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Optimal planning of solar photovoltaic and battery storage systems for grid-connected residential sector: Review, challenges and new perspectives

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ABSTRACT

Integration of solar photovoltaic (PV) and battery storage systems is an upward trend for residential sector to achieve major targets like minimizing the electricity bill, grid dependency, emission and so forth. In recent years, there has been a rapid deployment of PV and battery installation in residential sector. In this regard, optimal planning of PV-battery systems is a critical issue for the designers, consumers, and network operators due to high number of parameters that can affect the optimization problem. This paper aims to present a comprehensive and critical review on the effective parameters in optimal planning process of solar PV and battery storage system for grid-connected residential sector. The key parameters in process of optimal planning for PV-battery system are recognized and explained. These parameters are economic and technical data, objective functions, energy management systems, design constraints, optimization algorithms, and electricity pricing programs. A timely review on the state-of-the-art studies in PV-battery optimal planning is presented. The challenges, trends and latest developments in the topic are discussed. At the end, scopes for future studies are developed. It is found that new guidelines should be provided for the customers based on various electricity rates and demand response programs. Also, several design considerations like grid dependency and resiliency need further investigation in the optimal planning of PV-battery systems.

1. Introduction

Electricity demand is increasing in the global market. Fig. 1 shows the global electricity demand by regions from 2000 to 2018 [1]. The electricity demand was increased by about 72% from 2000 to 2018 in which the annual growth was around 4%. The global electricity demand at the end of 2018 was more than 23,000 TWh. Most of the electricity demand growth is observed in China and the other developing countries. This is the result of industrialization development, boosting of the human comfort level, and population increment [1]. As the electricity demand grows, the fossil fuels are decreasing in a way that they may not last for more than a few decades. Furthermore, the cost of petroleum products is rising. Therefore, the request for renewable energies as prominent alternatives for fossil fuels is increasing rapidly in the world [2].

Renewable energies are valuable sources in terms of sustainability since they can reduce the green-house gases worldwide. In addition, the falling cost of renewable energies such as solar photovoltaic (PV) has made them an attractive source of electricity generation [3]. Solar PVs take advantages of absence of rotating parts, convenient accommodation in rooftops, and less maintenance cost. Fig. 2 illustrates the global solar PV capacity and its annual addition [4]. The total worldwide PV generation capacity exceeded 625 GW at the end of 2019 compared to only 23 GW at 10 years earlier [5]. The annual addition of solar PV capacity was more than 115 GW in 2019 compared to only 8 GW in 2009. According to the estimations, solar PV would supply 3518 TWh and 7208 TWh by 2030 and 2040, respectively [6].

Solar PV is the most popular renewable energy resource in residential sector. A solar PV system in a grid-connected system would supply the load and export the extra power to the main grid with an feed-in-tariff (FIT). Integration of solar PV in a grid-connected residential sector (GCRS) would decrease the electricity bill (because of the FIT), grid dependency, emission, and so forth. In recent years, there has been a rapid deployment of PV in residential sector.

There are several challenges for further deployment of PV systems in GCRS. First, the FIT rates are decreasing in the countries with high penetration of rooftop PV systems [7,8]. Second, the intermittency of PV generation would be a challenge in the recent electricity markets when

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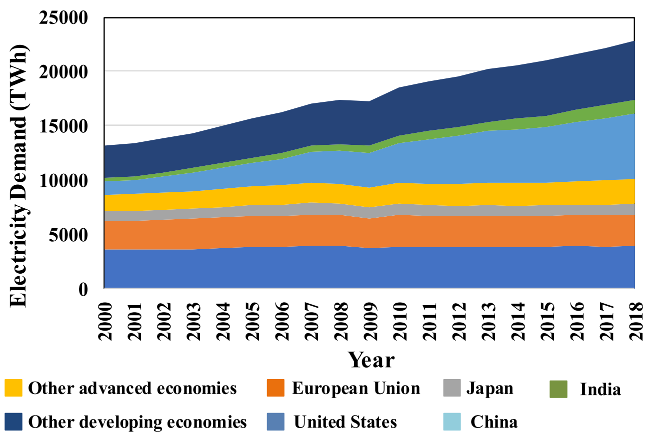

Fig. 1. Global electricity demand by region [1].

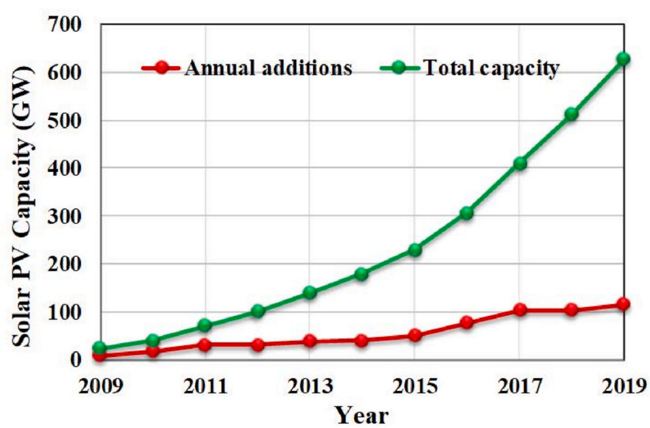

Fig. 2. Global solar PV capacity and annual addition [4].

the time-of-use (TOU) and real time pricing (RTP) are used. To overcome the challenges, the manifest destiny in GCRS is to integrate battery energy storage (BES). The BES is a qualified technology to absorb the extra power of PV (after feeding the load), and then supply the load when there is no renewable generation. Several applications of the PV-battery system have been reported such as energy arbitrage, resiliency improvement and time-shifting [9,10]. However, the high price of BES technology is an impediment for efficient integration. Thus, further investigations are required for PV and BES integration in grid-connected systems in terms of planning, operation, and control. In this regard, optimal sizing of PV and BES is a critical challenge for the consumers and network analyzers due to the high number of the parameters that can affect the optimization problem.

Literature survey indicates plenty of review studies on solar PV and BES in power systems. In Ref. [11], standards for grid-connected solar PV systems were investigated. Grid integration of small-scale solar PV systems was introduced in Ref. [12]. Technical specifications of solar PV systems were discussed in Ref. [13]. In Ref. [14], a review was conducted on the solar PV technologies. The potential problems and technical issues in grid-connected solar PV systems were described in Refs. [15,16], respectively. The inverter technology development in solar PV systems was reviewed in Refs. [17,18]. Self-consumption of solar PV system was investigated in Ref. [19]. The technical and economic aspects of solar PV for grid-connected homes was investigated for Palestine, Brazil, and South Africa in Refs. [20–22], respectively. However, the above-mentioned review studies did not investigate integration of the battery storage for the PV systems.

An overview on current developments of PV-battery systems for grid-connected buildings was conducted in Ref. [23]. The PV-battery architectures for residential sectors were investigated in Ref. [24]. The economic viability of PV-battery systems for residential buildings was surveyed in Ref. [25]. The economic aspects of solar PV and battery integration in residential sector was reviewed in Ref. [26]. In Ref. [27], an economic analysis was conducted for residential solar PV systems with battery in the United States. A review on the application of distributed solar PV system with battery was presented in Ref. [28]. Energy management of small-scale PV-battery systems in residential households was reviewed in Ref. [29]. The Australian consumers motivations for installing PV-battery system in their households was overviewed in Ref. [30]. Various battery discharge strategies for PV-battery in grid-connected households were compared in Ref. [31]. However, none of these studies investigated optimal planning of PV systems with or without battery.

Application of artificial intelligence methodologies for optimal sizing of solar PV system was investigated on [32]. In Ref. [33], a review was conducted on optimal sizing of energy storage and solar PV in standalone power systems. A review on optimal planning of solar PV for water pumping systems was conducted in Ref. [34]. In Refs. [35–37], optimal sizing of hybrid systems with PV and BES was surveyed. Optimal allocation of BES in renewable energy systems and distribution networks was investigated in Refs. [38,39], respectively.

Although several review papers were conducted on optimal planning, but to the best of authors' knowledge, the PV-battery optimal planning for GCRS was not investigated. This is a very critical area because of the high deployment of rooftop solar PV and BES systems in residential sector worldwide. An efficient optimal planning of PV and battery for grid-connected residential consumers may result in decreasing electricity bills. The recent high penetration of residential solar PV in distribution network has created serious challenges for the network operators. A strategical optimal planning of PV and battery can resolve the network problems.

The main objective of this paper is to review the optimal planning problem of solar PV and BES systems for GCRS. This is a timely review because of the extensive deployment of rooftop PV panels and BESs in GCRSs. From a practical point of view, this paper addresses a practicing engineering problem for PV and BES planning. The planning problem of solar PV and BES is formally defined as a static problem about the decision making for the capacity of PV and battery to achieve desirable objectives. The objectives can be defined by techno-economic factors or other factors like reliability or emission. The planning problem of PV and BES faces several challenges like obtaining input data, handling design constraints, and employing efficient energy management. Fig. 3 illustrates the technical roadmap for this review study accomplishment. The roadmap consists of four main stages. In the first stage, the optimal sizing problem of PV-battery system for GCRS is investigated. This includes recognizing the objective functions, design constraints, input data, electricity pricing programs, energy management systems, optimization methodologies and software tools. When the problem is recognized, the existing studies are categorized in the second stage. The classification is based on the decision variables. Then, existing studies are investigated based on optimization objectives, constraints, and methods, as well as the type of electricity rates and countries of the study. The technical challenges in the existing studies are also identified. In the third stage, the recent developments on optimal sizing of PV-battery system for GCRS are scrutinized. In the fourth stage, the shortcomings of existing studies are identified, and potential future perspectives are discussed.

The main contributions of this review paper as compared to the existing review studies are:

- A timely survey on the state-of-the-art in optimal planning of PV-battery for GCRS.
- A classification of existing studies on optimal planning of PV-battery for GCRS.

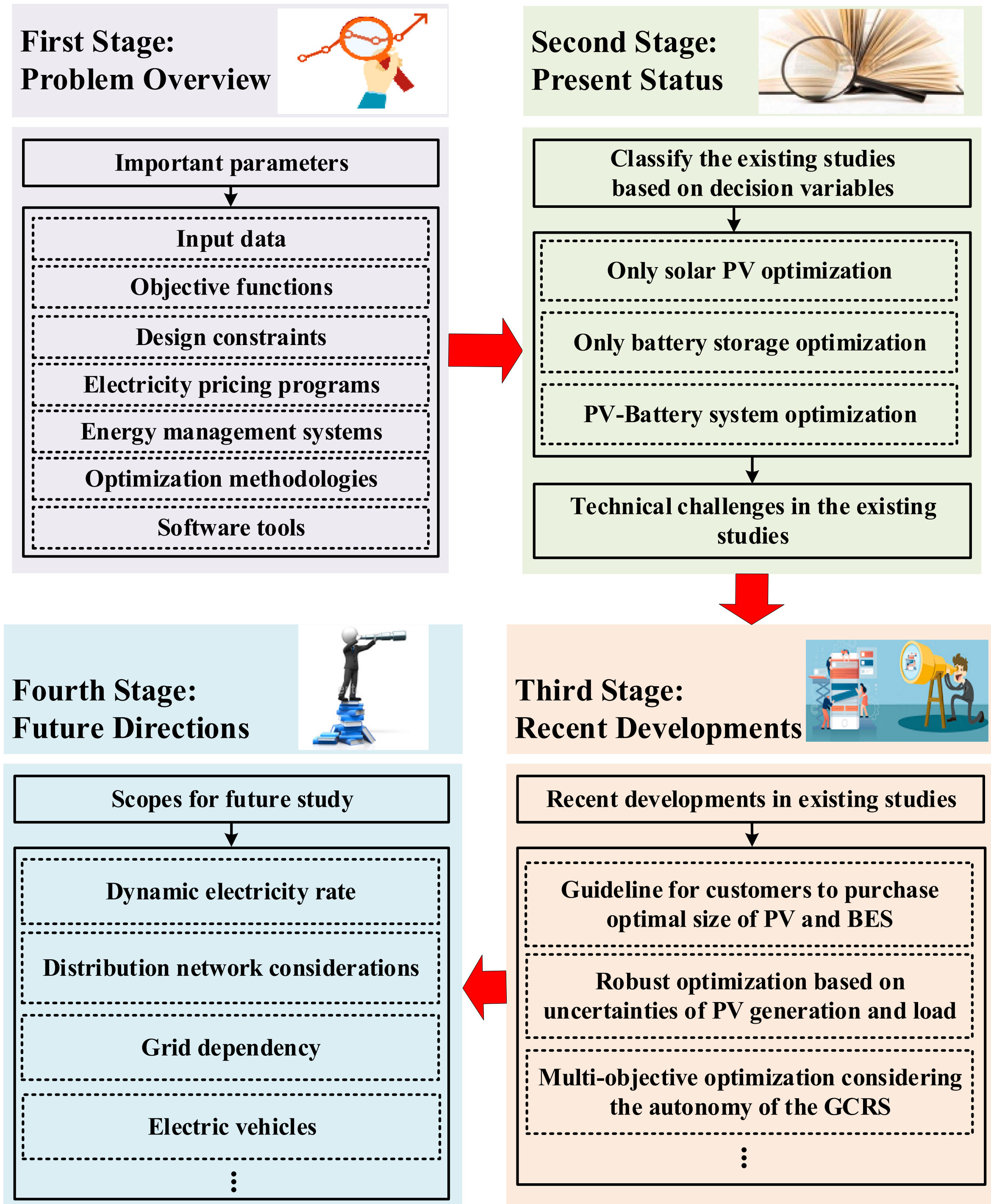

Fig. 3. Technical roadmap of this review study on PV-battery optimal planning for grid-connected residential sector.

- A review of the latest research developments on optimal planning of PV-battery for GCRS.
- An outlook of the future research scopes in optimal planning of PV-battery for GCRS.

The remainder of this paper is organized as follows. Section 2 explains the PV-battery optimal planning problem formulation. This section also explains important parameters for the planning of grid-connected residential sector. Section 3 classifies the existing studies on optimal planning of PV and BES in GCRS. Section 4 discusses the recent developments on PV-battery optimal planning. Section 5 describes the future trends for further studies in the field. Finally, section 6 concludes at the end.

2. PV-battery optimal sizing overview

A general schematic diagram of a GCRS with solar PV and BES is demonstrated in Fig. 4. The role of energy management system is to monitor and control the energy flow between the PV, BES, grid and GCRS based on the data from forecasting, smart meter, and available loads for demand response. The effective parameters on optimal planning of PV-battery for grid-connected residential sectors are discussed in

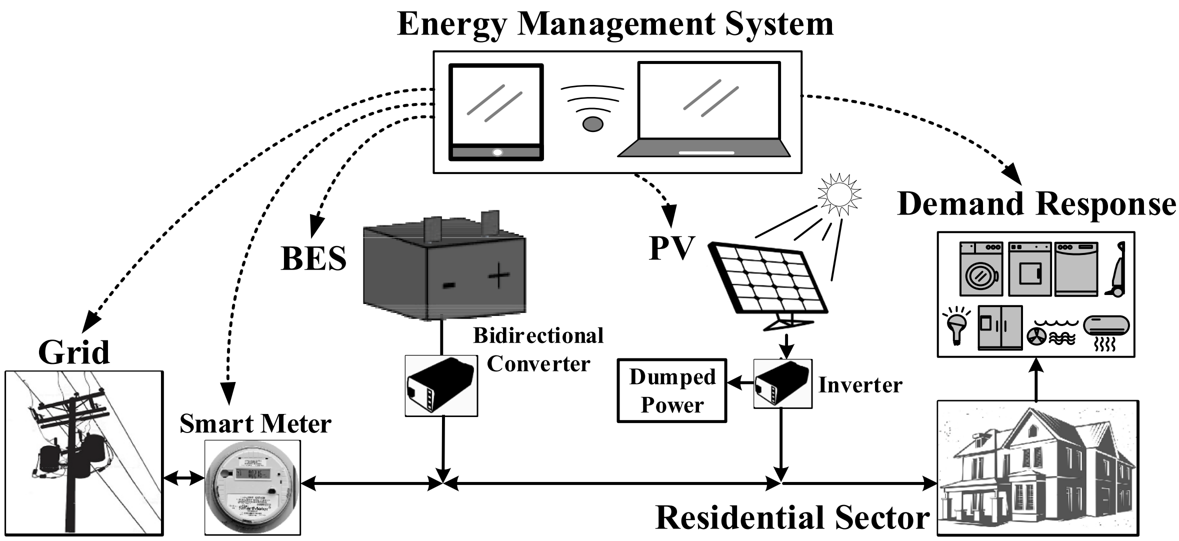

Fig. 4. A general schematic of a GCRS with solar PV and BES.

this section.

2.1. Input data

The input data for optimal planning of PV-battery system in GCRS are illustrated in Fig. 5. Three groups of input data are needed: (1) financial data, (2) periodic data, and (3) technical data.

Financial data contains the installation costs of PV and BES, interest/discount and escalation/inflation rates, as well as the electricity rates. In most of the cases, all these parameters depend on the country of the study. The electricity rate depends on the policies of the countries.

Since the optimal planning is a long-term problem, periodic data is used for electricity consumption, solar radiation, and ambient temperature. The periodic data can be realistic data or probabilistic data. The periodic data can be collected for very-short-period (e.g., one day of each season), short-period (e.g., one year) and long-period (e.g., ten years). The data can be arranged hourly or high temporal resolution (e.g., 5 min).

Technical data involves PV, BES, and grid data. The grid technical data is mostly associated with the limitations on export/import power to/from the main grid. The components' technical data are related to lifetime, efficiency and other data of PV and BES. The array tilt angle, system efficiency, temperature coefficient, and insolation at standard test conditions are among the important factors of technical data for

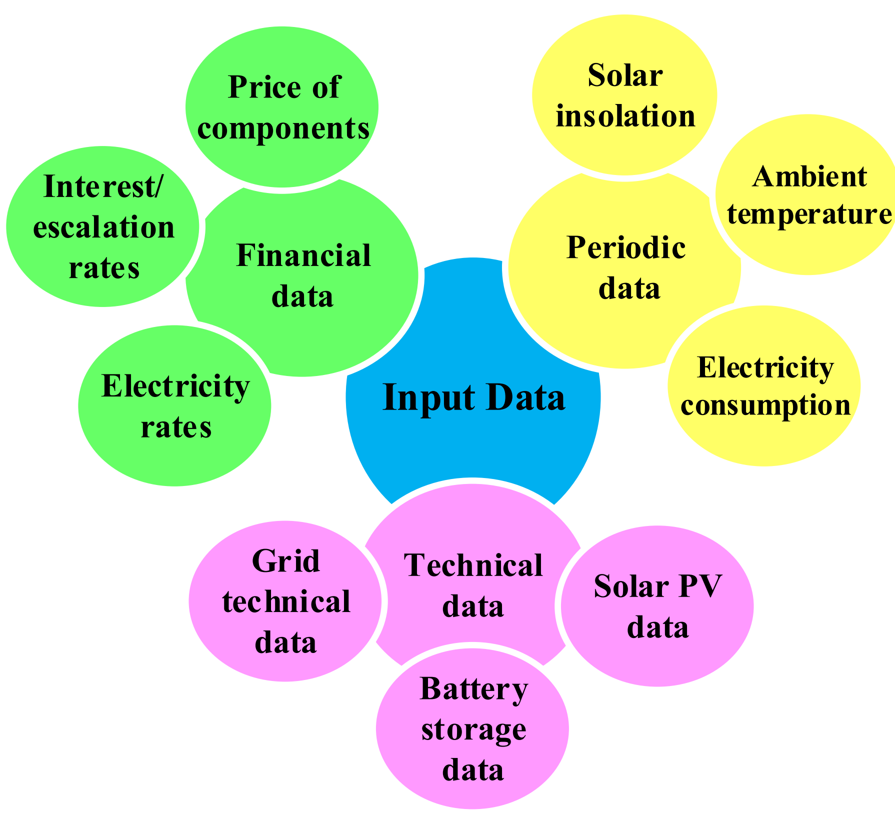

Fig. 5. Important input data for optimal sizing of PV-battery systems in grid-connected residential sectors.

solar PV system [40].

Table 1 lists the specifications of different solar PV technologies [41]. The first generation of solar PV technology is produced by semi-conducting p–n junctions from silicon. For this generation, a very pure silicon is required that increases the price of the technology. In most of the cases, the payback period of the first generation takes 5–6 years. The main idea for development of the second generation is to decrease the price of the first generation in the market. The used thin-film solar cell (TFSC) in the second generation takes benefits from compatibility with low-cost substrates, variety of deposition process, and low material usage. The TSFC technology has different types like copper–zinc-–in–sulfide (CZTS), amorphous silicon (a-Si) solar cells, and copper–indium–gallium–diselenide (CIGSe) [41]. The main aim of development of the third generation of solar PV cells is to improve the average electrical performance while maintaining a low cost of the technology.

Table 2 lists the technical characteristics of BES technologies that are suitable for PV systems in GCRS. These BES technologies are lead-acid (LA) battery, lithium-ion battery (LIB), sodium sulphur (NaS) battery, and vanadium redox battery (VRB) [42–44]. As illustrated in Table 2, the LIBs have higher efficiency and lifetime compared to other technologies. However, the LA batteries are traditionally used in electrical systems because of their lower cost. It is notable that the LA and LIB are generally used in residential systems.

2.2. Objective functions

Objective function is the most important parameter in an optimal planning problem. Fig. 6 demonstrates two groups of applied objective functions for optimal planning of PV and BES in GCRS. Objective functions should be maximized or minimized using the optimization algorithms. The optimization problems can be defined with one or more objective functions. If more than one objective function is assumed, then the problem is a multi-objective optimization challenge in which the results will be shown using set of non-dominated solutions in Pareto-fronts.

2.2.1. Financial

The financial objective functions are the important group of targets for residential consumers. There are five commonly used financial objective functions: (1) net present value, (2) cost of electricity, (3) annual profit, (4) payback period, and (5) internal rate of return. Each objective function is discussed in this sub-section.

2.2.1.1. Net present value. Net present value (NPV) is the most applied objective function among the targets in the first group. The total net present value ($\mathscr{NPV}_T$) of a GCRS with solar PV and BES is calculated based on the NPV of components ($\mathscr{NPV}_k$) and NPV of electricity ($\mathscr{NPV}_e$) [45,46].

$$f_1 = \min(\mathscr{NPV}_T) = \mathscr{NPV}_k + \mathscr{NPV}_e \tag{1}$$

The net present value of components is calculated based on the present values of capital ($\mathscr{PC}_c$), maintenance ($\mathscr{PC}_m$), replacement ($\mathscr{PC}_r$) and salvation ($\mathscr{PC}_s$) of the PV and BES.

$$\mathscr{NPV}_k = \mathscr{PC}_c + \mathscr{PC}_m + \mathscr{PC}_r - \mathscr{PC}_s \tag{2}$$

The net present value of electricity is calculated based on the exported and imported energies to/from the main grid [47].

$$\mathscr{NPV}_e = \left(\frac{(1+r)^n - 1}{r(1+r)^n}\right) \times \left(\sum_{t=1}^{T} \left(\mathbb{I}(t).\mathscr{P}_{im}(t) - \mathbb{J}(t).\mathscr{P}_{ex}(t)\right)\right) \tag{3}$$

where r is the electricity interest rate, and n is the project lifespan. $\mathscr{P}_{im}(t)$ and $\mathscr{P}_{ex}(t)$ represent the import and export powers at time t, respectively. $\mathbb{I}(t)$ and $\mathbb{J}(t)$ are the import and export rates of electricity at time t, respectively.

2.2.1.2. Cost of electricity. Cost of electricity (COE) is the other financial objective function applied for GCRS. The COE is calculated based on the total NPV and annuity factor [48,49].

$$f_2 = \min(\mathscr{COE}) = \frac{\mathscr{NPV}_k}{\mathbb{E}_g} \times \frac{\xi(1+\xi)^n}{(1+\xi)^n - 1} + \frac{\mathscr{NPV}_e}{\mathbb{E}_g} \times \frac{\vartheta(1+\vartheta)^n}{(1+\vartheta)^n - 1} \tag{4}$$

where $\mathbb{E}_g$ is the annual electricity demand of the GCRS. ξ is the discount factor of components value and ϑ is the electricity discount rate.

2.2.1.3. Annual profit. The annual profit (AP) of GCRS is the difference between the annual revenue of the system (saving of electricity bill) and the annual cost of the components ($\mathscr{AC}_k$) [50].

$$f_3 = \max(\mathscr{AP}) = \sum_{t=1}^{T} \left(\mathbb{I}(t).\mathscr{P}_{im}(t) - \mathbb{J}(t).\mathscr{P}_{ex}(t)\right) - \mathscr{AC}_k \tag{5}$$

2.2.1.4. Payback period. The payback period (PP) of components is another factor to measure the economic viability of a PV-BES system for a GCRS. The PP is the number of years that needs to pay back the capital cost of components by the annual profits [51].

$$f_4 = \min(\mathscr{PP}) = \frac{\mathscr{PC}_c}{\mathscr{AP}} \tag{6}$$

2.2.1.5. Internal rate of return. The internal rate of return (IRR) indicates how much money can be earned per year per investment. The IRR can be calculated by the discount rate that makes the NPV of all cash flows equal to zero [52].

$$f_5 = \max(\mathscr{IRR}) \tag{7}$$

$$-\mathscr{PC}_c + \sum_{y=1}^{Y} \mathscr{S}_y \times (\mathscr{IRR})^y = 0 \tag{8}$$

where $\mathscr{S}_y$ is the net cash flow in year y.

2.2.2. Technical

The technical objective functions mostly depend on the targets of the designer. The commonly used technical objective functions are: (1) autonomy of the GCRS, (2) dumped energy, (3) loss of power supply, (4) customer satisfaction, and (5) carbon emission.

Table 1
Specifications of different solar PV technologies [41].

Generation	First generation		Second generation			Third generation
Feature	Cristal silicon solar cells		Thin film solar cells			Perovskite, organic, multi-junction solar cells
Type	Mono-crystalline cells	Multi-crystalline cells	CdTe cells	Amorphous silicon cells	CIGS cells	Multi-junction solar cells
Efficiency	18%–25%	17%–21%	18%–22%	13.4%	20%–23%	45%
Price	High		Low			Medium
Discussion	accounted for 89.6% of commercial production in 2007		already entered into the commercialization stage nearly 10 years ago			still in progress

Table 2
Characteristics of four types of battery energy storage technologies available in the market [42–44].

Energy storage technology	Capital cost ($/kWh)	Power rating (MW)	Discharge time	Power density (W/l)	Energy density (Wh/l)	Efficiency (%)	Lifetime (years)	Lifetime (cycles)
LA	300–600	0–20	s-h	90–700	50–80	50–90	3–15	250–1500
LIB	700–3000	0–100	s-h	1300-10,000	200–400	85–95	5–20	600–1200
NaS	1000–3000	0.05–40	s-h	120–160	15–300	80–90	10–15	2500–4500
VRB	600–1500	0.03–3	1–10 h	0.5–2	20–70	80–90	5–10	12,000^{+}

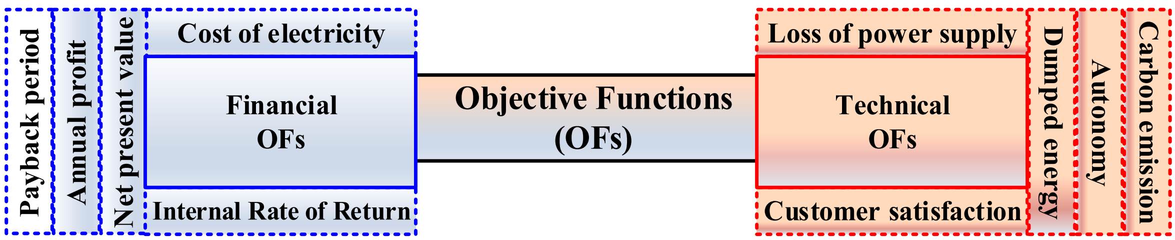

Fig. 6. Applicable objective functions for optimal sizing of PV-battery system in grid-connected residential sectors.

2.2.2.1. *Autonomy.* The autonomy of the GCRS is divided into two types of power autonomy and energy autonomy. The power autonomy ($\mathscr{PA}$) is defined as the grid-independency of the GCRS from the active power [53]:

$$f_6 = \max(\mathscr{PA}) = \left(1 - \frac{1}{T}\sum_{t=1}^{T}\frac{\mathscr{P}_{im}(t)}{\mathscr{P}_g(t)}\right) \times 100 \tag{9}$$

where $\mathscr{P}_g$ is the active power consumption of the GCRS.

Energy autonomy ($\mathscr{EA}$) is defined as the grid-independency of the GCRS from the energy [54].

$$f_7 = \max(\mathrm{E}\mathscr{A}) = \frac{\mathbb{E}_g - \mathbb{E}_{im}}{\mathbb{E}_g} \times 100 \tag{10}$$

where $\mathbb{E}_{im}$ is the total energy imported from the main grid.

2.2.2.2. *Dumped energy.* The dumped energy (DE) is the wasted electricity of the renewable energy resources [55,56]. The DE is calculated based on the excess electricity from the PV after feeding loads, charging BES, and exporting electricity to the grid.

$$f_8 = \min(\mathscr{D}\mathrm{E}) = \mathbb{E}_p - \mathbb{E}_{ch} - \mathbb{E}_{ex} - \mathbb{E}_g \tag{11}$$

where $\mathbb{E}_p$, $\mathbb{E}_{ch}$, and $\mathbb{E}_{ex}$ are the total electricity generated by the PV, total energy charging of BES, and the total exported energy to the main grid, respectively.

2.2.2.3. *Loss of power supply.* The loss of power supply (LPSP) is the failure probability of electricity supply by the imported power from grid, output power of solar PV ($\mathscr{P}_p$) and discharging power of the BES ($\mathscr{P}_{dis}$) [57,58].

$$f_9 = \min(\mathscr{LPSP}) = \frac{\sum_{t=1}^{T}\mathscr{P}_g(t) - \mathscr{P}_{im}(t) - \mathscr{P}_p(t) - \mathscr{P}_{dis}(t)}{\sum_{t=1}^{T}\mathscr{P}_g(t)} \tag{12}$$

2.2.2.4. *Customer satisfaction.* The customer satisfaction (CS) metric is used as an objective function for the GCRS with demand response strategy. The main aim of CM is to maximize the satisfaction of the consumers who participate in the demand response [59].

$$f_{10} = \max(\mathscr{CS}) \tag{13}$$

2.2.2.5. *Carbon emission.* Most of the world's grid energy comes from large-scale fossil fuel generators. Hence, the carbon emission factor is measured by the imported power from the main grid to the GCRS. The renewable factor (RF) can be efficiently used to minimize the air pollution [60].

$$f_{11} = \max(\mathscr{RF}) = \left(1 - \frac{\sum_{t=1}^{T}\mathscr{P}_{im}(t)}{\sum_{t=1}^{T}\mathscr{P}_p(t)}\right) \times 100 \tag{14}$$

2.3. *Design constraints*

Fig. 7 demonstrates the applicable design constraints for optimal planning of PV-BES systems in GCRS. The most important constraint is the power balance between generation and consumption sides of the GCRS [61]. The import/export power from/to the main grid is generally limited in distribution networks [62]. As a realistic example, the single-phase and three-phase GCRSs are not allowed to export more than 5 kW and 30 power, respectively, to the main grid using rooftop solar PVs in South Australia [63]. The constraint associated with the battery is the state-of-charge (SoC) level that should deviate between maximum and minimum rates [64]. The rooftop availability to install the solar

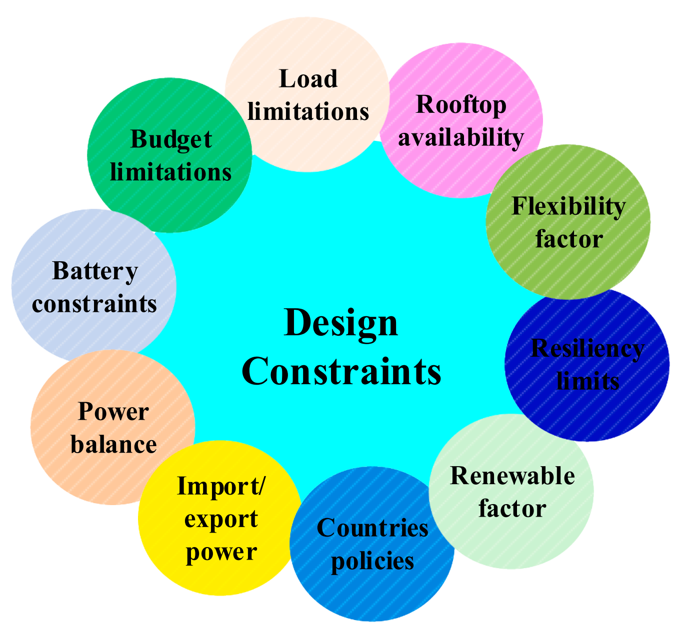

Fig. 7. Applicable design constraints for optimal sizing of PV-battery systems in GCRS.

panels is another constraint for the optimal planning of GCRS [65]. In fact, the maximum capacity of solar PV should be selected based on the rooftop availability of the residential building. The budget limit for the component's investment is the next constraint. The optimization model should consider the maximum budget to obtain the capacity of the components [66]. The countries policies for installation of rooftop solar PV and BES should be considered as a constraint in the optimization model. The renewable factor is considered as a constraint for the optimal sizing problems where higher load supply from the solar PV is expected [67]. Resiliency and flexibility are two new metrics that can be considered as constraints. The resiliency constraint is used to boost the robustness of the GCRS system with PV and BES against extreme events with low probability and high impact [68]. The other metric is to increase the operation flexibility of the power system to manage the variability of renewable energies [69].

2.4. Electricity pricing programs

Electricity pricing program can highly affect the profitability of a PV-battery system. Fig. 8 illustrates five types of electricity pricing programs: (1) flat price, (2) TOU, (3) stepwise tariff, (4) critical peak pricing, and (5) RTP. Using the flat rates, the import/export power is charged by a constant price [70]. In the TOU pricing, the electricity rates are usually divided into two or three time periods during a day [71]. Higher rates are assigned to peak load times of the day. In the stepwise tariff, the electricity rate is increased by increasing the electricity consumption of the GCRS [72]. The critical peak pricing is based on the wholesale market [73]. Once the utilities anticipate critical events in the power market, they may call for high prices during a time period (e.g., 2 p.m.–5 p.m. on a hot summer day). In RTP, the electricity rate is changed dynamically in an hourly basis [74]. This means that the electricity rate is assigned by the operator based on the market price. The type of electricity pricing in the system is very important to develop the energy management to make the highest profit.

2.5. Home energy management systems

Energy management system (EMS) is essential to monitor and control the power flow between generation and consumption sides in a PV-battery GCRS. The main target of the EMS is a safe power supply while minimizing the electricity cost [75]. The EMS monitors the electricity rates, existent appliances for demand response, forecasted solar PV generation, battery's SOC and loads of the GCRS [76]. Then, based on the monitored data, the EMS decides efficient power flow control [77].

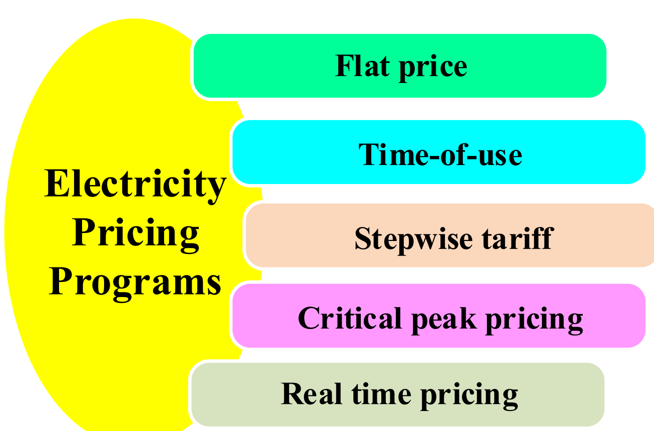

Fig. 8. Types of the electricity pricing programs for GCRS.

2.6. Optimization algorithms

Fig. 9 exhibits the optimization algorithms for optimal planning of solar PV and BES for GCRS. The applied optimization algorithms are probabilistic, artificial intelligence, iterative, analytical, sensitivity analysis, and intuitive approaches. The probabilistic methods can observe the stochastic model of uncertainties and then solve the problem analytically [78]. The artificial intelligence methods can efficiently overcome the nonlinearities of the optimization model [79]. These methods can be used for single-objective and multi-objective optimization problems. Particle swarm optimization (PSO) method and genetic algorithm (GA) are two worthy examples of single-objective artificial intelligence approaches [80,81]. The multi-objective (MO) artificial intelligence methods solve the problem in its nature by considering all objective functions and producing set of Pareto-fronts [82]. The non-sorting genetic algorithm II (NSGA-II) and multi-objective particle swarm optimization (MOPSO) are some substantial examples of these approaches [83,84].

In optimal planning by the iterative methods, the optimization problem should be repeated multiple times by random initial conditions. The methods based on sensitivity analysis can achieve the most sensitive capacities to the objective functions [85]. In classic mathematical methods, the computational model of the system is used for the optimization [86]. These methods ensure the convergence of the solution to the optimal result. The intuitive methods are useful when exact information and data about the system are not available [87]. The optimization algorithm should be selected based on the defined objective functions and the system model.

2.7. Software tools

Software tools can be used for operation analysis, techno-economic analysis and optimal sizing of PV and BES for GCRS. Some of the useful software tools are: HOMER [88], TRNSYS [89], RETScreen [90], HYBRID2 [91], iHOGA [92] and Sunny Design [93] that can be used for sizing of PV and BES in GCRS. A comprehensive review on software tools is provided in Ref. [94]. The advantages and disadvantages of software tools are discussed in Ref. [95].

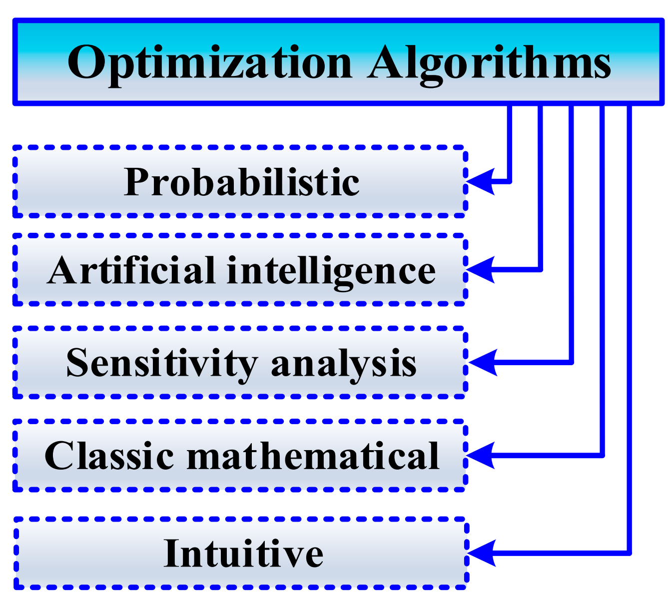

Fig. 9. Classification of the optimization algorithms for planning of PV and BES.

3. Present status and technical challenges in PV-battery optimal planning

The present status of the existing studies and technical challenges in PV-battery optimal planning for GCRS are investigated in this section.

3.1. Present status: review of the existing studies

A review on state-of-the-art studies on optimal planning of PV-battery for GCRS are investigated in this section. The studies are classified into three groups: (1) optimal planning of only solar PV system, (2) optimal planning of only BES, and (3) optimal planning of PV and BES. Each group is investigated based on the objective function, design constraint, optimization method, type of electricity rates, input data, and the country that the study was conducted. The first group is important for the households that are not equipped with solar PV. The second group of studies represents the optimal capacity of BES for the households who already equipped with PV panels. The third group of studies presents the optimal sizing of PV-battery for the households without any renewable resources and BES.

According to the literature review, more than 80 studies were deployed on optimal sizing of PV and BES for GCRS in all journals and conferences. Fig. 10 shows the number of publications per year from 2008 to 2020 in PV-battery optimal planning for GCRS. As illustrated in Fig. 10, the number of publications has increased from 2016. In 2017, 13 studies were published as the highest number per year. The main reasons for increasing the number of publications are awareness of the residential consumers about the emission, falling cost of the solar PV, technology maturity, and governments' subsidies.

3.1.1. Optimal planning of only solar PV system

Table 3 lists the reference number, optimization method, objective function and design constraints, as well as the electricity tariff and the studied country for optimal planning of only PV in GCRS. Several studies optimized the PV capacity and the other factors associated with the solar PV system. Various factors such as tracking system [96], inverter type [100], inverter capacity [103] and tilt angle [102–104] were optimized along with PV capacity. HOMER software, as the most used simulation tool, was employed by four studies to optimize the capacity of PV [96,98,102,103]. Other software tools like TRNSYS [97] and Sunny Design [105] were also used for optimal sizing. Although the NPV was used as the objective function by most of the studies, a few papers used COE [97], IRR [107] and PV system energy [100] as the objective function. The flat electricity pricing program was considered in most of the studies. TOU and stepwise electricity pricing programs were only used by Refs. [96,98], respectively.

3.1.2. Optimal planning of only BES system

Table 4 lists the characteristics of studies on optimal planning of only BES for GCRS with PV. In Refs. [109,110], the system operation was also optimized alongside the BES capacity optimization. The software simulation tools were not used for battery optimal sizing. Most of the studies developed the optimization code using MATLAB or GAMS. In Ref. [109], a multi-objective optimal sizing was developed by considering NPV and self-efficiency ratio as the objective functions. In Ref. [120], the optimal planning of PV and battery was examined for three types of batteries known as lead-acid, lithium-iron-phosphate, and lithium-nickel-manganese-cobalt. The results of their study showed that the lithium-iron-phosphate has the best economic results for GCRS if the consumer use 6 kW solar PV and a load demand of higher than 6 MWh per year. In Ref. [123], various objective functions were optimized using NSGA-II. The constraints of power balance and SOC of battery were applied in most of the studies. Unlike the studies for only PV optimal sizing (Table 3), the TOU pricing program was frequently used for BES capacity optimization. The studies mostly conducted for developed countries like Australia, Germany, etc. Optimizing the battery capacity, technology, and its replacement year was investigated, simultaneously, in Ref. [124] to minimize the total scheduling cost. In Ref. [126], a demand side management strategy was developed to investigate its effect on optimal planning of battery. It was found that the demand side management achieved around 50% capacity reduction for the BES.

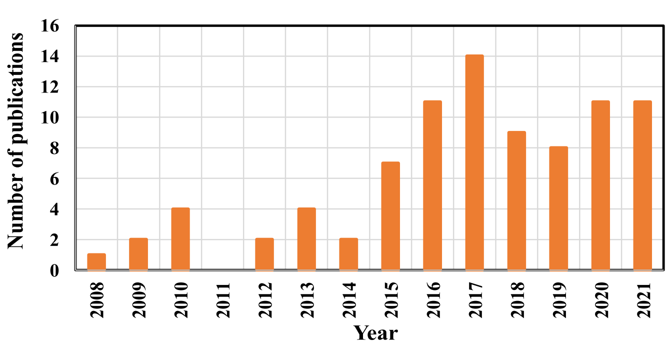

Fig. 10. Number of publications per year from 2008 to 2020 in PV-battery optimal planning for GCRS.

3.1.3. Optimal planning of PV-battery system

Table 5 lists the characteristics of studies on optimal planning of PV and BES for GCRS. A few studies considered the optimization of operation [127], dispatch [128], energy scheduling [129] and energy flow [134] alongside the PV-battery optimal sizing. Genetic algorithm was used as the optimization algorithm in Ref. [131]. The PSO algorithm was only used in Ref. [148] for optimal sizing of PV-BES system in a GCRS. Mixed-integer linear programming (MILP) was frequently used for optimal sizing. While financial objective functions were used in most of the studies, maximizing the amount of power fed back to the grid was considered as the objective function only in Ref. [135]. Various design constraints such as power balance, battery and grid limitations, as well as renewable factor were conducted in the existing studies. The flat and TOU were the most applied electricity pricing programs. Again, most of the PV-battery optimal sizing studies were conducted for developed countries. Different combinations of Flat and TOU electricity tariffs for import and export electricity prices were examined in Ref. [150]. It was found that using TOU for the import electricity, and Flat for the export electricity is the best option that GCRS can use to minimize the NPV. In Ref. [152], a spatial analysis was combined with techno-economic optimization to achieve a robust design of PV-BES system.

3.2. Technical challenges

Although several papers have studied optimal planning of PV and BES for grid-connected residential sector, there are still multiple technical challenges in the present status. Fig. 11 demonstrates the technical challenges of existing studies in terms of electricity rates, EMS, objective functions, battery degradation model, input data, and optimization methods.

The flat and TOU electricity rates were frequently used by most of the studies. The stepwise electricity rate was employed only in two studies [98,137]. The RTP was used only in Ref. [137]. It is notable that application of stepwise or RTP pricing is not a challenge alone. But new energy management systems should be developed to control the power flow in the GCRS based on the electricity price variations. For example, in a RTP program, the electricity price changes hourly or half-hourly. Hence, new EMSs should have the capability to receive the forecast data of solar insolation and load consumption to achieve the most efficient operation. The optimal planning of PV and BES for GCRS under stepwise, dynamic, and critical peak pricing tariffs should be adequately analyzed. The energy management systems were developed in several studies. A few considered the demand side management [109,127,146]. The load shifting and curtailment as well as incentive demand response

Table 3
Characteristics of studies on optimal planning of only solar PV for GCRS.

Ref.	Decision Variable	Optimization Method	Objective Function	Design Constraints	Electricity Tariff	Country
[96]	PV capacity and its tracking system	HOMER	Net present value	Power balance, PV size	Time-of-use	Saudi Arabia
[97]	PV capacity	TRNSYS	Cost of electricity	Energy balance	Flat	United Kingdom
[98]	PV capacity	HOMER	Net present value	Not specified	Stepwise	Malaysia
[99]	PV capacity	GA and PSO	Net present value	Power outage schedules	Flat	Lebanon
[100]	PV module technology and inclination, the inverter type and the location	Energy approach	PV system energy	Not specified	Flat	France
[101]	PV capacity	PSO and GA	Net present value	Not specified	Flat	Greece
[102]	PV capacity and slop of array	HOMER	Net present value	Not specified	Flat	Australia
[103]	PV array and inverter size	HOMER	Net present value	Not specified	Flat	Saudi Arabia
[104]	Number, tilt angle and arrangement of PV modules, and inverters	GA	Net present value Payback period Internal rate of return	Not specified	Flat	Greece
[105]	PV capacity	Sunny Design	Net present value	Not specified	Flat	Morocco
[106]	number, tilt angle and placement of PV modules	MOPSO	Net present value	Not specified	Flat	Greece
[107]	PV capacity	Self-developed	Internal rate of return	Not specified	Flat	Austria
[108]	PV capacity	Weighted Sum	Net present value Payback period Energy saving	Budget and rooftop limits	Not specified	South Africa

Table 4
Characteristics of studies on optimal planning of only BES for GCRS.

Ref.	Decision Variable	Optimization Method	Objective Function	Design Constraints	Electricity Tariff	Country
[109]	BES capacity and operation	NSGA-II	Net present value Self-sufficiency ratio	Power balance, SOC of battery	Time-of-use	Sweden
[110]	BES capacity and Charging/ discharging regime	Stochastic mixed integer nonlinear programming	Annual electricity cost	Not specified	Flat	Not specified
[111]	BES capacity	Not specified	Internal rate of return	Not specified	Flat	Germany
[112]	BES and converter capacities	Not specified	Self-consumption	Not specified	Flat	Germany
[113]	BES capacity	GAMS	Net present value	Power balance, SOC of battery	Time-of-use	United States
[114]	BES capacity	Mixed integer linear programming CPLEX	Net present value	SOC and energy of BES, peak shaving limit	Time-of-use	United States
[115]	BES capacity	Self-developed in MATLAB	Net present value	Not specified	Flat	Italy Switzerland UK
[116]	BES capacity	Convex programming in MATLAB	Net present value	Power balance, SOC of battery, import/export power	Time-of-use	United States
[117]	BES capacity	Self-developed in MATLAB	Net present value	Power balance, SOC of battery, purchase/sell power	Time-of-use	Australia
[118]	BES capacity	Stochastic simulation using Monte Carlo	Lifecycle cost	Not specified	Not specified	United Kingdom
[119]	BES capacity	Off-line linear programming in MATLAB	Return of investment	Power balance, SOC of battery, import/export power	Not specified	Not specified
[120]	BES capacity	Dual-simplex algorithm in matlab	Net present value	Power balance, SOC of battery	Flat	Germany
[121]	BES capacity	Mixed integer programming with ILOG CPLEX	Annual net payment	Power balance, SOC of battery	Flat	Luxembourg
[122]	BES capacity	Mixed integer programming with CPLEX-MATLAB	Total annual cost	Bidirectional power flow and SOC of BES	Flat Time-of-use	Australia
[123]	BES capacity	TRNSYS and NSGA-II	Net present value CO_2 emission PV efficiency Load cover ratio	Power balance, SOC of battery	Time-of-use	China
[124]	BES capacity, technology, replacement year	Mixed integer linear programming in MATLAB	Total scheduling cost	Energy, discharging power, and number of cycles of battery	Flat	United States
[125]	BES capacity and energy management within the grid	Self-developed	Total life cycle cost	–	Flat	Greece
[126]	BES capacity	Self-developed	Daily energy cost and annual cost	SOC of battery	Flat	Australia

need further investigations. Several objective functions like grid dependency, dumped energy and customer satisfaction were neglected by the existing studies. Battery capacity degradation model in optimal planning is an important factor that was not adequately studied in the literature. Most of the studies are conducted based on hourly arranged yearly data. Investigations of long-period data (e.g., 10 years) or high resolution (e.g., 5 min) was not addressed. A high-resolution data can assist the designers to not only examine the planning but also validate dynamic performance to achieve the most practical results. A good example of such studies is [69] where the optimal planning of a stand-alone system was done, and the dynamic performance of the system was validated through high resolution data. The robust optimization

Table 5
Characteristics of studies on optimal planning of solar PV and BES for GCRS.

Ref.	Decision Variable	Optimization Method	Objective Function	Design Constraints	Electricity Tariff	Country
[127]	PV-BES capacity and operation	Mixed integer programming with CPLEX-GAMS	Net present value	Power balance, charging/ discharging and SOC limits of battery	Flat	Not specified
[128]	PV-BES capacity and dispatch	NREL's Renewable Energy Optimization (REopt) model	Life cycle cost	Power balance	Time-of-use	United States
[129]	PV-BES capacity and energy schedule	Mixed integer programming, CPLEX	Net present value	Not specified	Time-of-use	Australia
[130]	PV-BES capacity	Mixed integer programming, GAMS	Net present value	Not specified	Flat	Australia
[131]	PV-BES capacity	GA	Net present value	Numbers of PV and BES Renewable factor	Not specified	Australia
[132]	PV-BES capacity	Mixed integer programming, CPLEX	Net present value	Not specified	Time-of-use	Australia
[133]	PV-BES capacity	HOMER	Cost of electricity	Not specified	Time-of-use	India
[134]	PV-BES capacity and energy flow	Mixed integer programming, Python	Net present value	Power balance Budget	Time-of-use	Australia Germany
[135]	PV-BES capacity	Probabilistic-based sizing tool	Maximize amount of power fed back to the grid	Not specified	Not specified	United States
[136]	PV-BES capacity	Self-developed in MATLAB	Cost of electricity	SOC of battery Budget	Not specified	United Kingdom
[137]	PV-BES capacity	DICOPT solver in GAMS	Annual operation cost	Power balance SOC of battery Import/export power	Time-of-use Stepwise Real time pricing	China
[138]	PV-BES capacity	Not specified	Self-consumption Annual electricity cost	Not specified	Flat	Germany
[139]	PV-BES capacity	Direct search method	Net present value	Not specified	Time-of-use	Australia
[140]	PV-BES capacity	Sensitivity tool	Life cycle cost	Not specified	Not specified	Turkey
[141]	PV-BES capacity	Mixed-integer linear optimization	Operating and investment costs	Power balance SOC of battery	Flat	Germany
[142]	PV-BES capacity	Stochastic mixed integer optimization in GAMS	Operating and investment costs	Power balance, charging/ discharging and SOC limits of battery	Time-of-use	United States
[143]	PV-BES capacity	Hybrid MILP and a heuristic optimization algorithm	Electricity cost	Power balance SOC of battery	Flat	Germany
[144]	PV-BES capacity	Self-developed in MATLAB	Annual electricity cost	Power balance, SOC of battery, grid limits, renewable factor	Flat	Not specified
[145]	PV and BES capacity	Not specified	Life cycle cost	SOC of battery	Flat	United States
[146]	PV-BES capacity	NSGA-II	Annual net profits and PV consumptive rate	Power balance SOC of battery	Time-of-use	China
[147]	PV-BES capacity	Robust optimization	Net present value	Power balance SOC of battery	Time-of-use	Australia
[148]	PV-BES capacity	PSO	Net present value	Power balance SOC of battery	Flat	Australia
[149]	PV-BES capacity	Sensitivity tool	Annual profit	Not specified	Flat	Australia
[150]	PV-BES capacity	PSO	Net present value	Power balance, battery SOC, grid constraint	Flat and Time-of-use	Australia
[151]	PV-BES capacity	GA	Self-sufficiency and payback period	Power balance, battery SOC	Time-of-use	Egypt
[152]	PV-BES capacity	HOMER	Cost of electricity and emission	SOC of battery	Flat	Algeria

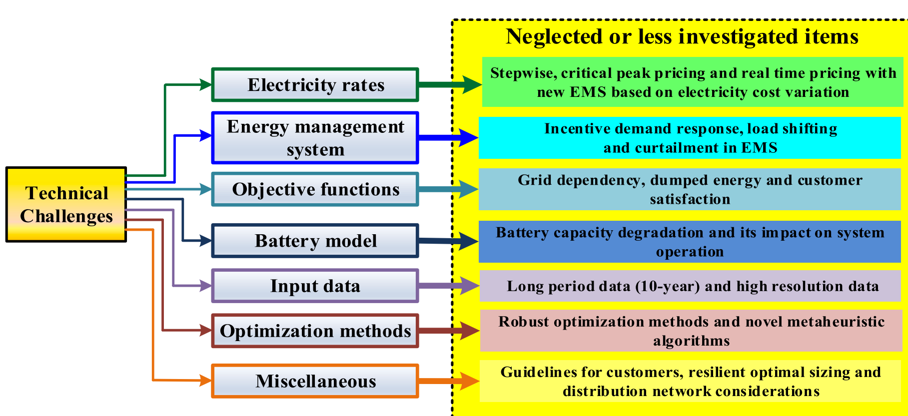

Fig. 11. Technical challenges in existing studies on the optimal planning of PV-battery systems for GCRS.

methods and novel metaheuristic approaches were not examined for PV-battery optimal sizing in GCRS. The new metaheuristic methods with the capability to reach global optimal results is useful to solve the planning problem with nonlinearities. Providing guidelines for the consumers is an important factor that was also overlooked.

4. Recent developments in optimal planning

Recently, several research developments have been done on PV-battery optimal planning for grid-connected residential sector. Fig. 12 demonstrates the recent developments in terms of guideline for customers, robust optimal PV-battery sizing, multi-objective optimization considering the autonomy of GCRS, detailed battery lifetime model, PV-battery optimal sizing by considering the operation of water heater, virtual power plant, multi-year stochastic programming, and multi-type BES.

4.1. Guideline for consumers

In [152], a guideline was provided for the consumers in Australia to purchase the optimal capacity of solar PV and battery. A flat electricity rate was considered for import/export energy from/to the main grid. The developed guideline was based on the available rooftop area and the average daily electricity consumption of residential households. It was shown that as the daily electricity demand of the household increases, the optimal capacity of PV increases. However, it is not beneficial to use more than 9 kW solar PV for the GCRS even with 30 kWh electricity demand per day. This is because of the grid constraints in Australia that limits the consumers to export less than 5 kW at any time. Based on the guideline, it is understandable that the recent BES price is not economically efficient for integration in the grid-connected households in Australia. Such guidelines are very helpful for consumers to render the most economic capacity of PV and BES for their households in urban area. Guidelines based on other electricity rates such as TOU or RTP are neglected in the literature.

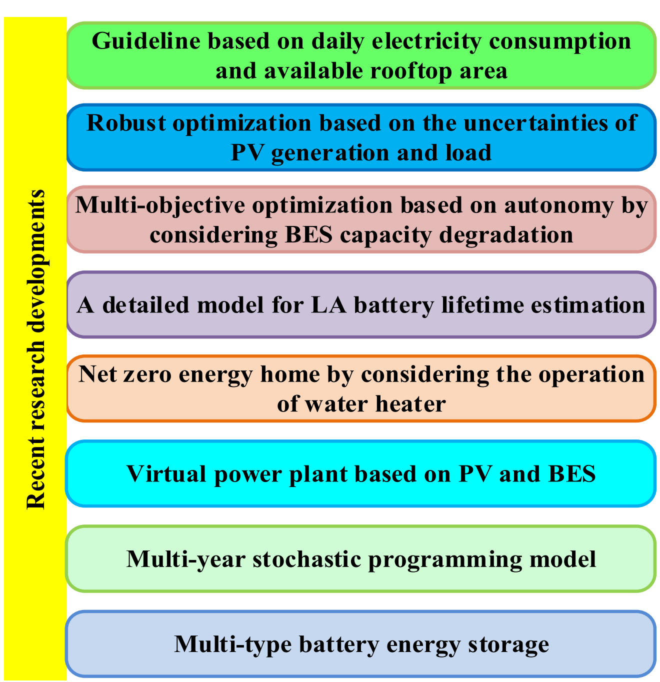

Fig. 12. Recent research developments on PV and BES optimal planning for GCRS.

4.2. Robust optimal planning

In [153], an adaptive robust optimal planning and operation was proposed for PV-BES in grid-connected homes. The polyhedral sets were used to model the uncertainties of solar PV generation and load consumption. The developed robust planning was based on the worst-case realization of uncertain parameters. The optimization problem was solved by an outer min challenge known as "here-and-now" decisions for PV and BES sizing, and an inner max-min challenge to determine the operation variables known as "wait-and-see" decisions. It was approved that reliability and tractability are the main features of robust optimization over conventional methods like scenario generation, Monte Carlo simulation, K-means data clustering and probability distribution functions. The robust optimization approach solves the planning problem based on bounded interval of uncertainty sets that eliminates the requirement of scenario generation. Robust planning of PV-battery system based on the uncertainty in RTP was not studied in the literature.

4.3. Multi-objective optimal planning considering the autonomy

In [154], the MOPSO methodology was used for multi-objective optimal planning of PV and BES in grid-connected households. Energy autonomy, power autonomy, payback period and lifetime capital cost were considered as the objective functions. The methodology achieved the optimal azimuth angle of PV panels and capacity of PV and BES. The lifetime of battery was estimated based on the total capacity fade. Such multi-objective studies are very useful for the customers to not only consider the cost as an objective function, but also check the autonomy of the system operation for various capacities of PV and BES.

4.4. Detailed model of lead-acid battery lifetime estimation

In [155], the optimal design conducted for a residential microgrid with lead-acid battery and PV by minimizing the COE. The decision variables were selected as the number of BES and PV panels, as well as the optimal value of battery depth-of-discharge (DOD) and the tilt angle of the PV panels. This paper deployed a detailed model of lead-acid BES based on the battery voltage, current and SOC performance. The developed model then considered the replacement of BES in the project lifespan based on the discharge current, SOC impacts, acid stratification, number of cycles and the sulfate-crystal structure. This study considered an annual loss of power supply based on the grid-interruptions to maximize the reliability of the designed PV-battery system. Optimal planning problem is a long-period challenge; hence such studies are very useful to achieve an accurate lifetime of BES. Based on the estimated lifetime of battery, more accurate economic analysis can be achieved for the project.

4.5. Optimal planning by considering the operation of water heater

In [156], a net zero energy home was investigated for optimal planning of battery based on electric water heater operation. In the developed model, the charging/discharging of BES and power consumption of electric water heater can be scheduled; hence, the GCRS could operate like a dispatchable load or generator in the grid. The results of the study showed that by coordinating the battery storage and electric water heater with the generated power of solar PV, smaller capacities of BES are achieved for the consumers.

4.6. Virtual power plant based on PV and BES

Aggregation of residential PV panels and BESs can create a virtual power plant (VPP) in smart grids. In Ref. [157], a two-layer optimal planning was investigated for BES sizing in a residential system with solar panels. The dispatching of the PV and BES system was also considered for the optimal planning. It was demonstrated that the optimal sizing resulted in lower cost of the VPP with mitigating the uncertainties of renewable generation.

4.7. Multi-year stochastic programming

A multi-year stochastic programming was proposed for optimal planning of PV and BES [158]. The uncertainties of load and PV generation were considered in the model. A new financial model was developed based on the multi-year operation that eased the cash flow analysis. The main features of the developed model were to consider the aging of the battery and a long-period uncertainties in the optimal planning.

4.8. Multi-type battery energy storage

In [159], an ε-constraint methodology was used to solve the multi-objective optimal planning problem by considering a multi-type BES. Three types of battery (LA, LIB, and NaS) were aggregated to be used with PV panels. The system total cost and the output power smoothing index were considered as the objective functions. It was found that changing the configuration of the BES has more effects on the power smoothing index rather than the system cost.

5. Direction for future works

Based on the aforementioned technical challenges and recent developments, the directions for future work are discussed in this section. Fig. 13 illustrates various trends for future scopes in optimal sizing of PV and BES for GCRS.

5.1. Demand response and optimal planning

Demand response is an impressive factor in optimal planning of a PV-battery system for GCRS. Forecasts of solar insolation, load consumption and electricity rates should be available to render useful insights for the demand response action. Efficient demand response programs can effectively decrease the capacity of the PV and battery, and hence decrease the cost of the system. However, the DR programs are not favourable for customers [160]. Objective functions like customer satisfaction (i.e., user's convenience/comfort level) are very helpful to be considered in the optimal planning with a DR framework [161,162]. The CS objective function indicates the satisfaction level of customers by the demand response program [163–165]. To achieve a maximum CS in GCRS, three strategies can be conducted; (1) the time for load shifting should be minimized, (2) the amount of load curtailment should be minimized, and (3) the incentive payments for contribution in DR program should be maximized. A multi-objective optimal planning of PV-battery system for a GCRS by considering the NPV and customer satisfaction is strongly recommended.

5.2. Dynamic electricity rates and optimal planning

Dynamic electricity rate (i.e., RTP) forces the consumers to develop efficient energy management systems [166,167]. In this case, demand response and charging/discharging of battery are the important aspects in the energy management [168]. The main aim is to maximize the profits by monitoring and controlling the energy flow of the GCRS based on market prices [169,170]. This trend completely affects the optimal capacity of PV and BES for residential sector. A bi-level optimization model is recommended to optimize: (1) the capacity of PV and BES, and (2) the operation (energy management system) of the system.

5.3. Resilient PV-Battery planning

A resilient PV-battery optimal planning is an opportunity to strengthen the load supply probability using the PV-battery system in grid outages [171]. Natural disasters are the main reasons for grid outages that can jeopardize the resiliency of the network [172]. Since the natural disasters are mostly unpredictable, considering probability distribution functions based on the type of the disaster can be integrated into the optimal planning problem [173]. This can be considered as a grid outage in the optimization model [174]. This can enhance resiliency of the designed PV-battery system [175]. New design factors like a limitation for the maximum load supply during the grid outage can be used for the resiliency of GCRS with PV-battery system.

5.4. Grid dependency in optimal planning

The consumers would like to decrease their dependency on the main grid by the installed PV-battery system. In such condition, grid dependency (GD) can be identified as a new objective function. Grid dependency is the fraction of imported electricity from the main grid over the total electricity demand by the residential sector. It is notable that when the GD is zero, the GCRS operates as a standalone system with PV and battery. Increasing the capacity of PV and BES can decrease the GD of the GCRS; however, this increases the system costs. Hence, a trade-off between the cost of electricity and grid dependency is important from the consumer point of view.

5.5. Distribution network considerations in optimal planning

Increasing the number of solar PV panels in low voltage distribution feeders may cause new challenges [176]. One of the main challenges is voltage increase [177], which may result in restriction of the PV's

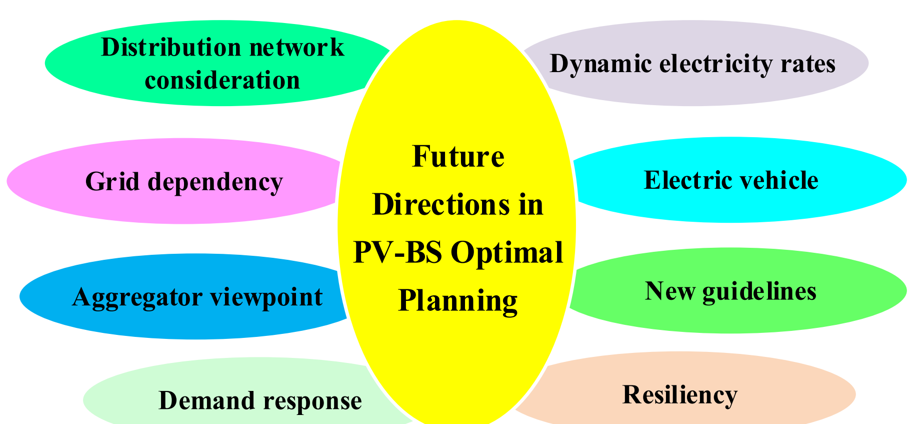

Fig. 13. Future scopes in the optimal planning of PV and BES for GCRS studies.

hosting capacity by the distribution feeders [178]. The BES and PV can be optimally integrated in distribution networks to mitigate the problems [179]. Efficient battery management and demand response programs are some solutions in GCRSs for distribution network problems [180,181]. Therefore, optimal planning of PV and BES by considering the voltage increase crisis in distribution network is a new trend for the future studies.

5.6. Aggregator viewpoint optimal planning

Aggregators have facilitated the participation of small-scale PV-battery system (e.g., in households) in electricity markets [182]. In this case, customers are needed to control their power consumption based on the aggregator's requirements for demand response [183]. In some cases, aggregators may encourage the consumers in a localized area to use a central battery storage [184]. Based on the contracts with the aggregators, the optimal capacity of PV and BES may be changed in GCRS.

5.7. Strategies for planning in households with EV

Recently, electric vehicles (EVs) have become popular transportation fleet due to environmental concerns. The EVs could be charged at home. This would increase the electricity bill of the residential consumer. When the EV is charged at home, the energy management system and subsequently the optimal planning of PV and BES are affected [185]. Since the EV arrives home at evening time, the PV generation is not available and hence the BES can be discharged to not only supply the home loads but also charge the EV' battery [186]. Hence, a larger capacity of the BES may be required for the residential households with EV. In addition, a higher capacity of PV may be needed to charge a large battery. On the other side, the vehicle-to-grid (V2G) [187,188] and vehicle-to-home (V2H) [189,190] capabilities of EV may increase the profitability of the PV-battery system in the GCRS. This makes the EMS of the household with EV more complicated. Therefore, the future studies can examine smart charging of EVs in the household while implementing the optimal planning of PV and BES.

5.8. New guidelines

Guidelines are very helpful for the consumers to choose the optimal capacity of PV and BES based on their electricity consumption, available rooftop, and electricity rate. To this end, new guidelines can be provided based on different objective functions like emission, GD of the GCRS, resiliency factor, reliability, and renewable factor. The only guideline provided in the literature was in Ref. [153] based on the COE. Hence, new guidelines can be arranged for various electricity pricing programs. Since the TOU electricity pricing has been extensively used for the householders with PV-battery system, new guidelines based on TOU tariff is highly recommended.

6. Conclusion

This paper investigated a survey on the state-of-the-art optimal sizing of solar photovoltaic (PV) and battery energy storage (BES) for grid-connected residential sector (GCRS). The problem was reviewed by classifying the important parameters that can affect the optimal capacity of PV and BES in a GCRS. The applied electricity pricing programs, objective functions, design constraints, home energy management systems, optimization methodologies, and input data were suitably investigated. The existing studies were classified based on the decision variables, (1) only PV sizing, (2) only BES sizing, and (3) PV-BES sizing. The technical challenges were identified, and recent research developments were explained. The future directions were introduced to the researchers.

The main implications of this review study are as follows:

- Practical guidelines would be useful for the customers in residential sector to purchase the optimal capacity of PV and battery based on all practical factors. However, only one practical guideline was published in the existing studies that provided the guideline based on flat electricity price. More guidelines should be generated by the researchers for the customers with other electricity prices.
- While several studies have been published on optimal planning by considering Flat and TOU electricity prices, the variable tariffs have been rarely investigated. By the advancement of smart grid facilities, optimal planning of PV and battery needs careful investigation under real time pricing for electricity exchange between the consumer and grid.
- Practical demand response strategies would be useful for consumers to reduce the capacity of PV and battery and hence the costs of the system. This would be possible by load shifting or curtailment of controllable loads such as heating, ventilation, and air conditioning (HVAC) loads at home.
- Optimal planning of the grid-connected consumers with electric vehicle would be a potential topic for the researchers. This is a major implication because of the growing penetration level of EVs in the residential sector.
- New factors like grid dependency, distribution network limitations, and resiliency are among the new topics. The consumers would like to see how much autonomy could be achieved by different capacities of PV and battery in their household. In addition, which capacity of PV and battery could achieve a resilient system against grid outages. The distribution network faces several challenges due to high penetration of rooftop solar PV systems. This needs critical strategies to create limitations and guidelines to the consumers to control the voltage and frequency.

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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