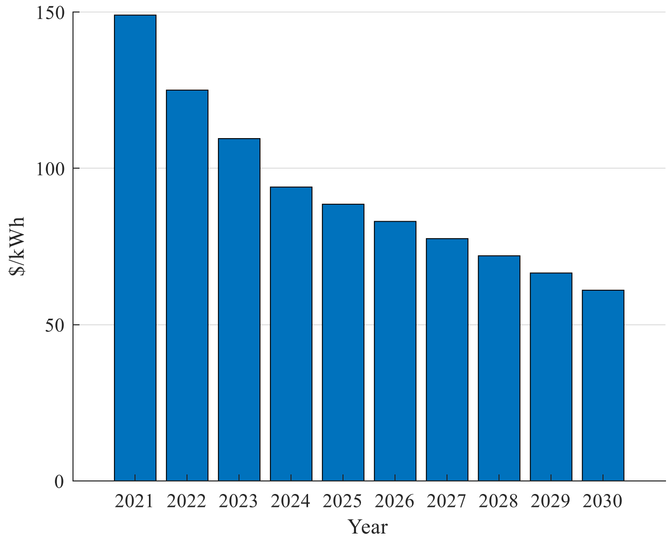


**Fig. 6.** The cost of lithium-ion battery [148].

American companies are developing the world's largest VPP in Japan. In the first phase, more than 10,000 BTM ESSs will be deployed for residential households [152]. Later, PV systems, plug-in EVs, and smart home thermostats will be integrated into this project, which turns it into a smart microgrid. End-users will not be charged for the installation of ESSs under this program, and the BTM resources will serve as a backup power supply in the event of a power outage.

### 6.4. United States

So far, many ESS projects have been implemented by utilities in the United States and many more are being implemented. For example, Vermont Green Mountain Power (GMP) has provided power backup services for its customers through the installation of BTM small-scale ESSs in their premises as part of an energy project known as Resilient Home [153]. GMP incentivizes end-users to install BTM batteries by subsidizing the purchase and installation of equipment (it costs customers $55 per month for ten years or one payment of $5,500) in exchange for permission to use the installed capacity for peak shaving on several days each year. Another example is the BTM storage project implemented by the New York utility Con Edison under New York's Reforming the Energy Vision initiative [154]. The project uses residential and commercial BTM batteries for capacity services, as part of an effort to defer $1.2 billion worth of network expansion. In California, low-income communities can avail of cash incentives (with a total budget of $100 million available) to buy and install BTM storage units in theirs premises, adding about 100 MW of new BTM storage to the grid. The decision was taken to protect the grid from the high risk of large-scale grid outages and rolling blackouts caused by natural disasters.

### 6.5. United Kingdom

Recently, UK Power Networks, a distribution network operator in the United Kingdom, announced its plan to implement a network of residential BTM systems to realize London's first VPP [155]. The project's pilot phase was completed in 2018, with 45 BTM batteries discharging during on-peak hours (peak-shaving) and charging during off-peak hours (valley-filling) to modify the network demand curve (demand--modification). The BTM resources are expected to be able to satisfy network demand during on-peak hours in winter, obviating the need for conventional fuel-based power plants thus reducing carbon emissions.

Table 5 summarizes some of the other BTM projects carried out so far.

## 7. Challenges

Integrating BTM energy storage systems into conventional power grids with outdated equipment may pose numerous challenges to the network's safe and efficient operation if not properly managed [81]. To this end, researchers and engineers have been working to improve the performance of these systems, as discussed in Table 4, but there are still challenges in the implementation of BTM technology that need to be addressed through further investigations. Therefore, in this section, an effort has been made to identify the primary technical and economic hurdles, as well as research gaps, in deploying BTM ESSs in power distribution systems.

### 7.1. Efficiency and profitability

Many reports summarized in Table 4 on the economics of BTM ESSs have found that the benefits of ESSs surpass the costs of installation and maintenance and that the costs may be offset. ESS owners may even generate net income after a certain period. With the progress of ESS

**Table 5**
List of some projects using BTM storage systems.

| Project | Location | year | ESS technology | Scale of ESS (MW) | Services |
|---|---|---|---|---|---|
| Johnson Control International's APAC headquarters [156] | Shanghai, China | 2017 | Li-ion | 0.1 | Demand charge reduction - Increasing PV self-consumption |
| Clemson University [156] | Wisconsin, United States | 2017 | Li-ion | 0.05 | Reducing energy purchase during peak hours |
| Case Western Reserve University's lithium-ion [157] | Ohio, United States | 2018 | Li-ion | 0.125 | Backup power - Frequency regulation -Smoothening of renewables generation |
| NMB MINEBEA [158] | Lincoln, United Kingdom | 2019 | Li-ion | 1 | Power resilience<br>Backup power |
| Monash university [159] | Melbourne, Australia | 2019 | Li-ion + VRFB | 1 | Increasing PV self-consumption -Power resilience |
| Georgian College in Ontario [160] | Ontario, Canada | 2020 | Li-ion | 2 | Demand charge reduction -Bill savings |
| TELEDATA [158] | Manchester, United Kingdom | 2020 | Li-ion | 2 | Energy, cost, and carbon savings |
| PANACEA [158] | Oxfordshire, United Kingdom | 2020 | Lead-acid | 1.5 | Power resilience |
| Lombardia's incentive program [161] | Lombardy, Italy | 2020 | Li-ion + flywheels | 11.2 | Increasing PV self-consumption -Demand charge reduction |
| LeConte Energy Storage [162] | California, United States | Projected-2022 | Li-ion | 40 | Increasing PV self-consumption -Backup power |
| Nexus Renewables U.S. INC [162] | California, United States | Projected-2022 | Li-ion | 27 | Demand charge reduction -Bill savings |

technology and a reduction in costs, BTM projects will likely be more efficient and cost-effective in the near future. However, the true value of a BTM unit to its owner depends on the network in which it is implemented, and the regulations set by the network operator, which has been fully discussed in the literature. In many cases, only net metering and ToU tariffs are considered in revenue-cost calculations, while, as stated, utilities are moving toward the implementation of the net billing system. Furthermore, many works are limited to short time spans and do not account for seasonal impacts as well as the battery calendric degradation behavior and its impacts on long-term costs for ESS owners. Also, the role of subsidies and support schemes have been largely overlooked. In networks where no subsidy for small-scale ESSs or variable tariffs are implemented, owners are generally unable to achieve the maximum value of their ESS, even if they offer services to the grid and utilities as well [24,59,163].

### 7.2. Battery degradation behavior

Battery degradation has been discussed in the literature in two ways; 1) it is not included in the objective function and has no effect on battery control, and 2) its effects on charge/discharge scheduling is investigated. From an economic standpoint, the first method cannot be accurate because, due to the high cost of batteries, failing to consider battery degradation in optimization means overlooking an important deterministic factor that can significantly alter how the ESS is used. In many works, battery degradation is added to the objective function as a cost, and the problem is treated as a single-objective optimization and solved using the weighting coefficient method. Although the degradation behavior is considered in the objective function, converting the problem into a single objective suppresses the number of charge/discharge cycles, and minimizes the charge/discharge power to minimize degradation-related costs. To resolve this issue, the coefficient of the objective function must be manually defined, which affects the accuracy of solutions. The most promising method is to solve the problem using a multi-objective optimization algorithm. However, the main challenge/research gap here is to use linear optimization methods to solve multi-objective problems.

### 7.3. Marginal value of BTM ESS versus grid-scale storage capacity installed in the grid

From an environmental standpoint, as the share of large-scale RESs in the generation side increases, the marginal value of rooftop PV decreases. Because increased generation capacity from RESs means reduced usage of fossil fuel-based power plants resulting in a reduced level of air pollutants [4]. Therefore, the decision whether to install distributed small-scale PV to reduce air pollution has no significant impact given the challenges and costs associated with these resources. The same could be said for small-scale BTM ESSs, since increasing the number of large-scale stationary ESSs on the grid might offer enough capacity to cover many grid services, obviating the need for additional BTM capacity. This may also lead to a reduction in the marginal value of existing BTM installations, as the services that have already been offered are being diminished. At present, this scenario is unlikely and is purely theoretical. However, the need for long-term planning to prevent such cases is essential for regulatory agencies, which has not hitherto been discussed in the literature.

### 7.4. Lost revenue by utilities

In networks where the utility employs dynamic electricity tariffs, customers equipped with BTM ESSs can move a portion of their demand during on-peak hours to off-peak periods at cheaper rates, lowering their billing costs, Table 4. On the other hand, part of the utility's revenue that was formerly generated by selling energy during peak hours is diminished [66]. So far, various pricing designs have been proposed to address challenges in systems with small-scale DGs, specifically to offset utilities costs, which can in turn increase costs for end-users [164]. Ideally, tariffs should be designed in such a way that they remain profitable for utilities even if most end-users are equipped with BTM resources and consume less energy from the grid, while not increasing overall costs for end-users. For example, part of the revenue from saving utility costs during reduced peak times can be allocated to support schemes for BTM installations. However, in addition to selling energy to customers, utilities may have other sources of revenue, such as performance-based rewards or energy conservation incentives granted by regulatory authorities.

### 7.5. Interactions between BTM ESSs and rooftop PV arrays

The real value of behind-the-meter PV systems and the design of feed-in-tariffs for their excess outputs have been and continues to be the source of heated discussion in the energy market. Some say that prosumers do not pay fairly for the costs of the system operation and maintenance, whereas distributed PV advocates say that PV arrays are extremely important in terms of the services they provide to local distribution networks and should be awarded more credit than they do under the existing retail system. The introduction of BTM ESSs paired with PV systems has given these discussions a new dimension [165]. As summarized in Table 4, BTM ESSs increase the rate of self-consumption and eliminate the duck curve effect,[4] lowering the costs of power generation, transmission, and distribution for utilities. Each of the services offered by BTM ESSs to on-site PV generators raises the marginal value of BTM systems and further complicates the design of compensation tariffs.

Reflecting the interactions between on-site PV generators and BTM ESSs on the design of feed-in tariffs is a complicated task, which has not been addressed in the literature. There may be two scenarios, both of which are controversial, 1) raising the compensation rate for BTM systems and/or 2) reducing compensation rates for prosumers without ESS. The former would be criticized as being a kind of cross-subsidization for ESS owners while it degrades the net value of PV systems without storage. The latter is opposed because it discourages end-users from installing PV on their premises. This dilemma has now led to the implementation of other methods and subsidies to support BTM ESSs that do not impair the value of PV generators [166].

### 7.6. Balance between individual control and aggregated control

As shown in Table 4, the primary factors that drive customers' investments in BTM ESSs are greater self-consumption, enhanced privacy, and independence in terms of grid consumption (self-sufficiency), as well as the desire to help increase the share of renewables in power generation to minimize air pollutant emissions [13]. But, it should be noted that these four frameworks are not always compatible and may lead to conflicts of interest. For example, when BTM ESSs participate in a demand-side management program to reduce the network peak demand, they can be managed in several ways; e.g., using smart pricing schemes and/or based on ruled-based schedules implemented by owners or a central controller [81]. In the case of implementing a centralized control, distributed BTM ESSs can be considered as a single large ESS, offering more efficient utility services and participating in ancillary services markets, where batteries with a size of less than 100 kW are not permitted to participate [13]. However, this may prohibit customers

[4] The gap between a network energy demand and available energy from PV arrays throughout the day, which will be widened as the number of PV arrays rises in the network. If there are no demand-side management programs, it results in a significant drop in the network net demand profile during peak PV generating hours, posing challenges for network operators in terms of frequency regulation and demand-supply balance [178].

from using ESSs as a backup power source. It also affects the ESS availability for PV self-consumption services, which contradicts the initial goals of self-sufficiency and privacy. On the other hand, in the absence of grid-scale control for coordination and harmonization, distributed ESSs that are managed independently and aim to maximize prosumers' self-sufficiency may not provide effective services for utilities [167].

### 7.7. Reliable communication and data privacy

BTM ESS owners, particularly prosumers, are often willing to enter into contracts with local utilities to earn revenue by offering ancillary services. The utilities are also pleased since it gives them access to more storage capacity and allows them to save on investments. Many authors assumed a perfect communication link between end-users and utilities, whereas the main challenge is establishing a reliable bi-directional connection to transfer data between end-users and utilities. For example, if the system operator sends the peak load signal to ESS owners but they are unable to receive it or simply do not set their devices to discharge, the potential capacity of ESSs is wasted [91]. Giving utilities access to control ESSs is one approach, but although it improves the quality of services, it also increases exposure to cyber-attacks. Moreover, customers are concerned about the prospect of access to their precise energy consumption data. There may be cyber-attacks by malicious third parties, such as sending fake signals to storage owners or stealing end-users information [168].

### 7.8. Electricity pricing to incentivize BTM ESS installation

In terms of pricing strategy for electricity retail markets, there is a need for tariff flexibility to provide a reasonable price signal that reflects the actual costs of the power system and creates a strong signal to boost investments in BTM technologies. In tariff design, the interests of all network players should be taken into account. Also, to incentivize BTM owners to contribute their storage capacity for network services, a fair compensation program should be defined [59]. Smart tariffs are currently used in many countries, however, their implementation in some regions has not yet been completed and is still under investigation. In the Netherlands, for example, several pilot projects under the national regulatory authority ACM are currently ongoing to facilitate the potential implementation of smart tariffs in the future. Although BTM ESS capacity has increased in recent years, this trend is expected to continue drastically with the implementation of innovative pricing schemes that maximize ESS efficiency for both owners and utilities [15].

### 7.9. Stacking revenues for BTM ESS owners

As mentioned in Table 4, ESSs can be configured and programmed to deliver multiple services at the same time, ranging from on-site power balancing for prosumers to fast response regulatory services for local utilities [84,92]. However, the effective implementation of such a value may be constrained by some potential regulatory limitations introduced by local regulatory agencies, which is underestimated by many authors. For example, the capacity allocated for fast response services may often not be allowed for backup energy reserve, regardless of whether the capacity is envisaged to be called or not, wasting the potential capacity [166]. Besides the current compensation programs, none have been designed depending on the type of service provided by ESSs to the grid. On the other hand, in the absence of an appropriate optimization strategy, the overall costs for customers may be increased due to the high costs of batteries and cutting-edge inverter technologies for such applications.

## 8. Potential direction for future work

In the literature, many works have focused on optimizing ESSs in low voltage networks to maximize their profitability and efficiency, especially in the case of services for end-users. Meanwhile, more efforts should be made to employ BTM ESSs to deliver services to utilities as well, aiming to maximize their value by offering multiple services to customers and the power system at the same time. In the following, potential directions for future research works are discussed.

### 8.1. Revenue stacking opportunities

Other than providing on-site backup power, small-scale ESSs can deliver a broad range of other general services for both their owners and utilities, such as participating in ancillary markets and providing energy services through aggregators. Each of these services, in the presence of effective compensating economic programs, can offer additional value to both end-users and utilities, lowering the costs for ESS owners and reducing its payback period. Hence, it is worth investigating how to design effective energy management strategies to enable BTM ESSs to provide multiple services at the same time.

### 8.2. Aggregation models for BTM ESSs

At present, due to their limited capacity and power, small-scale BTM ESSs are not able to participate individually in the energy and regulatory markets [13]. Therefore, aggregators have been introduced to the power system that group BTM ESSs to act as a single super-entity when participating in energy markets or selling ancillary services to utilities [84]. In a few countries, like the United States, residential BTM ESSs are being used to provide services for local utilities through aggregators as part of planning for future power systems. The New York Independent System Operator (NYISO), for example, has implemented a new energy policy that permits an entity to aggregate BTM residential ESSs to participate in grid services [169]. Therefore, it is critical to investigate how individual ESSs might be aggregated to offer services while avoiding negative impacts on system operational indices like stability and reliability.

### 8.3. Peer-to-peer electricity trading

The purchasing and selling of energy between multiple parties (generators, prosumers, and consumers) is referred to as P2P trading [170]. Pilot studies have seen that prosumers can transfer and sell excess PV production to another user via a secure platform. Individual end-users are turned from passive to active controllers of their local network thanks to P2P, which may eliminate network growth constraints while also offering savings on investment and operation costs. So far, various pilot projects have been carried out in different countries to assess the feasibility of implementing P2P trading mechanisms in microgrids, such as Solar Share in Singapore [171], ISGF in India [172], SEDA in Malaysia [173], and LO3 in the United States [174]. It thus requires studies on the potential impacts of BTM ESSs on P2P technology, which can lead to a secure platform with an effective pricing system to ensure the safe operation of microgrids.

### 8.4. Joint optimization of BTM ESSs and plug-in EVs

Electric vehicles as mobile ESSs can either be utilized to store excess PV output for later use or they can participate in the ancillary market through an aggregator. However, charging and discharging the battery several times shortens its lifetime and raises the costs to EV owners [118]. Some utilities have proposed incentive packages to attract EV owners to engage in regulatory programs. In the United States, for example, EVs are compensated for their frequency services to the grid, as set down by the Federal Energy Regulatory Commission (FERC) [175]. Therefore, designing effective incentive programs that lead to increasing the participation of EVs in utilities' desired programs is of great importance and should be deeply studied.

On the other hand, a large number of uncertainties in EV drivers' behavior, electricity prices, and PV output has made EV scheduling for regulatory services a challenging process [134]. Committed EV battery capacity may not be always available for regulatory services, resulting in calculation mismatches that jeopardize the systems' safe operation at key periods. One solution is to deploy joint optimization of BTM ESSs and EV batteries to compensate for possible inconsistencies in network scheduling [145]. In this way, a significant capacity of BTM residential/commercial ESSs no longer need to be occupied for reserve services, regardless of whether the capacity is required, and they are only utilized to compensate for the unpredictability of EV owners' behavior. Hence, developing effective ways for creating optimal coordination between BTM ESSs and EVs to minimize the costs and planning errors is a critical area for further studies.

### 8.5. Integrating batteries with electrolyzers – battolyser

Electrolyzers for storing excess RES generation in the form of hydrogen have lately sparked attention around the world, accelerated by the technical challenges and limitations associated with conventional ESSs. This technology, known as green hydrogen, uses RES output to split water into oxygen and hydrogen molecules while emitting no $CO_2$ into the atmosphere [45]. However, worries about low hydrogen roundtrip efficiency and degraded performance of a RES-powered electrolyzer have led to a focus on the use of batteries to increase the energy efficiency of the water electrolyzer. Battery-assisted electrolyzer technology, also known as battolyser, allows for the storage of electricity for both short-term and long-term periods [176]. The battery bank stores excess RES output to support the electrolyzer when the available power is less than the electrolyzer's power rating. This process reduces the frequency of the electrolyzer's startup/shutdown under intermittent RESs output and thus increases the overall system efficiency and electrolyzer's lifespan.

Because there is a strong dependence between the electrolyzer's power rating and the battery capacity, these values must be designed in such a way that the battery can enable the electrolyzer to run at maximum efficiency in either case of surplus RESs output or a case of energy shortage. If so, the electrolyzer's required capacity is reduced, while its efficiency with the leveling of RESs output is improved, lowering the levelized cost of hydrogen production. It can be a solution for remote areas with scarce solar and wind resources, where the output of RESs is often less than the required power to run an electrolyzer. However, this technology is still expensive, which highlights the need for further studies to provide methods to maximize energy efficiency and make it affordable for end-users and utilities alike.

### 8.6. Impacts of malicious attacks on BTM ESSs applications

With the proliferation of the internet and wireless networks in energy applications, an interesting and practical extension is how to protect BTM resources against potential malicious cyber-attacks [65]. For example, when ESSs are used for frequency regulation, a malicious third party may send a fake signal to customers instructing them to charge/discharge their devices when this should not be done, causing network frequency deterioration. In the case of centralized management, a cyber-attack on the communication system between SMs and the central controller may occur, manipulating data in transit, resulting in the loss of energy services provided by BTM ESSs and destabilization of network operation. One of the effective ways is to use BTM ESSs to send controlled noisy data to smart meters input to minimize the possibility of extracting raw readable information from meters output for malicious third parties [177]. Therefore, it is critical to simulate different possible scenarios and evaluate their impacts on BTM ESSs performance so that the system operator is prepared in advance for any eventuality.

## 9. Conclusions

In this work, an effort has been made to investigate in depth the technologies required to deploy a BTM system. Following that, different metering and billing systems, as well as their impact on the economics of BTM systems, were investigated as one of the most important factors. A full taxonomy of BTM ESS applications and services has been presented to delve deeper into the benefits and potential afforded by such systems. Optimization strategies implemented to address the energy management problems in the presence of BTM ESSs have also been studied, with each receiving a brief but thorough discussion. Following that, a summary of numerous case studies that have been implemented around the world is offered. Next, potential challenges in the deployment of BTM systems were investigated, followed by a comprehensive discussion on potential areas for further research to ensure the long-term viability of future BTM systems in addressing environmental and economic challenges. Finally, a conclusion of the materials is investigated.

Behind-the-meter ESSs have a great deal of potential to bring progress for their host networks by enhancing the reliability and security of electricity supply and paving the way for 100% renewable-based energy systems. Recent cost reductions and the emergence of new storage technologies, as well as the rise of industry expertise and innovative optimal control strategies, have given BTM ESSs even more potential and more efficient solutions. However, getting the most out of these resources requires the provision of appropriate infrastructure, including intelligent metering systems, power electronics, and decision-making strategies. Many countries have paved the way for the widespread use of BTM resources in the power distribution system by meeting its prerequisites, so that while end-users benefit from the on-site services, the potential accumulated storage capacity can be used to improve the overall performance of the power system. From case studies, lithium-ion batteries are currently the most widely used technology for BTM services, but the desire to enjoy the benefits of different technologies at the same time has recently led to the use of hybrid storage systems, such as Li-ion-flywheels and/or Li-ion-flow batteries. However, given the potential services offered by BTM ESSs versus the real case studies that have been implemented so far, it appears that many of them are still not fully leveraging these resources due to the challenges and obstacles to efficient implementation.

The presented work uncovered numerous influencing factors, opportunities, challenges, and potential solutions, as well as recommendations that could aid researchers, academics, and industries in modifying and improving existing BTM systems to a higher level. Thus, the main contribution of this study is a thorough investigation of BTM systems from various perspectives to provide useful insights into the value and role of small-scale BTM ESSs in realizing the concept of the smart grid powered by efficient and environmentally friendly resources. In addition, this work explores key areas and provides important and constructive suggestions for further development of BTM ESS technology in smart grids.

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**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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