A review on peak load shaving strategies

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A review on peak load shaving strategies

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ABSTRACT

In this study, a significant literature review on peak load shaving strategies has been presented. The impact of three major strategies for peak load shaving, namely demand side management (DSM), integration of energy storage system (ESS), and integration of electric vehicle (EV) to the grid has been discussed in detail. Discussion on possible challenges and future research directions for each type of the strategy has also been included in this review. For the energy storage system, different technologies used for peak load shaving purpose, which include their methods of operation and control have been elaborated further. Finally, the sizing of the ESS storage system is discussed. For the demand side management system, various management methods and challenges associated with DSM implementation have been thoroughly explained. A detailed discussion on the electric vehicle strategy has also been included in the review, which considers the integration, control and operation techniques for implementing the peak load shaving.

1. Introduction

Electricity demand or load varies from time to time in a day. Meeting time-varying demand especially in peak period possesses a key challenge to electric utility [1]. The peak demand is increasing day by day as result of increasing end users (excluding some developed countries where peak shaving has been already deployed such as EU member states, North America, and other similar countries [2]). Continuous growth in peak load raises the possibility of power failure and raises the marginal cost of supply. Therefore, supply (production of electricity) and demand (consumption of electricity) balancing or meeting peak load has become a major concern of utilities [3–5]. To mitigate the peak power demand, small capacity of power plants such as gas power plants are usually used. Diesel generators are also exceedingly use to meet peak demand in isolated power systems [6]. However, this type of power plants possesses expensive operation and maintenance (O & M) cost [7,8]. Since peaking or standby plants operate only during peak load hours, old and low-efficient plants are also used to cope the peak demand. The capital cost of these plants are low, but the O & M cost is high. In addition, the electricity of the peaking plants become more expensive than that of any base-load plants in order to recover the capital costs as well as O & M costs within their lifespans [9]. Thus, peak load shaving is becoming an important area of active research [10]. Peak load shaving is a process of making the load curve flattens by reducing the peak amount of load and shifting it to times of lower load [11]. There is a growing number of researches performed on peak shaving. In this study, three different strategies of peak load shaving have been reviewed thoroughly, which are:

1) Integration of Energy Storage System (ESS)
2) Integration of Electric Vehicle (EV) to grid
3) Demand Side Management(DSM)

A comprehensive literature review on peak the load shaving methods is presented in this study. Different approaches proposed by previous researchers have also been categorised in these three major strategies. The novelty of this review lies in the discussion of significant challenges and future research directions that are possible for the peak load shaving strategies. This study is structured as follows:

- Significant outcomes and benefits of the peak shaving for both utility and customer.
- Review on the demand side management technique for peak shaving and the challenges of implementing this strategy.
- Different energy storage technologies used for peak shaving are included in the review. Next, the operation, control and sizing of ESS are discussed further.
- The peak shaving methods using EV are also presented, by

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Table 1
Potential impacts and benefits of peak load shaving.

Market participant	Function	Impact or benefits
Power producers	Generating electricity from primary sources which is the first process of utility in delivering electricity to the consumer.	Less efficient and expensive peaking plants can be displaced [18–21].
T & D grid operators	Managing the real time security of power system and coordinating the electricity supply to individual consumers.	The need of expensive upgrades for T & D systems will be delayed as peak shaving allows the existing T & D systems to be used for a longer time [22–24].
Electricity traders	Buying electricity directly from producers or via energy suppliers and selling at competitive prices.	Electricity traders can take advantage of electricity price difference. They can store energy at off-peak period when price is low and sell out to customers when electricity demand and price are high.
Electricity consumers	The end user (residential, commercial, industrial, etc.) of electricity.	Monthly electricity bill can be reduced by shifting some of the load from peak hours to off peak hours when the price of electricity is relatively low [22,23,25,26].

reviewing on various integration, control, and operation techniques of EV.

2. Importance of peak load shaving

Peak load is a sensitive factor for the grids, as it occurs occasionally and takes place only for a small percentage of the time in a day. To supply the peak load, a conventional approach which involves capacity addition is commonly used. However, this approach is not economically feasible and inefficient in term of the generators usage, since the utilities need to maintain the generation capacity that will be used only for a few hours per day [12]. It also possesses several disadvantages, such as high fuel consumption and carbon dioxide (CO2) emission, increase in transportation and maintenance costs and faster deterioration of equipment [13–15]. Thus, peak load shaving is a preferable approach to overcome these disadvantages, associated with the capacity addition approach. As many countries (e.g. European Union member states) have already introduced completely unbundling of the power market, hence, it is important to distinguish the impacts and the benefits of peak shaving for market participants (shown in Table 1) - power producers, transmission and distribution (T & D) grid operators, electricity traders and electricity consumers [16,17].

However, the benefits of peak shaving can be grouped into three categories (in general).

- Benefits for the Grid Operator
- Benefits for End-User
- Carbon Emission Reduction

2.1. Benefits for the grid operator

The following subsections elaborate several factors that can be significantly improved by utilising the peak load shaving in the system.

2.1.1. Power quality

One of the significant ongoing challenges experienced by the utilities is to maintain a balance between electricity generation and demand [10]. If the generation system fails to match the electricity demand perfectly, several problems such as instability, voltage fluctuation, and total blackout will possibly occur, thus impacting the grid system [27,28]. Those problems can take the form of stress on generation machinery and low power quality. Previous researches had proposed different peak load shaving techniques to mitigate the generation-demand imbalance. These techniques particularly focus on creating an efficient demand profile, which will result in improved power quality [29].

2.1.2. Efficient energy utilisation

Load factor is a useful technique to measure the variability of consumption in a plant. It determines how efficiently electricity is being used. A low load factor means that load is highly variable. Load factor (*LF*) is defined as [1,30,31]:

$$LF\,(\%) = \frac{P_{AVG}}{P_{Peak}} \tag{1}$$

where, LF is load factor, P_{AVG} is average real power demand, and P_{Peak} is peak real power demand.

High load factor is essential for the economic feasibility of plant. From the load factor equation, high load factor results in low energy cost. So, the load factor improvement is obligatory to reduce the energy cost and make the plant economically feasible. To improve the load factor, peak electrical load needs to be reduced.

2.1.3. System efficiency

To mitigate the peak load, supply current need to be increased significantly. However, increasing the supply current will reduce the system efficiency, as current is nonlinearly related to the power loss [32]. The power loss can be calculated as

$$P_{LOSS} = I^2 \times R \tag{2}$$

where, P_{LOSS} is power loss, I is current flowing through the transmission line, and R is ohmic resistance in the transmission line.

As the power loss is proportional to the square of the current, it is necessary to reduce the supply current by reducing peak demand to improve the system efficiency [33].

2.1.4. Cost reduction

Generally, the utility has no storage system. Therefore, generated electricity should not be more than electricity demand. Otherwise, the wasted electricity will increase the per unit electricity generation cost. For this reason, peak shaving is emergent to match supply and demand perfectly. This will result in the reduction of energy production cost. However, typically a power grid is designed in such a way that it can meet maximum projected demand with peak. Since peak occurs occasionally, it is economically not feasible to design a system much higher than the capacity needed. In addition, peak shaving will increase the system efficiency, therefore, grid operator can enjoy saving in fuel costs and maintenance costs. Moreover, peak shaving will ensure efficient use of transmission and distribution (T & D) system. This will result in deferment of system upgrading and extend the life span of T & D systems equipment [34]. Therefore grid operator will enjoy saving in capital cost expenditure. Peak shaving will also minimise losses in transmission and distribution system which will contribute further towards the cost saving. Therefore, to ensure maximum financial benefit for utility, peak shaving is essential. The economic benefits of peak shaving are elaborated in [35–37].

2.1.5. Renewable energy integration

With a greater respect for the environment, the use of renewable energy sources is growing to reduce CO_2 emission [38]. Hence, future electricity generation will progress with diminishing reliance on fossil fuels [39]. However, because of intermittent nature of most renewable energy sources, maintaining the stability and reliability of power network has become a challenge [40].

In order to analyze the penetration level and the effect of large-scale

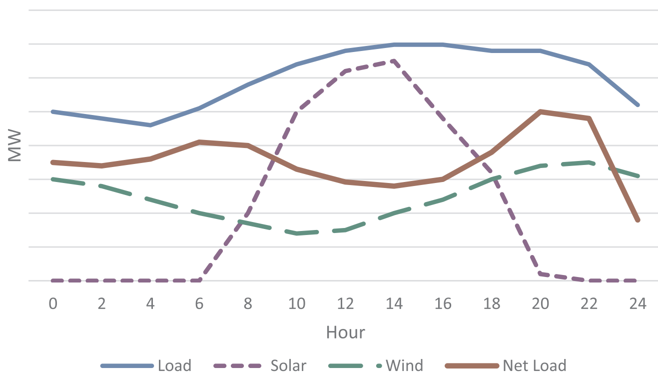

Fig. 1. Net load curve with integration of solar and wind.

grid-tied wind, solar, and other renewable sources, the net load (P_{net}) is important. The characteristics of P_{net} is significantly different than conventional load (P_{load}), which needs to be considered for operation planning of the grid. Net load (P_{net}) can be defined as the conventional load (P_{load}) minus the non-dispatchable generation, $P_{g(non\text{-}dispatchable)}$ [41]. This net amount of load must be supplied by dispatchable generator. Net load can be calculated as

$$P_{net} = P_{load} - P_{g(non-dispatchable)} \tag{3}$$

With large-scale integration of wind and solar power, the net load patterns changes significantly as shown in Fig. 1. Increasing amounts of non-dispatchable generation in grid increases the variability of net load which needs to be taken into account for the design and mechanism of electric grid [42]. For an instant, when solar and wind is integrated to grid, the net load demand reduces in the middle of the day and the highest peak shifted to the evening.

2.1.6. Power reliability of grid

Distribution system experiences a significant peak load, and it is increasing day by day, which can affect the reliability of grid [43]. Hence, installation of BESS for peak load shaving can also help to improve power reliability [44].

2.2. Benefits for end-user

In practice, to meet the time varying peak demand sometimes less efficient (concerning the economy and environment) generators (peaking generators) are required. Therefore, the per kWh electricity generation cost increases during the peak period. This high cost of per kWh electricity generation is ultimately passed onto the consumer during peak hours [45,46]. Therefore, peak shaving is also important for end users. Residential and industrial customers can save their electricity bills by shifting peak load from peak period (when energy price is high) to the off-peak period (when energy price is low) [47–50]. The end users may also enjoy saving in connection charges and capital cost for the distribution system. Peak shaving also offers some non-financial benefits to the end users such as improved reliability and power quality.

2.3. Carbon emission reduction

To deal with the peak demand, power plants consume extra fuels (due to the run of peaking generator with multiples start-stops). The consumption of more fuels increases carbon emission. Peak load shaving will ensure more efficient operation of power plants and reduce the variability in load. This will reduce the carbon emission [51,52].

3. Peak shaving using energy storage system

In this section, a brief overview of peak shaving strategy using ESS is presented. Then, research issues of this strategy are described. In the next subsection, the energy storage technologies and related projects that have been executed for peak load shaving are presented. Finally, challenges of implementing this strategy and future research direction are discussed.

3.1. An overview

Integrating energy storage system to the grid is the most potential strategy of peak shaving. This strategy can be used to achieve "peak shaving" in residential buildings, industries and grids. In this technique, peak shaving is achieved through the process of charging ESS when demand is low (off-peak period) and discharging when demand is high, as shown in Fig. 2 [53]. This function of ESS can provide economic benefits as it mitigates the need to use high-priced peak electricity generation. Among the different storage technologies, BESS is promising to provide peak shaving service for mid-term time scale (minutes to few hours < 5 h) [54].

An example of grid peak shaving through BESS can found in [55]. The main purpose of this study was to reduce per kWh energy cost by reducing the peak electrical demand with the help of storage system. Ehsan et al. [56] aimed to shave peak demand and smooth the load curve of a distribution grid with high renewable energy penetration. A distribution circuit of Maui in Hawaii was presented as a case study. Peak load shaving or power smoothing was achieved by injecting or absorbing the power determined by the forecasted load curve and the SOC trajectory. Son et al. [57] described a method of peak shaving using BESS. A charging and discharging schedule was determined based on threshold values of load. Using fuzzy algorithm, the wind power was

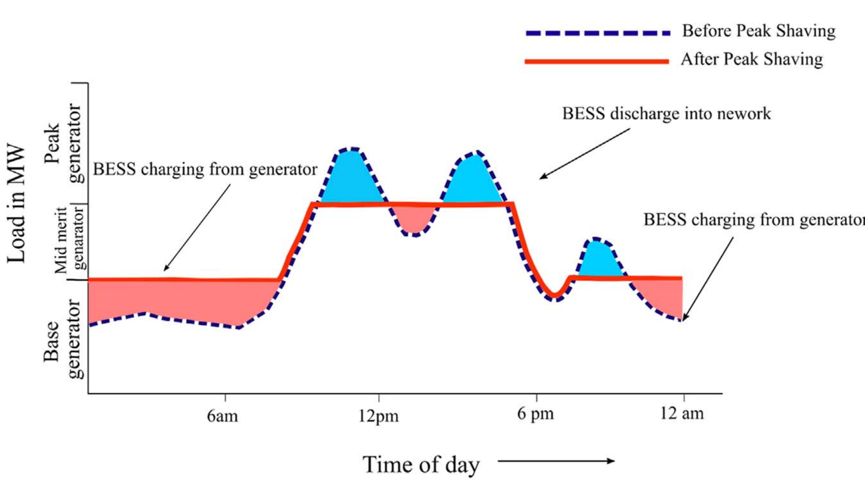

Fig. 2. Peak load shaving using ESS.

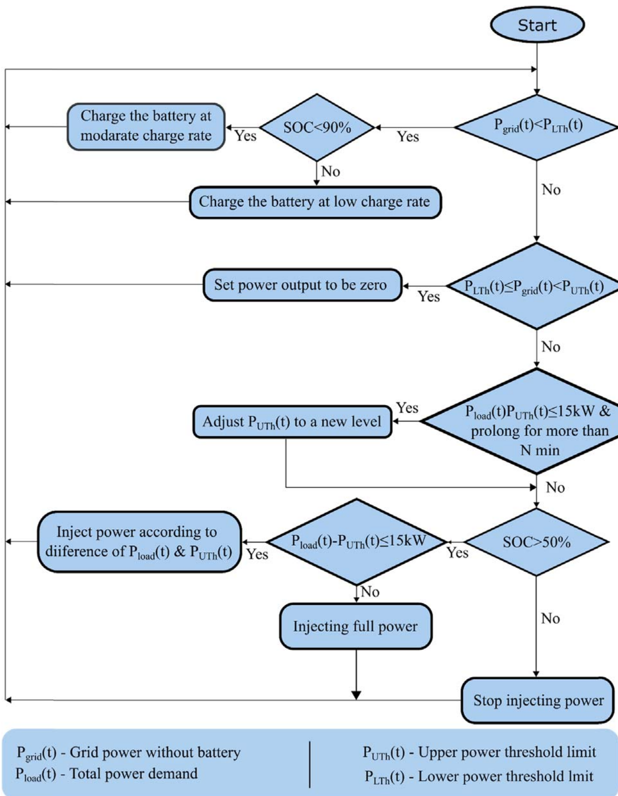

Fig. 3. Flow chart of the control algorithm to achieve peak load shaving [4].

forecasted and simulated by using MATLAB software. The simulation result was presented with small errors, which verify the effectiveness of the proposed model. Olga et al. [58] shifted the load and smoothed the peak on distribution feeder through the combination of BESS, smart meter and demand response (DR). The proposed system was rigorously modelled using the GridLAB-D software. Another study on peak shaving by Dejvises et al. [59] focused on the mathematical model of ESS to achieve peak shaving in Thailand.

Peak load shaving strategy through power diagram modification is shown in [60]. A case study was analysed in an office, where significant peak occurred during weekdays. To shave the peak in office, BESS is applied. BESS stores energy at the off-peak period and supplies to the load during the peak period. A modified power diagram of the office was shown from the simulation result. However, optimum operation and size of BESS were not determined. Previous researchers also performed parametric analysis to investigate the effects of several parameters on the economic feasibility of BESS for peak shaving [61]. This analysis was carried out by considering three parameters; the difference between high and low electricity price, peak demand charge, and investment cost for BESS. Economic feasibility results reveal that no battery energy storage technologies are cost-effective without incentives (based on the present price of BESS). However, it is expected that situation could be changed as the cost of BESS is expected to decline sharply in the coming years. Latterly, few researches have also focused on the application of ESS coupled with RES (renewable energy sources) for peak shaving. Grid connected [62], and standalone [63] systems are studied using this technique. Other detailed studies on the grid peak shaving using ESS can be found in [3,58]. Meanwhile, residential peak shaving using ESS can be found in [7,47,64].

3.2. Related work

Studies on peak shaving through energy storage system can be subdivided into three categories.

3.2.1. Optimum operation of ESS

Optimum operation is a key challenge of this peak shaving strategy. Therefore, many studies were carried out on the optimum operation of BESS. Lucas et al. had done a great effort to maintain optimum operation of BESS [65]. The battery storage system was programmed with two commands; charge at low demand (when demand is below 10 kW) and discharge at peak demand (when demand is above 400 kW). Charging command will be accepted if and only if BESS's state of charge (SOC) is below 10%. The opposite is true when SOC is above 90%, i.e., the command that leads to abortion of power will not be accepted when SOC is above 90%. However, variation in supply power is not studied. For the case of small scale generation system especially in the case of isolated mode, supply power varies in accordance with the significant change in demand. In this case, it is difficult to determine the upper and lower threshold power. A similar study on scheduling BESS can be found in [7]. Jason et al. also set demand limit for discharging of BESS but charging time kept fixed at late night when the energy demand is low [47].

Zheng et al. developed a control technique for BESS SOC by setting demand limit (DL) [48]. When the aggregate demand is greater than the DL, the storage system will be discharged to meet the excess demand. When the energy demand is less than the DL, the storage system will absorb power (if SOC is below the maximum limit). Alexandre et al. used a dynamic programming (DP) algorithm to determine the optimum operation of BESS [55]. Then, a test was carried out with an example of a large industrial consumer. From the test result, it was shown that this approach was effective for only short time peak. However, for a peak width (BESS discharge time) of more than 1 h, this method was not profitable. Ehsan et al. proposed a simple algorithm to control BESS SOC in real time [56]. Chua et al. developed an adaptive control algorithm to manage the optimum operation of BESS [4]. The flow chart of the Chua's developed control algorithm is shown in Fig. 3.

Rahimi et al. presented a simple but effective algorithm to control charge and discharge operation of BESS [3]. The controller of the main station will command BESS in its territory to charge or discharge at the beginning of each time interval. The time interval was set depending on availability of forecasted load in a shorter interval. To test the validity of the algorithm, a simulation was performed in MATLAB with IEEE 34 bus test system. The simulation result had shown a reduction in the peak value. More studies on the optimum operation of ESS to achieve peak shaving also can be found in [66–70].

3.2.2. Sizing of storage system

As BESS plays an important role in the operation of the grid, hence their sizing is essential for assuring the correct operation. Installation of BESS at a random size or non-optimum size can increase cost, system losses, and larger ESS capacity. If the sizing of ESS can balance the capital cost of storage system and electricity bill savings, the maximum financial benefit will be achieved from peak shaving. Many researches have been carried out to address this question. Chua et al. [4] proposed a novel sizing method to obtain the optimum size of energy storage for commercial and industrial customers, based on their historical load profile.

Alexandre et al. proposed a method of finding optimum size of BESS for providing peak shaving service [55]. To optimise the size of BESS, “extrema” method is used where the objective function is calculated for a set of input values (the size to be calculated). Optimal sizing and placement of energy storage for distribution networks are addressed in [71]. A genetic algorithm-based ESS sizing for microgrids is proposed in [72]. Khasawneh et al. evaluated the size of BESS for micro-grid to match supply power and electrical demand [73]. Sizing of ESS was also investigated using several test case scenarios. In [47], an algorithm is developed to size the ESS for application of residential peak shaving. A grid demand limit, power capability, and the storage capacity are considered for developing this algorithm, but capital cost of the energy storage is not considered. Therefore, determined size of ESS using this algorithm may not ensure the maximum financial benefit for the end user (customers). Based on rolling method, Chao et al. proposed a model of BESS sizing to achieve peak load shaving [74]. They evaluated the energy capacity required to meet daily peak based on the forecasted daily load curve. Next, the optimised size of BESS is determined based on the evaluated results. Thongchart et al. determined an optimum size of BESS using particular swam optimisation (PSO) technique [75]. This optimum BESS size ensures peak shaving with minimum BESS cost. For peak shaving application, another BESS sizing in power distribution feeders with integrated PV system is proposed in [76]. More researches on the sizing of ESS are also elaborated in [33,77,78].

3.2.3. Economic feasibility analysis

High capital cost is the major practical barrier for implementing the ESS system. Therefore, a thorough study on the economic benefits of peak shaving particularly for the consumer and the utility is needed. For instance, a computer tool was proposed by William et al.[79], which is capable of analysing the economic feasibility of the grid connected BESS.

However, the economic feasibility of ESS installation for peak shaving can be justified by taking into consideration all associated cost of investment and benefits. Possible benefits of peak shaving using ESS can be categorised into two; (i) economic benefit of the utility company, and (ii) economic benefit for the customer.

3.2.3.1. Economic benefit of the utility company. The utility can enjoy economic benefit through ESS installation for peak shaving as follows.

Replacing expensive peaking plants –ESS stores energy during off-peak periods and discharges at peak periods. This action displaces less efficient and expensive peaking plants to meet growth in peak demand [18–21].

Transmission and distribution (T & D) system upgrade deferral – ESS reduces the impact of peak period electricity demand. This allows the existing T & D systems to be used for a longer time. Therefore, the need of expensive upgrades for T & D systems are delayed [22–24].

Energy loss reduction – peak load shaving also reduces the energy loss in grid [33].

Reactive power (VAR) support – installation of ESS for peak shaving contributes to maintaining the grid voltage by injecting or absorbing reactive power [80–82].

Economic arbitrage – utility companies can take advantage of electricity price difference through peak shaving using ESS. They can store energy at the off-peak period when the price is low and sell out to customers when electricity demand and the price are high.

Reduction in CO_2 emission – peaking plants consume more fuel and emit significantly more carbon dioxide and nitrous oxide than the base power plant. ESS substitute the peaking plants and provide peak shaving service at lower CO_2 [34,83].

Considering the above benefits, researchers analysed the economic feasibility of this peak shaving strategy (use of ESS) for utility. D. Pudjianto et al. [84] evaluated the contribution of the grid-connected ESS. The finding of this work showed that grid-connected ESS has an economic benefit for the whole power system cost (including operation cost and investment cost for the generation, transmission, interconnection, and distribution). However, type BESS used in this study is not specified. L. Sigrist et al. [85] investigated small isolated power systems with the renewable energy sources to understand whether peak using ESS is profitable or not. However, change in efficiency of plants (gas-fired) with load variation is not considered. As a result, this economic assessment may not be complete.

3.2.3.2. Economic benefit for the customer. From the customer perspective, ESS reduces their monthly electricity bill by shifting some of their load from peak hours to off peak hours when the price of electricity is relatively low [22,23,25,26]. However, the potential economic benefits for customer occurs only when tariff system reflects the variation between peak and off-peak period. The main advantage of ESS over other peak shaving strategies is that it allows customers to save their electricity bill (through peak load reduction) and carry out daily activities simultaneously as usual.

3.3. Storage technologies used for peak shaving

Over the last century, energy storage technologies have been widely developed. ESS technologies can be divided into four main categories as shown in Table 1 [54,86–90]. Among various energy storage technologies, electrochemical technology based BESS is mostly used for peak load shaving. The use of different battery energy storage technologies for peak shaving can be found in the previous literature [33,70,77,91–95]. Sodium sulphur (NaS) batteries can be used for peak shaving and improve power quality of grid [96]. Application of this storage technology is found in [97]. Fly wheels [90] and thermal storage system [98,99] are also used for peak shaving application. Supercapacitors can also be implemented for peak shaving purpose. This technology response faster than BESS, but it lasts shorter than BESS [100]. However, current interests are focused on the use of redox flow battery for providing different ancillary services. This technology is advantageous over other BESS [66]. The potential of the redox flow battery (RFB) is well documented for providing ancillary service [65,101–103]. RFB is suitable for selection of peak shaving, emergency power supply, and renewable energy storage [104,105].

Alongside the peak shaving services, the ESS can provide several types of ancillary services which are the prerequisite to maintain the stability and reliability of the grid. The familiar ancillary services are voltage regulation & support, reactive power support, frequency control, spinning reserve, and emergency power during a power outage, etc. Most of these ancillary services are provided by the conventional power plants and large pumped-hydro energy storage. With the rapid development of renewable generation and microgrid, some large conventional power plants will be shut down [100]. Therefore, something is required to take over this responsibility. Considering these issues, integration of ESS with high penetration of renewable energy can be a better solution. From the market point of view, to monitor the ESS a storage management system is necessitated. The integration of renewable sources along with ESS will not only modify the demand curve but also reduce the expenses of ESS.

3.4. Major projects on peak shaving using ESS

In this subsection, several major projects on peak shaving using ESS have been reviewed, as shown in Table 2. These projects are categorised by their respective countries, power capacities, and utilities (Table 3)

3.5. Challenges

Although EES has potential benefits for peak shaving, some significant challenges in the deployment of ESS need to be solved, such as;

- Scheduling of ESS for optimum operation.
- Determining the perfect size of BESS is another challenge for implementation of the system. This is because installation of BESS at a random size or non-optimum size can result in higher cost, system losses and larger BESS capacity.
- High capital cost of ESS is a practical barrier to implement this peak shaving method.
- Using ESS for grid peak load shaving is more effective but challenging because of difficulties in large scale ESS installation. Operation and maintenance of large scale ESS are also more challenging.

3.6. Future research

The directions for future research on the EES system that can be

Table 2
Energy storage technologies.

Type	Storage technology
Electrochemical	Sodium Sulphur (NaS) Liquid Metal (Mg-Sb) Nickel Metal Hydride Advanced Lead-Acid Zebra Battery (NaNiCl) Nickel Cadmium Flow Batteries - Vanadium Redox (VRB) - Zinc Bromine (ZnBr) - Polysulphide Bromide (PSBr) Fuel Cell plus Electrolyser Lithium-Ion
Electromagnetic	Supercapacitors Superconducting magnetic energy storage
Thermodynamic	Compressed Air Energy Storage Thermochemical Energy Storage Thermal Batteries (Ice Battery) Thermal Batteries (Molten Salt)
Mechanical	Pumped Hydro Flywheels

considered are:

- Development of an algorithm based on variable demand limit, which will overcome the limitation of scheduling the ESS for optimum operation.
- Investigation on the economic feasibility of the ESS system to offset the high capital cost. This can also be extended to developing physical storage technology with high-efficiency and low-cost.
- Implementation of distributed ESS in the grid for peak load shaving to overcome the difficulties of large scale ESS installing.
- Asses the feasibility of the proposed strategies for the ESS system by conducting a specific study on small grids in rural areas with marginal or no access to the primary grid.

4. Peak shaving using electric vehicles

In this section, the existing works on peak load shaving using electric vehicles have been reviewed. A detailed discussion on previous techniques has also been discussed. Finally, several research challenges and possible future research directions on peak shaving using electric vehicles have been proposed.

4.1. A brief review

Nowadays, Electric vehicles (EVs) have not been widely deployed yet. However, they are expected to become globally more popular in the coming years because of the growing concern on energy depletion. Since storage energy of electric vehicles is usually not fully utilised each day, this technology has the potential to provide peak shaving service. Alam et al. [123] proposed an effective strategy to utilise PEV batteries for both travelling and peak shaving purpose. A dynamic discharge rate was implemented to ensure the best use of PEV batteries for peak shaving. Finally, the proposed strategy was tested with practical PEV data in Australia.

Controlling of the vehicle to grid (V2G) mode is also a challenge. Wang et al. proposed a control technique of V2G mode for peak load shaving [44]. Marek et al. [124] proposed a distribution substation topology, which allows EVs to act as an energy source during peak demand of utility. This substation acts as a service provider to a micro-grid. Distribution substation model was then simulated in MATLAB. Based on the simulated results, a micro-grid prototype was developed. This model can provide peak shaving service for a short term. Some other studies on peak shaving using EVs can be found in [43,125–129], where peak shaving was achieved by optimising charging strategy, without providing the storage service.

4.2. Challenges

The possible challenges of implementing EVs for peak shaving are:

Table 3
Energy storage system projects around the world.

Project name	Technology	Power capacity	Energy capacity	Location	Year	Ref.
N/A	–	1 MW	–	California	2015	[106]
Prudent Energy Inc	VRFB	600 kW	3.6 MWh	California	2014	[107]
Toshiba Unga Station TESS	BESS	1 MW	–	Japan	2014	[108]
N/A	BESS	510 kW	1.54 MWh	Monrovia California	2014	[109]
Wailea, HI	BESS	1 MW	1 MWh	Maui, Hawaii	2013	[110]
Soma, Japan (IHI)	BESS	1 MW	2.8 MWh	Japan	2013	[111]
N/A	–	2 MW	–	Italy	2013	[112]
Yerba Buena Battery Energy Storage System Pilot Project	BESS	4 MW	–	–	2013	[113]
Peak Shaving to Reduce Energy Costs: Eagle Picher Power Pyramid™ Hybrid Battery	BESS	1 MW	2 MWh	Joplin,MO	2012	[114]
Zurich battery energy storage system	BESS	1 MW	0.5 MWh	Deitikon, Switzerland	2012	[115]
100 kW PCS100 ESS Taiwan Project	–	100 kW	–	Taiwan	2011	[112]
Santa Rita Jail Smart Grid	BESS	2 MW	–	Alameda, California	2011	[116]
New York bus terminal energy storage systems		1.2 MW	6.5 MWh	New York, USA	2008	[117]
NYPA, Garden City, NY	–	1 MW	6.5 MWh	New York, USA	2006	[112]
High-Tech factory in Japan	VRFB	500 kW	2 MWh	Japan	2003	[117]
Tottori Sanyo Electric, Japan	VRFB	1.5 MW	1.5 MWh	Japan	2001	[117]
ESKOM Power Corporation at Stellenbosch University	VRFB	250 kW	500 kWh	South Africa	2001	[107]
Gwansei Gakuin University	VRFB	500 kW	5 MWh	Japan	2001	[107]
Sumitomo Densetsu office battery system	VRFB	3 MW	0.8 MWh	Japan	2000	[117]
Kansai Electric	VRFB	200 kW	1.6 MWh	Japan	2000	[107]
Sumitomo Electric Industries (SEI)	VRFB	450 kW	900 kWh	Japan	1996	[107]
Crescent electric membership cooperative BESS	BESS	0.5 MW	0.5 MWh	Carolina, USA	1987–2002	[118]
Peak Shaving and Demand Charge Avoidance: Prudent Energy Vanadium Redox Battery Energy Storage System (VRB-ESS®)	BESS	600 kW	–	Oxnard, CA	–	[119]
Smarter Network Storage	BESS	6 MW	10 MWh	Bedfordshire, England	–	[120]
DESI Project Orange County	–	2.4 MW	3.9 MWh	California, USA	–	[121]
N/A	BESS	6 MW	10 MWh	Leighton Buzzard, UK	–	[122]

- The main challenge of this strategy is the availability of EVs because EVs can only deliver power while being parked. Also, EVs have not been widely deployed yet.
- A single EV is incapable of meeting the peak load alone. Therefore, the discharge operation of a large number of EVs needs to be controlled together. However, the reluctance of vehicle owner to grant control of their vehicles to the third party is another challenge to implement this strategy.
- It is quite challenging to synchronise the charging and discharging operation of a large number of EVs.
- As the EVs have not been widely deployed yet, the parking place for EV in ready everywhere. Besides, the proper infrastructure and control system for EVs integration with the grid is not available everywhere. These could be the great challenges for implementing EVs in highly urbanised areas.

4.3. Future work

The directions for future research on this strategy that can be considered are:

- V2G for peak shaving may be more effective in small isolated grids, such as islands which are not connected to the main grid. Therefore, research can be done in such areas to determine the maximum benefits of peak shaving using EVs.
- Research also requires developing an algorithm that will enable synchronisation of charge and discharge operation of a large number of EVs.

5. Peak shaving using demand side management

In this subsection, the demand side management for peak load shaving is elaborated in depth. Existing works on the demand response programs and the demand side management have also been reviewed thoroughly. Finally, some future research directions and challenges of this type of peak shaving strategy have been proposed.

5.1. An overview

In terms of electric utility, demand side management refers to the programs that may influence the customers to balance their electricity consumption with the generation capability of power supply system. DSM is categorised into two main parts:

5.1.1. Energy efficiency

It is defined as the capability of providing same or improved service to the consumer by using less energy and in an economical way [130].

5.1.2. Demand response (DR)

It is defined as the changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [131].

DR is mainly used for peak shaving. Therefore, in this review, the DR methods of the DSM strategy have been discussed in detail. It plays an important role to shave the electricity peaks balancing the electricity generation and consumption. For that reason, DR is expected to become a part of the system operations in the future grid [132]. Various types of DR techniques have been used to shave the peak load, as shown in Fig. 4 [133–135]. The overview of DR programs can be found in [136]. Some of these programs (such as incentive-based direct load control programs) are the best tools for distribution systems operators to handle the emergency situations in peak period [137]. Benefits of these programs are addressed in [138]. A real example of large scale peak shaving by implementing DR program is given in [139].

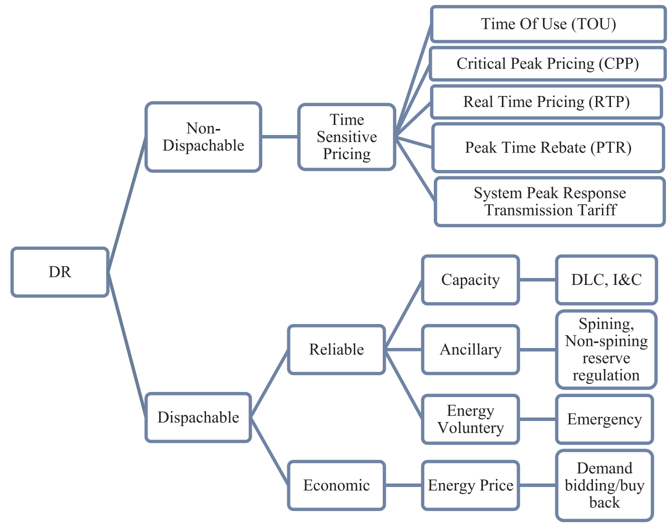

Fig. 4. Classification of demand response schemes.

5.2. Related work

Previous researches have been found on overview of demand response [140–143]. Different studies have also proposed different demand response techniques to get maximum peak shaving. Rozali et al. [144] aimed to achieve maximum peak shaving through DR under the guide of power pinch analysis (PoPA). The authors proposed two load shifting strategies; (i) the amount of outsourced electricity requirement during peak hours can be reduced by reallocating it to the time intervals with electricity surpluses occurring during off-peak hours, (ii) electricity demand during peak hours can be shifted to the time intervals straddling the peak and off-peak hours, provided that the time interval where the demand is shifted to is preceded by the time interval with a large electricity storage. Meanwhile, Tascikaraoglu et al., had conducted research on the DR techniques by classifying home appliances into two categories, which are controllable and non-controllable [145]. With the help of Zigbee/Wi-Fi/ wireless communication, controllable appliances are connected through smart plug so that these devices can unplug from the grid remotely. Controllable appliances are also monitored based on the forecasted load profile. This is an interesting technique but challenging because it requires previous load forecasting. An industrial peak load shaving in India is shown in [146], using time of use (TOU) demand response program. In the next subsection, a detailed discussion related to the DR programs for peak load shaving has been carried out, which includes the challenges and possible future research directions.

5.3. Challenges

Application of DR programs is more challenging. Possible challenges of this strategy are:

- Customers may not be willing to shift their activities from peak period to off-peak period. This happens especially in a country where the peak demand price has not been applied yet.
- Customers' comfort level might be affected by the implementation of the demand response programs.
- Information and communication technology (ICT) infrastructures such as advanced metering, communications system, control methods and information technologies are not completely available in present electricity systems. These infrastructures need to be ready before implementing the DR program successfully, as it involves a multi-million dollar investment.
- The complexity of the overall system operation will be increased by

implementing the demand response techniques.

5.4. Future work

The directions for future research on DSM that can be considered are:

- Future research on this strategy may focus on the application of smart home energy management system (which is consist of advanced metering infrastructure, utilisation of sensing devices, enabling information and communication technology, smart appliance, and etc) along with DR. This will reduce the dependency on customer willingness to implement the DSM strategy for peak shaving. However, to maximise the effectiveness of DR, technical assistant education for the customer is requisite.
- An energy storage system (ESS) application is more advantageous than the demand response program, where it allows customers to simultaneously shave peak load and perform daily activities as usual. Therefore, future research should emphasise on the proper application of DSM with ESS system for peak shaving purpose.

6. Conclusion

A comprehensive review of peak load shaving techniques has been discussed, as proposed by previous researchers. The review discovered three major peak shaving techniques, namely DSM, ESS, and integration of EV to the grid. This paper has highlighted the researches and real project carried out to perform the peak shaving worldwide. For each strategy, there are unique challenges to be overcame and therefore demanding for further research and investigation. In this paper however, another possible method to perform peak shaving, which is to utilise mix energy (renewable sources) has not much been deliberated. Therefore, it would be very interesting for readers to also consider that possibility.

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