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Review

Smart Distribution Networks: A Review of Modern Distribution Concepts from a Planning Perspective

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Academic Editor: Josep M. Guerrero
Received: 31 January 2017; Accepted: 3 April 2017; Published: 7 April 2017

Abstract: Smart grids (SGs), as an emerging grid modernization concept, is spreading across diverse research areas for revolutionizing power systems. SGs realize new key concepts with intelligent technologies, maximizing achieved objectives and addressing critical issues that are limited in conventional grids. The SG modernization is more noticeable at the distribution grid level. Thus, the transformation of the traditional distribution network (DN) into an intelligent one, is a vital dimension of SG research. Since future DNs are expected to be interconnected in nature and operation, hence traditional planning methods and tools may no longer be applicable. In this paper, the smart distribution network (SDN) concept under the SG paradigm, has presented and reviewed from the planning perspective. Also, developments in the SDN planning process have been surveyed on the basis of SG package (SGP). The package presents a SDN planning foundation via major SG-enabling technologies (SGTF), anticipated functionalities (SGAF), new consumption models (MDC) as potential SDN candidates, associated policies and pilot projects and multi-objective planning (MOP) as a real-world optimization problem. In addition, the need for an aggregated SDN planning model has also been highlighted. The paper discusses recent notable related works, implementation activities, various issues/challenges and potential future research directions; all aiming at SDN planning.

Keywords: microgrid (MG); multi-objective planning (MOP); looped distribution networks; smart distribution network (SDN); smart grid; smart grid package (SGP); virtual power plant (VPP)

1. Introduction

The ever increasing load demands, aging infrastructure, limited expansion options, and environmental concerns make it difficult for hierarchical-based traditional grids (TGs) to keep pace with modern era requirements [1]. Nevertheless, power grids have not been upgraded considerably for decades. Moreover, the competitive electricity market and service requirements close to the technical limits of current technology, have resulted in overstressed grid operations (at the transmission/distribution level), particularly in the distribution network (DN). Conventionally, the DN has purposely been planned to retain unidirectional power flow with radial topology, aimed at efficient power delivery to the end consumer. However, escalating load requirements over large geographical distances have resulted in serious technical issues in DNs, predominately higher system losses, lower voltage regulation, compromised power quality, reliability concerns, and expensive planning alternatives [2,3]. The possible solution strategy calls for planned (long/medium/short-term) modernizations that include countermeasures to deal with technical and commercial issues. The anticipated modernization needs to investigate the potential key enablers and associated developments; in planning and transforming traditional into smart DNs (SDNs) [4]. Still, smooth transition to SDNs is a concept that is easier said than done.

2. The Smart Distribution Network (SDN) Concept in Smart Grids

The Smart Grid (SG) as an emerging concept, concerns with the modernization of grid functionalities, supported by state of the art technologies, which were limited in the TG [5]. The SG as a term does not have any single universally accepted definition. In general terms, SG is an intelligent grid, capable of accommodating the bi-directional flow of power and communication, besides being capable of modernizing the power grid and related functionalities [6]. The grid modernization spreads across multidimensional concepts of revolutionizing power systems, the introduction of intelligent technologies, new key concepts, maximizing achieved objectives and addressing critical issues from a future perspective. The possible keys enabling SG technologies include information and communication (ICT), control, sensing and measurement, storage, automation, renewable generation integration, etc. [7]. The future's DN or simply SDN (under the SG paradigm) are envisioned to be interconnected in structure and complexity in operation; including the use of high penetration of distributed energy resources (DER). However, limitations in current DN infrastructure restrict the maximum utilization of DERs. On the other hand, adoption of SDN may be jeopardized without acquiring aforementioned intelligent technologies and infrastructure modifications [8]. Also, technical and cost-related issues at the distribution level may negatively impact the end consumers on a long-term basis.

2.1. Need for SDN Planning

The traditional DN planning (TDP) aims at finding feasible economic solutions. Primarily, "where, when and what" type of substations and branches/lines will be added or replaced/removed to reach an optimal DN configuration that supplies the load demands over the whole planning horizon [9]. However, TDP is further complicated with the inclusion of distributed generation (DG) units and the associated problems, primarily related to optimal topology or reconfiguration, reliability (protection) concerns, electricity markets (retailers and wholesalers), load uncertainties, cost and risk management issues. SDNs are expected to be compatible enough with intelligent technologies to accommodate various DG types and associated components; mainly renewable DGs (REGs), various storage technologies (SST), electrical vehicles (EVs) and demand responses (DRs). In addition to that, major power industry stakeholders are becoming encouraged to recognize the needs to address challenging issues and replan the DN structure according to the SG paradigm [8,10]. Thus, the current DN structure and relevant planning approaches will not remain applicable for SDNs and are under review for both normal and fault conditions. In this way, SDN as a new consumption model can become an attractive alternative to enhance system flexibility and improve services, aiming at serving the end consumers' demands in an efficient manner [11].

2.2. Literature Review

The necessity of smooth grid evolution needs to initiate plans as roadmaps for the construction of new consumption models. The SDN is somewhat related to the upgrading/modification of current DN systems and initiation of new distribution concepts/mechanisms with high-technology support in accordance with the anticipated future requirements. Several SDN concepts available in the literature, have been primarily based on modification of the DN structure, reliability, DER, RES, ICT, power electronics (PE), scale, and active network management (ANM) techniques. Unlike the DNs of the past, today's DN is somewhat better than its older counterparts in terms of initiating the use of ANM-based techniques to achieve various benefits under certain constraints. Most prominent among them is DG integration while retaining the radial topology (reconfiguration) of the DN, also known as active radial DN (ARDN) [10]. To date, the DNs of today have some scope for modifications supported by various studies, mainly under the paradigm shift of active DN (ADN), as mentioned in [5,10,12].

The SDN concept on the basis of voltage stability, interconnected topology, reliability to consumers and high DG penetration favors loop and mesh topologies, aiming primarily at advanced power distribution configuration in SG [13,14]. Gamarra et al. [15] presented a technical review of the literature on optimization techniques for planning, applied to one of the most popular SDN concepts, known as a microgrid (MG). The reviewed work serves as a guideline for innovative planning methodologies, primarily based on economic feasibility. Also, new MG planning approaches and a few trending techniques are pointed out. Siddaiah et al. [16] presented a review of the research work carried out in planning, configuration, modeling, and optimization techniques of hybrid RES for isolated/off-grid applications. The reviewed work offers several mathematical models proposed by various researchers. The models are developed based on objective functions, reliability and economics studies involving design parameters. Besides MG, virtual power plant (VPP) is a concept that deals with providing a reliable electricity supply to the end consumer. Comprehensively reviewed work on MG and VPP concepts has been carried out by Nosratabadi in [17], aiming at solving the DER scheduling problem. The problem has surveyed from perspectives of formulation type, objective function, solution techniques, uncertainty, reliability, reactive power, control, automation, emission, stability, demand response and multi-objective optimization.

On a small scale, smart homes (SHs) and smart building (SBs) are concepts which reside on the consumer side of the grid. Lobaccaro et al. [18] presented a review of works carried out on SHs, from the perspectives of concept, smart home technologies, selection criteria, challenges, benefits and associated benefits. In addition, Zhou et al. [19] offered a review of the development status and research progress on smart home energy management systems (HEMSs) with renewable and stored energy sources. The work provides initially an overview of HEMS architectures and fundamental functions, followed by configurations and home appliances, finally covering utilization techniques for various RES in a SH. Similarly, on the large and complex scale, Calvillo et al. [20] have reviewed the smart city concept, aiming at energy-related work on planning and operation models. Moreover, the scopes of the reviewed works can be classified into five interventions, namely; generation, storage, infrastructure, facilities, and transport. In addition, complex urban energy models integrating more than one intervention area are also reviewed with their respective benefits, limitations, trends, challenges and applications. Also, a methodology is proposed for developing an improved energy model for a smart-city. The literature review indicates that considerable amounts of literature regarding SDN concepts are available. Still, there is a need to consider planned grid modernizations and new planning strategies from the viewpoint of SDN. The anticipated grid transformation and modifications aiming at DN are shown in development (modernization) stages of the past, today (present), and future [21], as shown in Figure 1.

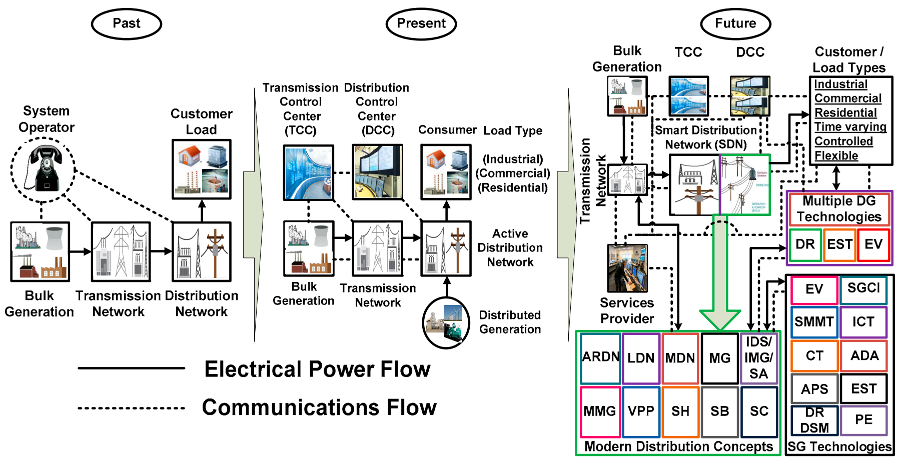


Figure 1. Development process of distribution grids from the past to a smart future (adapted from IEA [21]).

2.3. Futuristic SDN Planning: Aim and Scope of Work

In the SG paradigm, diverse stakeholder participation is inevitable from various SDN viewpoints, primarily planning. Foremost stakeholders in the electricity industry include primarily utilities, manufacturers, vendors, regulators, governments, research organizations, and consumers. The need to motivate the stakeholders enables them to recognize, participate and address the challenges in SDN planning, development and deployment respectively [8]. The expected compromise or trade-off solutions addressing conflicting objectives for satisfying multiple stakeholders, make multi-objective planning (MOP) a suitable choice for SDNs [22]. The real-world planning problem can be considered a multi-objective (MO), constrained and practically stochastic basic optimization problem [15]. The optimal DER sizing and placement will be the focus of SDN planning [23]. Various test (demonstration) and pilot projects are in progress across the globe that identify and realize the associated SG features. In addition, such developments point out the potential areas to addressed concerns and new challenges that can arise, from a future perspective.

Hence, in the light of the above literature, a real world, deeper, wider and aggregated planning approach is inevitable. The usual planning problems focus on finding a feasible economic (cost effective) solution. In addition, objectives like reliability, power quality and low (negative) environmental impact, system stability, energy efficiency and customer satisfaction can also be considered in SDN problem formulation. The SDN planning problems have been classified as follows [15,17,24,25].

1a. Long-term SDN planning: Long (several years) and medium term (one year) planning problems have been carried out over large (single and/or multi-stage) planning horizons. The classification mainly deals with a number of energy sources (DG, DER, RES, REG, storage, ESS, EV, DR, associated devices, reinforcements, etc.) selection, their sizing, and location within SDN.

1b. Off-line planning problem: Off-line (scenario/model-based) planning studies have been carried out for a specific operational scenario, since practically a planning problem is an off-line problem. Hence, scenario-concerned problems in coordination with ANM-based schemes are considered a variant of the classification above.

2. Scheduling: Medium (seasonal–year) and short-term (one–several days) planning problem studies have been carried out over a scheduled horizon (one day–a season–a year). The classification primarily deals with scheduling problem of renewable/conventional sources (energy sources assets) selection and demand forecasting within a SDN framework.

3. Real-time operational planning (RT-OP): The real-time (15 min–day) operational planning problems have been studied over a short term operational horizon. The classification primarily deals with operational planning problem of asset selection and topology alteration based on state-estimation algorithms and communication-based signals. In addition, real-time operational planning (RT-OP) has expected to be critical in complex real-time SDN operations.

This study aims to present a systematic review of distribution grid modernization from the planning viewpoint. It offers an overview of the status of SDN planning by featured intelligent technologies, anticipated functionalities, modern distribution concepts (MDC), policies, work maps, related pilot projects and MOP as a real world planning option. This study should serve as a guideline for researchers and planning engineers to formulate approaches, addressing future SDN planning scenarios. In the literature, several methods are available concerning the planning of current power DN and [10,12,14,23,26] and the abovementioned planning problems have been separately addressed.

The traditional planning methods may not be applicable to plan new DN models or transform current DNs into SDNs [24,26]. In addition, few accounts are available in the literature that considers grid modernization from the planning perspective of future distribution mechanisms. Hence, new interconnected SDN concepts, exploitation of SG functionalities, key enabling smart technologies, ANM schemes, multiple stakeholders, MOP as real-world planning problems and integrated planning strategies; constitute the key features of modern SDN planning. Thus, SDN as a grid modernization concept, supported by a detailed account of research works in several aspects, is comprehensively surveyed in the paper. This works compliments existing works by offering:

(1) Examination of the SG package (SGP) concept, including key enablers that aim at future SDN planning.
(2) Current planning status of real world (multi-objective) optimization from a SDN's viewpoint.
(3) The challenges in SDN planning and future research directions.

The paper is organized as follows: Section 3 provides an overarching diagram of smart grid packages (SGPs), offered for SDNs. Section 4 describes an overview of enabling technologies and functionalities for SDN concept realization. A brief overview of potential modern distribution (SDN) concepts in the SG paradigm is presented in Section 5. Section 6 summarizes an overview of policies, workmaps, leading countries, pilot projects and focused objectives from the standpoint of SDN. Section 7 presents a composite review of the current MOP status from an SDN's perspective. Current challenges in SDN studies and future research directions have been presented in Section 8. The paper concludes in Section 9.

3. Smart Grid Packages (SGPs) for Smart Distribution Networks (SDNs)

The literature review indicates that a considerable amount of research work has been carried out on various aspects of SG in particular and the benefits offered are amalgamated in general with overall SG concepts. In his study, key enablers involved in development and deployment of SG concepts, in particular SDN is arranged in accordance with the proposed smart grid package (SGP) concept. SGP and its prominent features are presented in this paper as the overarching diagram in Figure 2 and aree discussed in the following Sections 4–7. The key components in SGP are indicated as follows:

(1) The enabling technologies and anticipated functionalities in SGP	→	SGTF
(2) Modern distribution (consumption) concepts (models) in SGP	→	MDC
(3) Policies by leading countries, work maps and pilot projects for SG concepts realization	→	PWP
(4) Real world optimization planning problems (in multi-objective planning framework)	→	RWO

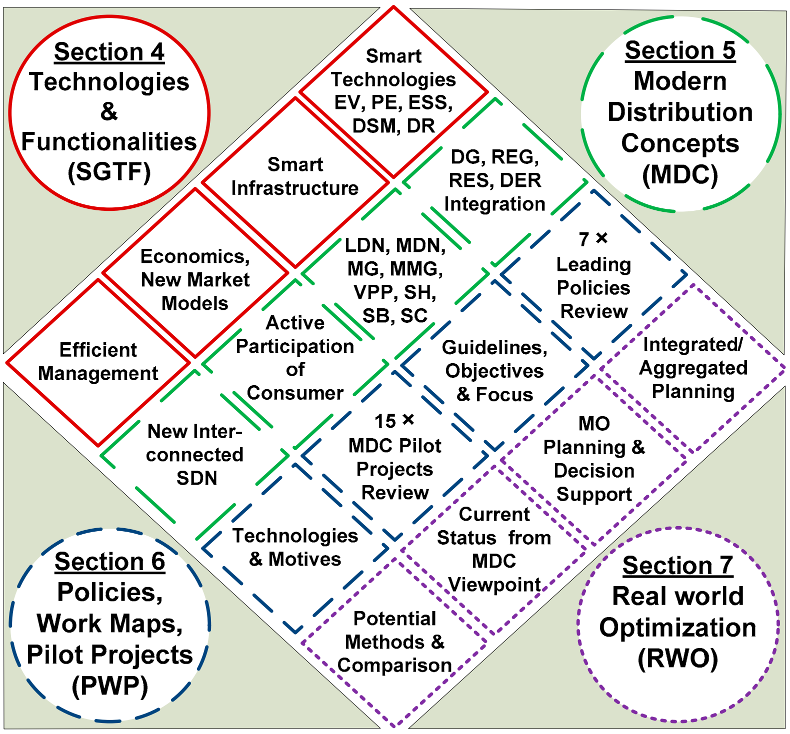


Figure 2. Overarching Diagram of the Smart Grid Package (SGP) in the paper.

4. Enabling Technologies and Anticipated Functionalities in SGP (SGTF)

4.1. Major SG Enabling Technologies (SGET)

4.1.1. SG Components Integration (SGCI)

The future SDNs are expected to house large DG/DER/REG penetration and to be capable of accommodating bidirectional power flow [27–29]. The developments in power electronics (PE), mainly power converters, enables smooth integration of DER/REGs in coordination with storage and ICT, respectively. The major SG components primarily include various DER/DG technologies, smart metering systems, flexible loads, storage systems, smart substations equipped with automated transformers and online tap changers (OLTC), all interconnected with advanced automation and control infrastructures [30].

4.1.2. Information and Communication Technologies (ICT)

The widespread information and communication (ICT) infrastructure forms the backbone of sensing, measurement, monitoring, and metering operations. Besides, the implementation of modern distribution concepts (MDC) like SHs, SBs, VPP and SC; depends on the advancements in ICT. The ICT enable data flows from sensing devices to smart meters, further to utility data centers, and back [31]. The advanced metering infrastructure (AMI) empowers SG with nearly real-time condition monitoring, ensuring accurate bills and allowing consumer a position of decision-making towards their energy use [5]. Communication technologies (wired and wireless) serve as a medium to implement SG solutions aiming at control, protection, automation and monitoring [32,33]. The research issues include; homogenization of standards to attain interoperability and scalability.

4.1.3. Advanced Distributed Automation (ADA)

The ADA together with AMI facilitates DN modification, particularly the implementation of SG functionalities at the distribution grid level, employing transformer/feeder monitoring, effective fault detection/isolation, outage management (quicker fault restoration), electrical vehicle (EV) integration and protection of assets. The ADA can assist implementation of new distribution topologies like loops to improve DN reliability and stability. Moreover, the use of intelligent electronic devices (IED) enables ADA by performing control, communication, protection, metering and logic processing functions autonomously, resulting in coordinated operation of the key enablers [34,35]. The important research issues include [30]; integration of ICT and ADA into one SG based control solution considering generation, distribution, EST, and loads. Also, new methods for design, development, and validation represent research-worthy areas.

4.1.4. Energy Storage Technologies (EST)

The energy storage applications include consumer energy management, seamless REG integration on various scales (utility and consumer), EV infrastructure support, and short-term active and reactive power support to the system [36,37]. The prime EST-based objectives include better voltage and frequency support during transients, long term REG integration, power quality and reliability of the service [38,39]. The MDC-based EST applications mainly include optimized storage utilization with DG, EV, and DR for asset planning and scheduling [40]. The research-worthy issues in EST include cost effective economic solution and advance control functions provided by EST, DER, and controllable loads.

4.1.5. Power Electronics (PE)

The PE devices, interfaces and mechanisms are vital components of future power distribution mechanisms. Colak et al. in [41] have broadly reviewed the PE contributions to SG on the basis of their applications in SG, particularly REG integration and MG. The notably associated objectives include improving reliability, sustainability, stability and power quality. The research worthy issues include; parallel inverter operation in MG, stability in large-scale centralized solar energy generation, bidirectional power flow control, agent-based control and optimization of fault tolerance, respectively.

4.1.6. Electric Vehicles (EVs)

EVs are one of the important paradigms of the SG package. It broadly encompasses the concepts of EV, plug-in hybrid EV (PHEV), vehicle to grid and grid to vehicle (V2G & G2V). The major attributes of EVs include system stability, reliability, and efficiency of the grid [42–44]. The objectives are achieved in terms of REG storage/backup, spinning reserve (SR) and contribution to the decreasing peak power demand curve in coordination with demand response (DR) The REG and EV infrastructure, interaction and integration to the current DN and SDN, are new research dimensions [45,46].

4.1.7. Sensing, Measurement, and Monitoring Technologies (SMMT)

The sensing devices mainly includes smart meters, wireless sensor networks (WSNs), remote terminal units (RTU) and phasor measurement units (PMUs). The SMMT detect anomalies such as deviation from normal conditions and assist in remote monitoring of energy sources and related equipment [47].

4.1.8. Control Technologies (CT)

Control technologies have generally been classified in terms of centralized (high computation cost), decentralized/distributed (high synchronization time) and hybrid methodologies. Tuballa et al. [7] have arranged SG-based control methods/technologies on the basis of a multi-agent system (MAS), power electronics (PE), advanced fault management (AFM) and virtual power plant (VPP)-based control technologies, respectively. Decentralized control schemes, known as MAS, unlike their centralized counterparts, can manage a large amount of interconnected SG components and micro grids (MGs). PE-based control schemes can manage large scale DG using inverters into the grid. AFM through coordination of local automation, relay protection and switchgear control for optimum MG islanding can serve critical consumers during main grid outages. The real-time control approach for VPP aiming at REG fluctuation and nonlinear loads can be addressed in an effective manner. Intelligence-based architectures such as service-oriented architecture (SoA), MAS-based control and artificial intelligence (AI)-based control solutions in MDC concepts (Section 5) need further research consideration [30].

4.1.9. Advanced Protection Schemes (APS)

The modernization challenge of distribution grids aiming at protection in coordination with ADA is emphasized to coordinate advanced control on the basis of information provided by sensor networks and smart meters in the field to integrate REG/DER with DMS to enhance overall performance. Moreover, the incorporation of intelligent electronic devices (IEDs) will facilitate self-adaptive protection (mainly fault location, isolation, and service restoration or FLISR and high impedance fault detection or HIFD), metering, and control and communication functions. The anticipated major objectives expected to be achieved include system stability, reliability and personal safety [35,48]. Mirsaeidi et al. [49] reviewed current protection schemes and proposed advanced protection schemes considering a digital central protection unit and PMUs. The proposed method aims at interconnected MG with complicated power flows during both normal and islanded operations.

4.1.10. Demand Side Management (DSM) and Demand Response (DR)

Demand Side Management (DSM) is an important planning tool, aimed at ensuring the reliability and stability of power systems on a long-term basis. The utilities implement DSM programs to manage demands on the consumer side of the meter. The primary DSM objectives include energy efficiency, peak load management; load shifting, rebound peak shifting, valley filling, strategically addressing load growth and reshaping demands [50,51]. DSM allows consumers "freedom of choice" regarding decision making in their energy consumption and enables utilities to reduce peak load demands [52]. Demand response (DR), as a subset of DSM, are programs design to encourage consumers to involve in grid operations on short-term basis, by shifting their loads/consumption patterns (during peak to low demand periods) on the basis of financial incentives. A state-of-the-art survey is presented by Siano et al. [53], encompassing various aspects of DR, prominently concepts, potential benefits, enabling smart technologies, applications and case studies. The DR technologies are classified based on control, monitoring (information) and communication systems, respectively. The prominent research dimensions include DR provider implementation and associated infrastructure for plugged-in EVs.

4.2. SG Associated Anticipated Functionalities (SGAF)

4.2.1. Efficiency ($\acute{\eta}$) and Effective Management (EM)

The asset optimization in SDN demands promising functionalities and services for efficient operation and effective management of resources [5]. In particular, peak loadings, unexpected rebound peaks and valley filling (low load demand) must be optimized, to avoid overprovision of resources. The key SG enabling technologies for "efficient grids" primarily consist of advanced forecasting support for optimized operations (generation-load balance) [30], DR for energy management support at small levels [53] and greenhouse gas (GHG) emission control [5]. Also, DSM on a large scale proactively addresses complex consumption dynamics (utilities' and consumers' behaviors); with the support of (ICT) and dynamic pricing schemes, respectively [50]. In addition, advanced active network management (ANM) techniques mentioned in [54] and enhanced outage management systems (OMS) described in [6]; have expected to play a vital role in optimized asset utilization. The SDN-based management models need to consider factors like load forecasting, uncertainty, and economic viability. In addition, the management problem must also be evaluated from the viewpoint of solutions considering the environment and social benefits.

4.2.2. Power Quality and Stability (PQS)

The ability to maintain power quality is vital, particularly to allow higher hosting intermittent renewable sources capacity, free from power interruptions, voltage sag, and spikes, respectively [8,55,56]. In relation to that, renewable DG technologies may lead to various challenges in system stability, mainly low voltage stability resulting from low support for power sharing, decrease in angular stability due to overall lower system inertia (in photovoltaics), low frequency power oscillations and inability to serve as reserve for the power system. SDN under the SG paradigm has expected to ensure reasonable power quality and power system stability, during transients and high DG penetration [8,57,58].

4.2.3. Advanced Real Time Monitoring (ARTM)

Traditionally, distribution system operators (DSO) have limited capability in terms of remote monitoring and control abilities, which restrict quick fault tracing and isolation. The smart meter with ICT support enables two-way communications among the distribution operating center (utility) and consumers. The amount of data (information) exchange provides real-time monitoring/display of energy consumption data (of the consumer), dynamic tariff negotiations and load control [59]. In addition, real-time condition monitoring and system state estimation capabilities have expected to be provided in medium/low voltage SDNs. Other potential enabling technologies include sensor networks and PMUs.

4.2.4. Reliability (Rel.)

Reliable SG operation and particularly SDN are vital in terms of accommodating high DG, complex power flows and the interconnected structure of distribution mechanisms. The associated SG requires improvement in fault detection, self-healing, adaptive protection, and proactive fault detection and prevention mechanisms, respectively [5,7,30,49]. The primarily SGETs include APA, ADA, ICT, CT and storage technologies aiming at SGCI.

4.2.5. Security and Privacy (S & P)

The expected high penetration of information technology and consequential huge data generation, transmission and storage may result in privacy and (cyber) security violations, on both the utility and consumer levels [60]. The security (passive and active attacks) must be addressed to realize secure MDC (for example, SH) from the consumer and utility's viewpoint (further details are given in Section 5.8). An intrusion detection system (IDS) was proposed in [61] to counter cyber-attacks on information networks under the SG paradigm. Prominent proposed SG-based cyber-security solutions include cryptographic algorithms (and protocols), privacy (billing) protocols, encryption, decryption and authentication keys [62]. Yu et al. in [63] discussed new technologies, mainly big data, cloud computing and internet of things (IoT) in SG.

4.2.6. New Market Models, Opportunities, and Management (NMOM)

The SG enables a new era of "plug-and-play" opportunities from the electricity market (operators' and participants') perspective. Divshali et al. in [64] presented an overview of electrical market management and opportunities from the perspective of supply side management (SSM), DSM and EV. Major enabling technologies include ICT, ADA, DR, DSM, SG components and SMMT. Moreover, competitive environment and decision making are new research dimensions in new market models, particularly for DSM and DR providers in long-term market feasibility studies [65].

4.2.7. Implementation of New Concepts and Paradigms (INC & P)

The high DG penetration backed by SG technologies has led to several new distribution mechanisms. Notable future distribution paradigms include MG and VPP [17]. The structure of the future DN has expected to be more interconnected (topology/structure), aiming at ensuring reliability and voltage stability to end consumers. A detailed account on INC & P or MDC is presented in Section 5 to follow.

4.2.8. Distributed Intelligence Decision Support (DIDS) and Interoperability

The SG realization at the distribution level needs several mandatory features, mainly distributed intelligence, decision support, and interoperability. Strasser et al. [30] have categorized distributed intelligence on the basis of subcomponent level (PE/inverters/power converters), component level (DER and associated services), subsystem level (MG) and system level (DSM), respectively. Decision support in particular, for consumer participation in market operations, is the main feature of SG. Interoperability among various stakeholders, for infrastructure modernization and standard harmonization, is a vital requirement in planning and implementing new grid structures.

4.2.9. Smooth SGCI realization (SGCIR)

The ICT, ADA, control, advanced protection, PE, protection, and measurement technologies are inevitable, mainly for REG/DER integration connected to DN with PE converters and supported by energy storage systems (ESSs) [36–46]. The aforementioned technologies can be employed to address and possibly prevent undesired conditions [8], notably voltage instability (sag and swell) conditions, resulting in grid instabilities (voltage, frequency, and angular stability), faults and loss of DERs synchronization.

4.2.10. "Freedom of Choices" (FoC) for Consumers

This attribute is particularly important from the viewpoint of empowering consumers with their participation in the decision-making process of SG operations through incentive-based DSM and DR programs, respectively [53,64].

5. Modern Distribution Concepts (MDC) and Models

Recent trends and discussion regarding new consumption models from a future perspective have given way to the implementation of non-conventional generation and new distribution concepts in the SG environment. The new power delivery paradigms or MDCs are expected to constitute the building blocks of SGs, capable of accommodating a wide range of high DG (particularly REG) penetration. The current distribution infrastructure (being radial in structure) has limitations for integrating REG, since it may result in challenges like protection issues, dynamic stability issues, complicated power flows and complex control mechanisms. The modifications in the current infrastructure should be made in accordance with the developments in technologies. However, such planning needs to be coordinated in accordance with future needs and SDN concepts. In this section, a few future distribution concepts are briefly discussed, that constitute the backbone of future SDN as a whole in, as shown throughout in Figures 3–7, respectively

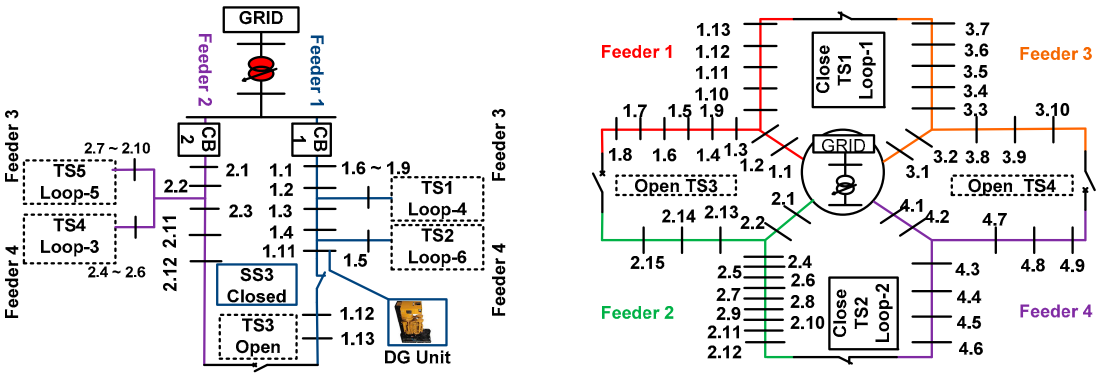
5.1. Active Radial Distribution Network (ARDN)

The radial topology constraint was considered by the researchers in various studies while studying the implementation of SG concepts [26,66]. The ARDN concept is basically RDN reconfiguration, facilitating DG placement and loss minimization. The reconfiguration is realized by changing the open/close status of switches (tie-switches or TS/normally-open and sectionalized–switches or SS/normally-closed) in order to transfer loads among a group of interconnected radial feeders and to retain unified power flow [67] (as shown in Figure 3a). However, reconfiguration problems aimed at DG placement become a complex mixed-integer non-linear optimization problem (MINLP), since they have to deal with a bidirectional flow rather than a unidirectional one [10,12].

5.2. Loop Distribution Network (LDN)

The loop distribution network (LDN) is an upgraded version of the conventional DN under the application of an advanced power distribution system (APDS) [13,68,69]. Such a DN structure/topology is advocated over its radial counterpart, primarily due to better reliability than the radial counterpart, voltage stability, fault traceability and high DG/REG penetration, respectively [13]. However, higher upgrading cost constraints, upgraded protection requirements, advance automation, expected increase of short-circuit currents (SCCs), complex control needs and comparatively high losses usually ocurr in LDNs compared to traditional planning methodologies. Costs and losses are among the major constraints that force DN operations to adopt a radial configuration. Some power utilities still serve their consumers using LDNs from a high-reliability perspective like Singapore Power, Taiwan Power, Hong Kong Electrical Supply Company, etc.

LDNs are also considered as a configuration of the future SDN, since the previous limitations are expected to be met with future SG technologies like advanced distribution automation (ADA), robust control, advanced PE, advanced protection design (including protection device coordination to meet bidirectional power flow) and cost of reliability, respectively [13,70–73]. The normal distribution topologies in LDN include need-based loops and normally closed loops. Both modes are achieved by closing a select number of tie switches (TS) to convert a part (two feeders/laterals) or a selection of TS to convert the whole system into a loop [13,70,71], as shown in Figure 3b. The need-based loops are addressed on an "if and when needed" basis for load balancing between high and low loaded feeders (partial LDN) [72]. The latter mode works under normal operation (complete LDN) and can include other loop options to retain the quality of service [72,73].



(**a**) Active Radial DN (ARDN) (**b**) Loop DN (LDN)

Figure 3. An overview of various MDC (SDN) concepts: (**a**) ARDN and (**b**) LDN, respectively.

5.3. Mesh Distribution Network (MDN)

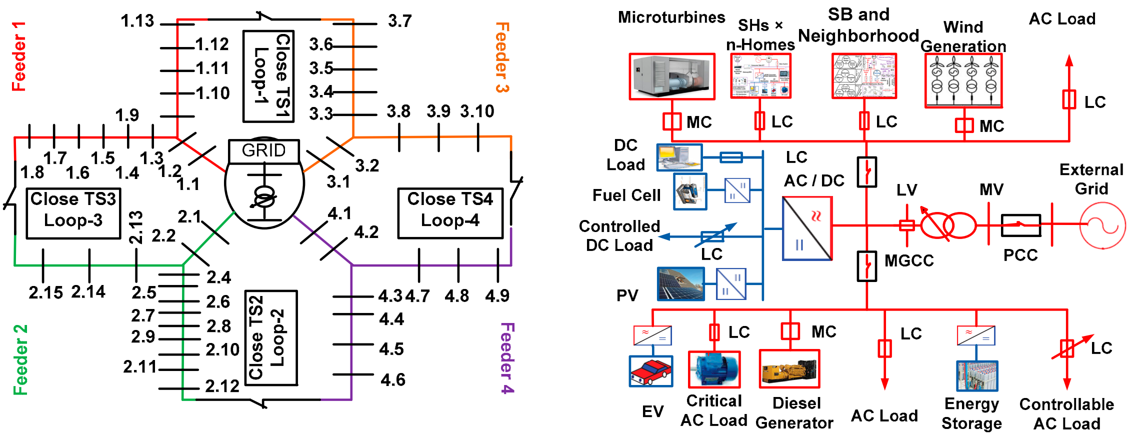
The meshed distribution network (MDN) is also considered as a multi-loop network, as shown in Figure 4a. It is usually subjected to same issues and more or less same requirements as LDN. It has advantages of comparatively higher reliability, DG penetration, better voltage response (for DG critical voltage mode) and comparatively fewer power losses compared to LDN from objective viewpoint [74,75]. However, complex fault traceability makes is more susceptible to faults and early recovery from reliability viewpoint in traditional planning methods [76]. The limitations in MDN, serve as a vital research area, from planning and operation perspective. The normal topologies in MDN include weakly mesh or all mesh [77,78]. The former mode is realized with topologies attain by closing a selective number of TS, whereas the later mode works under normal operation by closing all TS [12,14,26,75].

5.4. Micro Grid (MG)

The MG, according to CERTS, is defined as a cluster of generators, including heat recovery, storage, and loads, and operated as single control entity as shown in Figure 4b. It is considered to be a building block of future distribution mechanisms and a vital component of future SG, including fixed number of resources within restricted geographical area [5,79]. MG is a confined consortium of DG/REG, storage technology (ST, in particular, electrical/energy storage system or simply ESS), PE, concerned loads, information and ICT support with defined electrical boundaries. A detailed account of control levels with concerned MG architecture and applications can be found in [80,81].

The MG as a distribution mechanism is capable of operating in synchronization with utility grid (grid tied) at the point of common coupling (PCC) as well as an independent islanded mode to serve consumers during main grid blackout [82,83]. The modes of operation for DER based MG in SG paradigm includes grid/utility connected mode (centralized power control), the transition to island mode, islanded/isolated mode (decentralized power control) and reconnection to the main grid mode [84].

The intentional islanding is not allowed in TDP, mainly due to voltage stability and synchronization issues; among DG units, substation and interference with protection mechanisms, respectively. Moreover, the normal working topology of MG is usually considered radial or reconfigured radial in order to synchronize concerned operation with current utilities [14]. However, Che et al. [85] have proposed integrated (graph partitioning and integer programming) methodology, aiming at loop topology in MG planning (with controllable DERs); from the reliability and operational efficiency's perspective.



(**a**) Mesh DN (MDN) (**b**) Micro-Grid (MG)

Figure 4. An overview of various MDC (SDN) concepts: (**a**) MDN and (**b**) MG, respectively.

The multi-objective-based independent mode transitions of MG in favor of stakeholders is another research dimension in SG environment and is required to be examined [86]. Several pilot projects, notably CERT MG, has attributed to addressing various potential issues [87]. The possible key enablers offered by SGP include ADA, high performance coordinated protection (especially during islanding and reconnection to the main grid), advance PE for efficient power control in various modes, essential storage technologies and high-speed communication infrastructure for enabled support. The MG primarily depends on hardware innovations (in PE, storage, etc.). Normal trading in MG involves retail distributions. The anticipated objectives include reliability, cost optimization, voltage/frequency stability, improved efficiency and stakeholders' satisfaction [17].

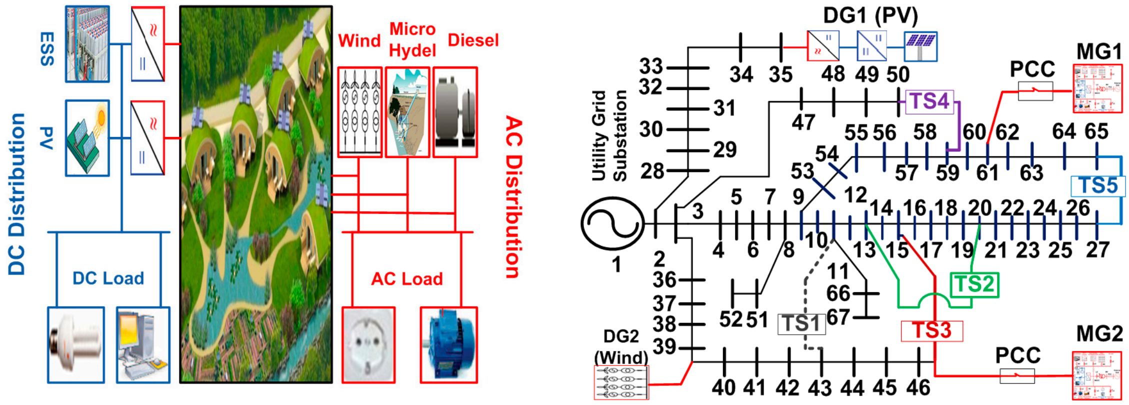
5.5. Isolated (Off-Grid) Distribution System (IDS)

The IDS concept as shown in Figure 5a refers to the applications like stand-alone (SA) off-grid rural electrification. The normal operating mode of IMG is same as that of islanded mode MG. IMGs can be generally classified in terms of stand-alone/(home and community-based) systems and isolated distribution network based MG. Off-grid small-scale technologies are mainly divided into conventional (diesel-based generation), non-conventional (small-scale hydro, solar, the wind, storage) and hybrid (both conventional and non-conventional) [16,88].

The normal distribution topologies in IMG (with distribution network) includes passive radial, active radial and active (loop/mesh), whereas AC/DC distribution systems for SA homes and communities are separate [2]. However, voltage and frequency (V & F) regulation along with reactive power compensation and storage system optimized operation; are important research areas [3]. The concerned key enablers in SGP for IMG are the same as that of a MG under islanded mode.

5.6. Clustered/Multi-Micro Grids (CMG/MMG)

The CMG/MMG concept as shown in Figure 5b refers to a group of *MGs that* offers new ways to cope with control complexity in new distribution scenarios and achieve certain objectives notably power quality, reliability and multiple DG placements. The normal distribution topologies in MMG includes loop (for urban) and radial (for rural) distribution mechanisms. A detail discussion regarding MMG operation can be found in [89]. Still, MMG concept has not addressed in detail. The concept and offers valuable research directions such as MG penetration (multi-DG in each MG) and islanding within test MMG incorporating features such as; ADA, upgraded protection, DSM, market support, communication, AMI, ICT, PE, advanced control, storage technologies (STs), etc.



(**a**) Isolated/Off-grid DS (IDS) (**b**) Multi-MG (MMG)

Figure 5. An overview of various MDC (SDN) concepts: (**a**) IDS and (**b**) MMG, respectively.

5.7. Virtual Power Plants (VPP)

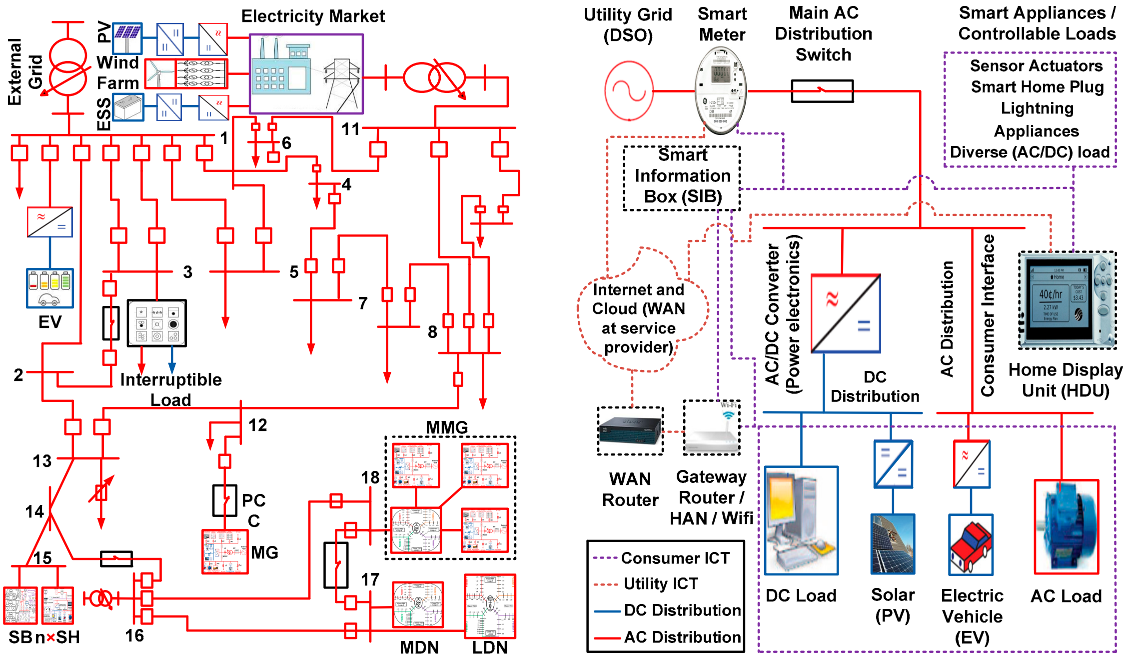
The VPP concept, as shown in Figure 6a, is similar to the cluster MMG concept that is controlled and managed by a central entity and comprises a variety of DG units with responsive loads spreading either over large geographical areas or across a number of clustered MGs [90]. The VPP (connected in grid-tied mode only) can be classified in terms of operational type (technical and commercial VPPs), ownership, capacity and asset optimization planning (with location and the optimal size of the VPP components) [91]. Some notable key enablers for VPP operations in SG package includes ICT, new market concept, energy management system (EMS), Demand side management (DSM), AMI, STs, monitoring, PE, advanced control devices, sensor networks, etc. [92]. Information and smart metering technologies make the backbone of VPP, enabling both retail and wholesale market trading.

5.8. Smart Homes (SH)

SH is a distribution mechanism that unlike previous concepts, resides on the consumer side of the grid. SH normally comprises of sensor networks, home area network (HAN), smart information box (SIB), home display unit (HDU) as consumer interface, in-house AC/DC distribution with smart plugs, advanced PE (converters and inverters for DG, EV and ESS) and diverse (AC/DC) loads. The general architecture of SH based on HAN has presented in Figure 6b. Saponara et al. [93] have reviewed SG to SH connection from the realization perspectives of architecture, security concerns and hardware employment for HAN in SG environment. Authors have also employed the ZigBee protocol in proposed solutions.

HAN architecture in Figure 6b consists of a smart meter (via a transceiver), SIB, appliances, smart plugs and distribution components, respectively. The smart meters collect energy utilization information from HAN through SIB. The gateway (simple WiFi) router is an interface between HAN, distribution utility's local area network (LAN), server provider based wide area network (WAN) and respective interactions among them. Hence, the overall SH-based HAN model enables the consumer to access SIB and remain in contact with server providers. The HDU is the consumer's graphical user interface (GUI), connected with HAN and WAN based service platforms, and enables preference based energy information, aims to generate optimize power consumption plans.

The anticipated benefits offered by SH model under SG environment includes effective feedback on energy aware consumption, DR programs encouraging the customer reduced tariffs in the end-of-month electricity bill, dynamic pricing schemes enabling peak shaving and energy interchanges among consumers owning DG units [18,19,32]. Despite various benefits offered by SH under SG environment, the secure communication among various entities may prone to malicious cyber-attacks and security issues. Komninos et al. [32] have reviewed security issues of SH to SG models from the viewpoints of mandatory objectives, countermeasures to several types of security threats (SH to SG and vice versa) and concern standardization followed across the globe. The security objectives include; ensure confidentiality of data to authorized parties only, maintain integrity (consistency) of data, validating (authenticity) of the actual interactive entities, guarantee (authorization) access privileges to defined parties and confirm irrefutable proofs (non-repudiation) against any entity's claim.



(**a**) Virtual Power Plant (VPP) (**b**) Smart Home (SH)

Figure 6. An overview of various MDC (SDN) concepts: (**a**) VPP and (**b**) SH, respectively.

The security threats have generally classified into passive (illegal system monitoring) and active (deliberate data modification) attacks. The intensity of attack depends on the violation of any aforementioned objective and respective extent of impact from low/L-medium/M-high/H in SH to SG model (operation, entities/stakeholders, components, resources, etc.). The security attacks associated with SH normally aim at; energy consumption report (L-M), energy interchange signal at HAN/WAN (M), interfering with a physical smart meter (L), alterations to remote home monitoring and control (L-H) and impersonation attack for energy consumption data (L-M). Similarly, security attacks linked with SH-SG interaction aims at; DR signals at HAN/WAN (L-M), impersonating outage report (L), false DG isolation-shutdown report (M-H) and forward consumer data to a third party (L-M).

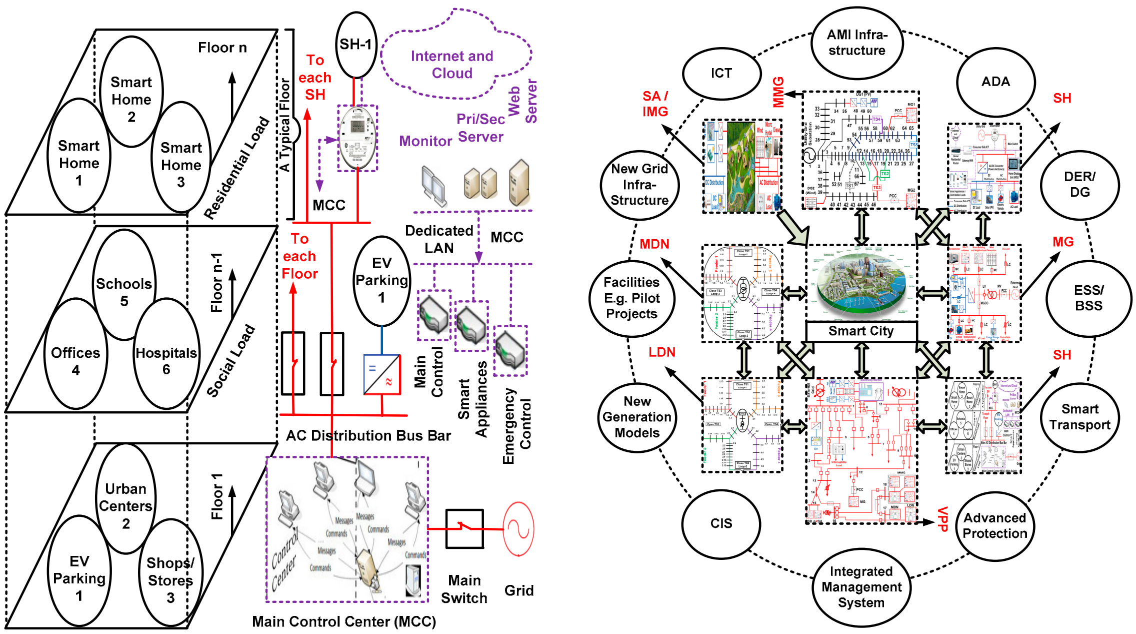
Details on security solutions and relevant approaches to effective countermeasures can be found in [32,93], whereas modern encryption techniques stand out amongst the most prominent. The aim of these solutions is to attain maximum security objectives and ensure the intensity of malicious attacks intensity is the lowest possible level. The future research directions associated with SHs include enabling automation to accommodate smart devices, harmonization of associated standards, security solutions to realize multi-functionalities, adaptable enough to predict and meet users' requirements in an interactive manner, resulting in efficient operation in favor of consumers' bills and time [18,19].

5.9. Smart Buildings (SB)

This concept, like SH as shown in Figure 7a, concerns the efficient operation of SB and the neighborhood. This concept is broadly spread across residential, commercial and industrial loads. The SGP regarding SB includes smart building EMS (SBEMS), AMI, ICT, IoT, EV parking lots, DR, load forecasting techniques, etc. [94]. A few SB objectives include reducing GHG emissions, minimize cost with energy optimization, real-time pricing, EV accommodation and REG/DG integration [95]. Also, SH and SB concepts under SG environment; allows consumers to participate in control, monitoring and shaping their energy demands.

5.10. Smart Cities (SC)

The SC is a futuristic concept as shown in Figure 7b, which besides being a new research area; envisions a distributed, hierarchical and autonomous structure with the incorporation of smart technologies for solutions to address challenges in large scale SDNs. The notable technologies for SC include; DER, ICT, AMI, ADA, DSM, etc. [96]. The main objective of the SC includes improvement in performance and quality of urban electricity delivery. Moreover, other objectives include optimized utilization of electrical infrastructure for demand management, minimization of overall costs, reducing GHG emissions, maximize power quality, benefit in terms of pricing, availability, and reliability [20].



(**a**) Smart Building (SB) (**b**) Smart City

Figure 7. An overview of various MDC (SDN) concepts: (**a**) SB and (**b**) SC, respectively.

6. Policies by Leading Countries, Work Maps & Pilot Projects (PWP) for SDN Concepts Realization

An overview of prominent leading countries, with policies and work maps pertaining to SDN realization, are briefly shown in Table 1. The review of policies and work maps around the globe; is vital for paving way for implementation of new concepts in various SG domains. In addition, pilot projects, test beds, and their findings are helpful in addressing SDN issues of various natures. It is important to mention that any planning process aims towards achieving maximization (↑↑) and minimization (↓↓) of certain objectives, respectively. The prominent countries regarding PWP have indicated with main guidelines, major objectives, and core focus respectively. Please refer to Section 4 (SGTF) and Section 5 (MDC), regarding core focus, respectively.

An overview of notable pilot projects on ground with relevant attributes and future objectives to be addressed are shown in Table 2.

Table 1. Leading countries/unions with SG Policies/SG guidelines.

Countries	Main Guidelines	Major Policy Objectives/Goals		Core Focus
Euro-pean Union (EU)	- European energy policy - 578 Projects - Vision 2020 - [97–99]	- 20:20:20 objectives - GHG emission reduction - REG Penetration - Energy Efficiency - Security and Power Quality - Smart Metering with high benefit to cost ratio	(20%↓↓) (20%↑↑) (20%↑↑) (↑↑) (↑↑)	**4.2.1.** DER controlled by Smart DSM **4.2.6.** New Market Models **4.2.7.** Smart infrastructure progress **4.2.8.** Multiple stakeholder decision- making **4.2.10.** Consumer engagement **[99]** Associated pilot projects
United States (US)	- GRID 2030 - NIST IOP Framework roadmap 1.0 - GridWise Program by U.S. Department of Energy - Microsoft SERA - [5,7,100–102]	- Total electricity costs - Environment Protection - Reliability - Efficiency of Power Supply - Variety of DG Penetration - Security and Power Quality - Optimization (asset utilization)	(↓↓) (↑↑) (↑↑) (↑↑) (↑↑) (↑↑) (↑↑)	**4.1.** Infrastructure growth (SGET) **4.2.** Infrastructure modernization (with SGAF) **4.2.1.** Investment in REGs **4.2.10.** Active consumer participation **Table 2.** Associated pilot projects **5.** Modernization (with MDC)
China	- SG corporation of China (SGCC) - 12th Five Year Plan by Ministry of Science and Technology, China - [8,100,103]	- Environment Protection - SG technologies improvement - REG Penetration - Efficiency of Power Supply - Security and Power Quality	(↑↑) (↑↑) (15%↑↑) (↑↑) (↑↑)	**4.1.** 18 SG Technologies (SGET) **4.1.** Infrastructure growth (SGET) **4.1.1.** Smart Substation (SGCI) **4.2.** Smart Infrastructure (SGAF) **5.** Strategic Planning **5.** Intelligent DN **[103]** Associated pilot projects
Japan	- 2010 Strategic Energy Plan - Roadmap to Intl. Std. SG - SG Policy by Ministry of Economy, Trade and Industry Japan (METI) - [7,104]	- Security and power quality - REG penetration - Environment protection - Efficiency of power supply - Economic growth	(↑↑) (70%↑↑) (↑↑) (↑↑) (↑↑)	**4.1.** Infrastructure development **4.1.1.** REG (PV + Wind) integration **4.1.2.** Smart Metering **4.1.5.** Electrical Vehicles (EV) **4.1.10.** DSM **5.4.** Micro Grids (MG) **5.10.** Eco Model Smart Cities
South Korea	- Vision 2012-2022 for (10% increase in REG penetration) - SG Roadmap 2030 - Government/Private sector consortium for SG fields implementation - [7,105,106]	- Optimization (asset utilization) - REG Penetration - GHG Emission Reduction - Diverse Supply Mix - Security and Power Quality - Economic Growth - Social Objectives - Electricity Consumption	(↑↑) (↑↑) (↓↓) (↑↑) (↑↑) (↑↑) (↑↑) (↓↓)	**4.1.1.** Smart Renewable **4.2.1.** Electricity Saving **4.2.6.** Smart Service/Market **4.2.10.** Smart Consumer **5.** Smart Power Grid **5.10.** Smart Transportation **[106]** Jeju SG Test-Bed Project
Australia	- Vision 2020 - Energy policy frame-work by Council of Australian Government - DER friendly policy - [7,107,108]	- REG Penetration - Time-of-use Tariffs (ToU) - Security and Power Quality - Efficiency of Power Supply - Demand Management	(20%↑↑) (↓↓) (↑↑) (↑↑) (↑↑)	**4.1.** Infrastructure growth (SGET) **4.1.6.** SGT initiatives (SGET) **4.2.** Infrastructure modernization (SGAF) **4.2.1.** Incentives for SG investments **5.10.** Smart City Program
Canada	- National SG Technology and standards task force - SG Canada - [7,109]	- REG Penetration - GHG Emission Reduction - Security and Power Quality	(↑↑) (↓↓) (↑↑)	**4.1.** Research and development of SG technologies (SGET) **4.2.** SG awareness (SGAF) **[109]** Associated SG Pilot Projects

Table 2. Notable SDN-based pilot projects, anticipated objectives, and motives.

MDC (5)/SDN	Pilot Project Name/Organization/Country/Year	SGTF 4.1) SGET	Major Objectives and Focus/Motives 4.2. SGAF	OI
5/5.2. LDN [110]	Belgium east loop active network management (ANM)/Ores and Elia/Belgium/Sep 2010–Jun 2011	**4.1.1.** SGCI (DG) **4.1.3.** ADA	**4.2.1.** Improve load management **4.2.2.** Power quality and stability **4.2.7.** Improve switching operation	(↑↑) (↑↑) (↓↓)
5/5.2. LDN, **5/5.3.** MDN [111]	ESB, Smart green circuits, Networks—SG demonstration project/ESB Networks/Ireland/Jan 2010–Dec 2012	**4.1.1.** SGCI (REG) **4.1.3.** ADA **4.1.8.** CT (MDC)	**4.2.1.** Improve asset utilization **4.2.2.** Improve Power Supply (DGs) **4.2.(2,9).** Reduce system Losses **4.2.(2,9).** Improve system voltage **4.2.4.** Improve Reliability (Loops) **4.2.7.** Improve switching operation	(↑↑) (↑↑) (↓↓) (↑↑) (↑↑) (↓↓)
5/5.4. MG [87,112]	CERTS MG Test BedDemonstration Project/American Electric Power/USA/2006	**4.1.1.** SGCI (DER) **4.1.3.** ADA **4.1.8.** CT (MG) **4.1.10.** DR	**4.2.(2,9).** MG (voltage & frequency) stability at critical operating points **4.2.(6,8).** Flexibility of control modes **4.2.(7,9).** Autonomous islanding/reconnection **4.2.9.** DER/REG Integration in MG	(↑↑) (↑↑) (↑↑) (↑↑)
5/5.4. MG [113,114]	DER-IREC 22@Microgrid/GTD Sistemas de Informacion SA/Spain/Jun 2009–Nov 2011	**4.1.1.** SGCI (DER) **4.1.(3,6).** ADA/EV **4.1.8.** CT (MG)	**4.2.6.** New research platform **4.2.7.** New components integration **4.2.9.** DER and EV integration	(↑↑) (↑↑) (↑↑)
5/5.4. MG [97,115]	Microgrids/ICCS National Technical University of Athens/Greece/Jan 2006–Dec 2009	**4.1.1.** SGCI (DER) **4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.7.** SMMT **4.1.8.** CT **4.1.10.** DR	**4.2.3.** Agent base control and monitoring **4.2.6.** Test centralized and decentralized control in interconnected mode **4.2.7.** Integrated DN **4.2.9.** Development of DER smart module **4.2.10.** Home application (consumer conduct)	(↑↑) (↑↑)
5/5.7. VPP [98]	Fenix/Iberdrola Distribution/Spain/Oct 2005–Oct 2009	**4.1.1.** SGCI (DER) **4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.7.** SMMT **4.1.8.** CT **4.1.9.** APS **4.1.10.** DR/DSM	**4.2.1.** Large scale VPP decentralized management **4.2.3.** Development of communication **4.2.4.** Normal/abnormal operations **4.2.6.** Integration with management and market **4.2.7.** Validation with field deployments **4.2.8.** Development of control solution **4.2.9.** DG and DER penetration (↑↑) **4.2.9.** Two future scenarios for DER penetration	
5/5.7. VPP [97,98]	GAD/Iberdrola Distribucion/Spain/Oct 2005–Oct 2009	**4.1.1.** SGCI (DER) **4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.7.** SMMT **4.1.10.** DR/DSM	**4.2.1.** Optimize energy consumption **4.2.(1,6).** Minimize associated costs **4.2.6.** Focus on DSM Projects **4.2.8.** Maintain quality standards **4.2.10.** Home application (consumer conduct)	(↑↑) (↓↓)

Table 2. *Cont.*

MDC (5)/SDN	Pilot Project Name/Organization/Country/Year	SGTF 4.1) SGET	Major Objectives and Focus/Motives 4.2. SGAF	OI
5/5.7. VPP [116]	Smart Power System—First trial/Energy research Center of the Netherlands (ECN)/Netherlands/2006–2007	**4.1.1.** SGCI (DG) **4.1.2.** ICT **4.1.3.** ADA **4.1.8.** CT	**4.2.1.** Show ability of VPP to reduce local peak load **4.2.1.** Improve efficiency of overall system	(↑↑)
5/5.7. VPP [97]	Virtual Power Plant/RWE DAG DE/Germany/2008–2010	**4.1.1.** SGCI (DG) **4.1.2.** ICT **4.1.3.** ADA **4.1.8.** CT	**4.2.1.** Show economic and technical feasibility of VPP **4.2.1.** Show project completion within time constraint **4.2.6.** Show decentralized power production with DGs like CHP (combine heat and power) plants, wind turbines and biomass.	
5/5.8. SHs [19,117]	Energy@home/Indesit, Enel Distribuzione, Telecom Italia, Electrolux/Italy/Jan 2009–Dec 2011	**4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.7.** SMMT **4.1.10.** DR/DSM	**4.2.1.** Helps consumer with energy cost incentives **4.2.3.** Informs consumer with mobile or display device **4.2.9.** Development of smart appliances **4.2.10.** Adjust demand patterns in favor of consumer **4.2.10.** Home application for consumer behavior	
5/5.9. SBs [19,97]	BeyWatch/Investigaciony Desarrollo SA/Spain, UK, Slovinia, Italy, Greece/Dec 2008–May 2011	**4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.7.** SMMT **4.1.10.** DR/DSM	**4.2.1.** Develop user-centric and energy aware solution **4.2.3.** To monitor, control and balance the demand **4.2.6.** Consumer aware energy consumption **4.2.7.** Enabling intelligent control of devices	
5/5.10. SCs [97,98]	Model City Manheim/MW Energie (DE)/Germany/Nov 2008–Oct 2012	**4.1.1.** SGCI (DG) **4.1.2.** ICT **4.1.3.** ADA **4.1.8.** CT	**4.2.(1,9).** Large REG penetration and decentralized electricity sources in unban DN (↑↑) **4.2.7.** Large scale project deployment in two cities **4.2.8.** Show, translate & applied to other regions	
5/5.10. SCs [106]	Jeju SG Test-Bed Project/SK and KT telecom, KEPCO, LG electronics, etc. (179 Companies)/Aug2009	**4.1.1.** SGCI (REG) **4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.4.** EST **4.1.5.** PE **4.1.6.** EV **4.1.7.** SMMT **4.1.8.** CT **4.1.9.** APS (IED) **4.1.10.** DR/DSM	**4.2.1.** Optimization of asset utilization **4.2.1.** GHG Emission Reduction **4.2.1.** Diverse Supply Mix **4.2.1.** Economic Growth **4.2.1.** Social Objectives **4.2.1.** Electricity Consumption **4.2.(1,9).** REG Penetration **4.2.(1,10).** Electricity saving **4.2.(2,5).** Security and Power Quality **4.2.(2,9).** Superior protection **4.2.3.** Enhanced monitoring **4.2.(4,8).** Improved control **4.2.6.** Service, marking **4.2.7.** Smart transportation **4.2.10.** Smart consumer behavior	(↑↑) (↓↓) (↑↑) (↑↑) (↑↑) (↑↑) (↓↓) (↑↑) (↑↑) (↑↑) (↑↑) (↑↑) (↑↑) (↑↑) (↑↑)
5/5.10. SCs [118,119]	Yokohama Smart City Project	**4.1.1.** SGCI (REG) **4.1.2.** ICT (AMI) **4.1.3.** ADA **4.1.4.** EST **4.1.6.** EV	**4.2.(1,6,9).** Complete energy (REG Integration) solutions **4.2.1.** GHG emission reduction **4.2.2.** Power system stability with REGs **4.2.7.** Smart Transport, SH(5.8), SB (5.9)	(↓↓) (↑↑) (↓↓)
5/5.10. SCs [120]	Colorado Smart City Project, Boulder, Co USA	**4.1.1.** SG Tools **4.1.2.** ICT (AMI) **4.1.10.** DR/DSM	**4.2.1.** Exploitation of SG tools in real world problem **4.2,(6,7).** Implementation of various DSM Programs **4.2.10.** Consumer Participation	

7. Real World Optimization (RWO) Planning Problems (Multi-Objective Planning)

SG technologies and associated enabling functionalities result in the realization of new MDC concepts. The lack of current and need for new standards, have motivated researchers to propose various MDC models, mainly from the perspectives of economic viability, scale of implementation (size) and consumer contentment (reliability of service, power quality, and environment impact). Every planning process, regardless of classification (in Section 2.3), is proposed around particular objectives and system constraints (technical, social, geographical, environmental and regulatory). Moreover, diverse stakeholder participation, an uncertainty factor (outside and within the control of decision maker) and decision-making (DM) for solutions among conflicting objectives (e.g., cost effectiveness vs. reliability); describe real world MDC planning problems as a MOP problem. It is also a well-established fact that real world planning problems are mostly multi-objective in nature. Hence, in this section, the various MDC concepts have reviewed on the basis of MOP problems.

7.1. Need for an Aggregated Planning Model for SDN

Previously in Section 2.3, three broader classifications of SDN planning were proposed, namely: long-term (with off-line variant), scheduling and operational planning, respectively. Conventionally, these problems have been individually addressed in the literature. The multi-objective-based RWO problems aiming at SDN planning has to be addressed in a deeper, broader and integrated/aggregated manner, as advocated in [15]. The aggregated planning model (APM)-based primitive approach has proposed in this subsection, aiming at the implementation of RWO based SDN aggregated planning, as shown in Figure 8.

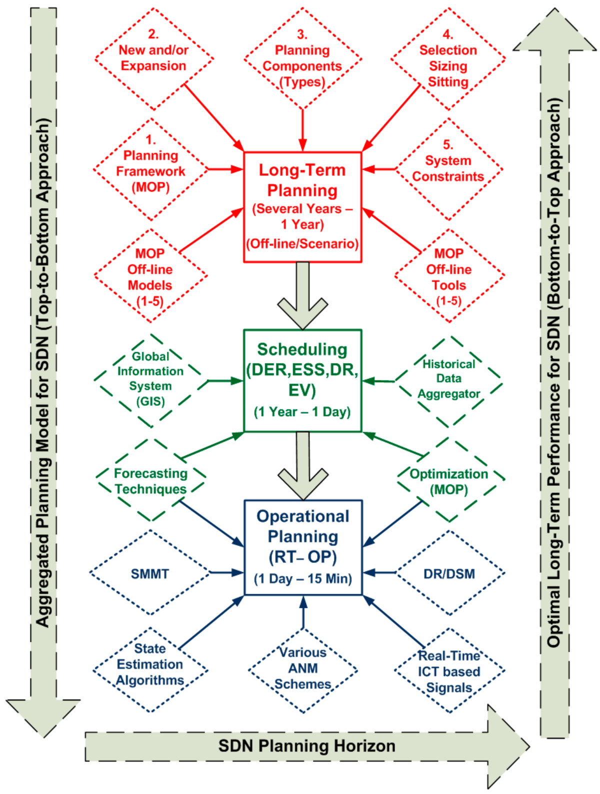


Figure 8. An aggregated planning model for MDC concepts in SDN (adapted from [15,17,54]).

The approach starts from top-to-bottom manner and deals with new long-term SDN planning and implementation of new infrastructure across the horizon (several years–1 year). Later, scheduling of available resources on preferential basis is followed over a scheduled time horizon (year/seasons–1 day). Finally, the operational planning (real-time and off-line) is followed on the short-term operational horizon (15 min–1 day).

The first step in a bottom-to-top approach is realizing real-time operational planning (RT-OP). The distribution system operator (DSO) backed by state estimation algorithms, ICT (AMI and SMMT) infrastructure (as discussed in Section 5.8), is capable of monitoring SDN systems in real time (RT), during a short-term operational horizon. The DSO takes necessary actions by employing ANM techniques, DR (on the very short term) and DSM (on the long term and large scale) to obtain certain objectives and satisfy the system constraints, aiming at the optimal operation of SDN.

In RT-OP, MDC on the utility (discussed later in Section 8.2) or consumer side (SH and SB), can also plan for supplying ancillary services, prominently; voltage control, active/reactive power support, DER control, power factor (adaptive) control, network reconfiguration management, optimal spinning reserve provision (with DR and ESS) and peak load reduction (with DSM).

Later, scheduling of available resources (DER, ESS, DR and EV) within each MDC on utility or consumer side, is supported by multi-agent system (MAS) that integrates; forecasting techniques (load, price, weather dependent DER), global information system (GIS), historical data aggregator (market, utility, consumer consumption, DER, etc.) and MOP based optimization methods. This stage of bottom-to-top approach needs to ensure; reliability, reactive power support, control, automation, stability and emission reduction, across scheduled horizon.

Finally, long-term multistage expansion planning is followed, based on the futuristic smart components reinforcement, demand side (load) and supply side (DER) requirements, respectively. The main aim of aggregated planning approach is to ensure, overall short-to-long-term technical and economic success of MDC, across all three planning horizons in SDN planning.

7.2. Current Status of SDN from the Perspective of Multiple-Objective Planning MOP

The MOP formulations are classified into two major types: The a priori class (MO + W) and a posterori class (MO-P). In the a priori class, the multiple objectives transform into a single objective function. Later, individual weights are assigned to each objective by the decision maker (user-defined) preferences before execution of the optimization algorithm. In other words, in the MO + W formulation, decision making precedes optimization to sort out trade-off (qualitative) solution among a set of conflicting objectives. In the a posterori class (MO-P), optimization is preferred over decision making to achieve realistic (quantitative) solutions among a set of potential solutions (Pareto frontier). The decision maker then chooses a solution from the resulting Pareto frontier, on the basis of respective preferences, also known as a posteriori articulation of preferences.

On the basis of a literature review of MOP, a detailed study is presented in Table 3, from the viewpoint of the aforementioned MDC models and real world planning. The works in literature have arranged according to reference, MDC model under SDN paradigm, decision variables, objectives considered, major system constraints, test SDN, planning type (horizon-based), MOP formulations, optimization methods and load characteristics (load level and profile), respectively. Furthermore, from the readers' comfort viewpoint, the information about MOP under MDC models have been presented in a self-explanatory manner. For MDC (SDN concepts), please refer to Section 5 of this paper. The decision variables have been indicated by type, number, size, and location in MDC concept. The objective function indicates aimed multiple objectives in each reviewed work. The test SDN indicates the work bench, which is used to validate respective idea under each MDC concept. Later, planning types as shown in Section 2.3 have indicated. The major constraints that a problem must abide, are also shown in detail for each reviewed work. Also, the reviewed works are shown in the context of respective SGTF (in Section 4.1) and SGAF (in Section 4.2) respectively. The MO optimization (MOO) techniques are shown with the respective classifications (in Section 7.2) and associated decision making (DM) techniques, respectively. Finally, year of publication is highlighted with associated load model and load profile (as load level or LL) in the respective MOO problem, as shown in Table 3.

Table 3. MOP from the perspectives of various MDC Models.

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[121]	**5/5.1.** ARDN	Multiple (DG + DR + SR) Location + Type)	Minimize (↓↓): 1. Total cost of operation 2. Greenhouse gases (GHG) emissions	1. Voltage & Power-flow limit 2. Feeder (current) capacity 3. DG capacity limit 4. Standard component size 5. DRP & SR constraints	69 bus ARDN	- **2.3.2.** Scheduling (24 h)/ - **4.1.10.** DR (Demand response) - DR provider (DRP) - Spinning reserve (SR)	- (MO-P)/ - Augmented ε-Constraint Method (AεCM)/ - DICOPT solver in GAMS for MINLP/	- Mar 2014/ - Probabilistic load (PLd)/ - Probabilistic load level (PLL)/
[122]	**5/5.1.** ARDN	Multiple DG (Size + Location + Type)	Minimize (↓↓): 1. Energy not supplied (ENS) with conditional value at risk (CVaR) 2. Expected global cost (Cg)	1. Voltage & Power-flow limit 2. Feeder (current) capacity 3. Radial DN constraint4. Cost constraints 4. Budget constraints 5. Number of SG components	IEEE 13 bus ARDN	- **2.3.1a.** Long-term (10 years) planning/ - **4.1.1.** SGCI (REG) - **4.1.4.** Storage (ESS) - **4.1.6.** EV - **4.2.1.** Uncertainty	- (MO-P)/(Fast NSGA-II) - Fast non-sorting genetic algorithm II/ - Monte-Carlo simulations (MCS) for OPF (optimum power flow) framework	- Jun 2014/ - Probabilistic load (PLd)/ - Probabilistic load level (PLL)/
[123]	**5/5.1.** ARDN	Multiple Feeders (Size + Loc.), Automatic Reclosers (RAs) (Loc.)	Minimize (↓↓): 1. Overall costs (fix + variable) 2. CLLI (Reliability index) 3. Overall power loss 4. Voltage deviation	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Radial DN constraint 5. Standard component size	54 Bus - - - - - - - - - - 100 Bus ARDNs	- **2.3.1b.** Operational (Off-line) planning/ - **4.1.3.** ADA	- (MO + W)/ - MO seeker optimization algorithm (MOSOA)/ - Min-Max weighted aggregation	- Jun 2014/ - Constant load (CLd)/ - Single load levels (SLL)/
[124]	**5/5.1.** ARDN	Multiple DG (Size + Location + Type)	Single OF with weights: 1. Voltage deviations 2. Feeder current flow 3. Network power losses 4. External cost of electricity 5. Distributed storage system (DSS) energy losses	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Radial DN constraint 5. DG capacity limit 6. Cost Constraints	IEEE 34 bus ARDN	- **2.3.1a.** Long-term (5 year) dynamic planning - **2.3.2.** Scheduling (24 h)/ - **4.1.1.** SGCI (DG), - **4.1.4.** Distributed storage system (DSS).	- (MO + W)/ - Mixed integer second order cone programming (MISOCP)/ - GUROBI Solver - Analytical Hierarchical process (AHP)/	- Sep 2014/ - Controllable load (CL)/ - Time varying load level (TVLL)/ - Weights (1–5): [0.0562; 0.0396; 0.2535; 0.6421; 0.0086]/
[125]	**5/5.1.** ARDN	Multiple DG (Size + Location)	Single OF: 1. Payback in years 2. Active power losses (↓↓) 3. Voltage stability level (↑↑)	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Radial DN constraint 5. DG capacity limit 6. Standard component size 7. REG penetration constraint	28 Bus rural ARDN	- **2.3.1a.** Long-term (1 year) planning/ - **4.1.1.** SGCI (REG), - **4.1.10.** DSM	- (MO + W)/ - Multi-objective particle swarm optimization (MOPSO)/ - Newton Raphson LF - Fuzzy decision making (FDM)/	- Jan 2015/ - Probabilistic load (PLd)/ - Probabilistic load level (PLL)/

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[126]	**5/5.1.** ARDN	Multiple Feeders (Size + Location), (RAs) (Loc.), DSTATCOM (Loc.)	Minimize (↓↓): 1. Overall (fix + variable) costs 2. CLLI (Reliability index)	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Radial DN constraint 5. Cost constraints 6. Planning Periods	54 Bus ARDN	- **2.3.1b.** Operational (Off-line) planning/ - **4.1.3.** ADA - **4.1.5.** Power electronics (PE), FACTS devices	- (MO-P)/ - MOSOA/ - Min-Max weighted aggregation	- Dec 2015/ - Constant load (CLd)/ - Single load levels (SLL)/
[127]	**5/5.1.** ARDN	M/(DG) + Reconfiguration (DSR) + DR (Number + Loc. + size + Type)	Minimize (↓↓): 1. Net present value (NPV) of total investment and operation cost 2. Expected energy not supplied EENS	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Radial DN constraint 5. DG capacity limit 6. DR constraints 7. Private investor limitation	IEEE 33 Bus ARDN	- **2.3.1a.** Long-term (4 year) planning - **2.3.1b.** Off-line - **4.1.3.** Distributed system reconfiguration (DSR) - **4.1.1.** SGCI (DG), - **4.1.10.** DR	- (MO-P)/ - MOPSO + Sensitivity analysis/	- 2016 - Time varying load (VLd)/ - Multi-load level (MLL)/
[128]	**5/5.2.** LDN/ **5/5.4.** MG	Multiple DG + MG (Type + Size + Location)	Minimize (↓↓): 1. Real power loss 2. Load voltage deviation 3. Annualized investment cost	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. DG capacity (P & Q) limit	33-Bus-ARDN - - - - - - - - - - 69-Bus-LDN	- **2.3.1a.** Long-term (10–20 years) planning/ - **4.1.1.** SGCI (DG), - **5/5.2.** LDN - **5/5.4.** MG	- (MO-P)/ - Loss Sensitivity to identify MG area in DN - NSGA-II for DG (Number, location & size) in MG/ - FDM (for final trade-off)	- Jan 2011 (2012)/ - Time varying load (TVLd)/ - Multiple load levels (MLL)/
[129]	**5/5.2.** LDN/ **5/5.3.** MDN	Multiple DG (Size + Location)	Minimize (↓↓): 1. Average voltage deviations 2. Total power (line) lossesMaximize (↑↑): 3. Total DG installed capacity	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Power-factor limit 5. V-deviation by DG	Sample DNW with 3 Feeders	- **2.3.1b.** Operational (Off-line) planning/ - **4.1.8.** DER Control	- (MO + W)/ - Genetic algorithm (GA)/ - Newton Raphson LF - DM: MCDA based weighted method	- Nov 2012/ - Constant load (CLd)/ - Single load levels (SLL)/
[85]	**5/5.2.** LDN/ **5/5.4.** MG	M/(DG + ESS) (Num. + Loc. + Size + Type)	1. Power balancing and storage facilities sharing 2. Minimizing the interactions among adjacent loops	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity	37 bus Test LDN	- **2.3.1b.** Operational (Off-line) planning/ - **4.1.1.** SGCI (DG), - **4.1.4.** ESS	- (MO + W)/ - Graph-partitioning and integer programming (IP) integrated methodology	- Jan 2016/ - Constant load (CLd)/ - Single load levels (SLL)
[130]	**5/5.3.** MDN	Multiple DG, Substations, Feeders (Type + Size + Loc.) and sectionalizing switches (Loc.)	- **Stage I:** 1. {Overall complete system cost (OCS) + Total operating cost (TOC)} (↓↓) 2. contingency load loss index (CLLI) (↓↓) - **Stage II:** 1. {(OCS + TOC); CLLI} (↓↓); 2. P-loss (↓↓); 3. DG penetration (DGPL) (↑↑)	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Standard component size	21 bus - - - - - - - - - - 100 bus MDN	- **2.3.1a.** Long-term (1 year) static planning/ - **4.1.1.** SGCI (DG), - **4.1.3.** ADA - **5/5.3.** MDN	- (MO-P)/ - MOPSO/ - Penalty factor method	- Aug 2010/ - Constant load (CLd)/ - Single load levels (SLL)/

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[131]	**5/5.4.** MG	M/(DG + ESS) (Loc. + Size + Type)	Minimize (↓↓): 1. Total 24 h energy losses 2. Total 24 h production cost 3. Total 24 h GHG emissions	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Radial DN constraint	LV MG (CESI) Model, Milan, Italy	- **2.3.2.** Scheduling (24 h)/ - **4.1.4.** ESS - **4.2.1.** Resource scheduling - **5/5.4.** MG;	- (MO-P)/ - NSGA-II/ - Constraint domination concept with GA	- April 2011/ - Controllable load (CL)/ - Time varying load level (TVLL)/
[132]	**5/5.4.** MG	Multiple DG + Storage (Type + Size + Loc.)	Minimize (↓↓): 1. Operation cost 2. Pollutants/emissions.	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Battery (charge/discharge rates) limit	LV Three feeder (14 bus) MG Model	- **2.3.2.** Scheduling (24 h)/ - **4.1/8.** Control, - **4.2.1.** Resource scheduling (PV, ESS, MT & CHP) - **4.2.1.** Uncertainties - **4.2.3.** Monitoring - **4.2.6.** New Market,	- (MO-P)/ - Hybrid Adaptive modified PSO (AMPSO) + Chaotic local search (CLS)/Weight factor/ - MT: Micro turbine - CHP: Combine H & P/	- Oct 2011/ - Time varying load/ - Multiple load level/
[133]	**5/5.4.** MG	Multiple DG + Storage (Type + Size + Loc.)	Minimize (↓↓): 1. Total operation cost (Bidding cost of DG and ESS units) 2. Total operation emissions.	1. SR requirements (SRR) 2. Power-flow limit (grid) 3. Feeder (current) capacity 4. DG capacity (P & Q) limit 5. Battery Limit	Typical (14 bus) LV MG Models	- **2.3.2.** Scheduling (24 h)/ - **4.2.1.** Resource Scheduling - **4.2.6.** New Market	- MO-P/ - ITLBO with SAPMS - FCM for DM	- Jul 2012/ - Probabilistic load (PLd)/ - Probabilistic load level (PLL)/
[134]	**5/5.4.** MG	Multiple DG + Storage (Type + Size + Loc.)	Minimize (↓↓): 1. Operation cost 2. Pollutants/emissions.	1. SR requirements (SRR) 2. Power-flow limit (grid) 3. Feeder (current) capacity 4. DG capacity (P & Q) limit 5. Electrical/thermal power output limit	1-LV MG Model - - - - - - - - - - 2-MG Model	- **2.3.2.** Scheduling (24 h)/ - **4.1.4.** ESS - **4.2/1)** Resource Scheduling	- MO-P/ - Modified Bacterial Foraging Optimization (MBFO) Tradeoff method/ - DM: Min-max approach	- Feb 2013 - Time varying load/ - Multiple load level/
[86]	**5/5.4.** MG	Multiple DG + ESS (Loc. + Type)	Minimize (↓↓): 1. Operation cost 2. Pollutants/emissions.	1. DG capacity limit 2. Number of ESS and DG 3. Battery limit (charge/discharge rate)	LV MG Model	- **2.3.2.** Scheduling (24 h) - **2.3.3.** Real-time (online) operation planning/ - **4.2.(1,9).** ESS Management	- MO + W/ - Neural network ensemble (NNE)/ - Fuzzy decision making	- April 2013 - Time varying load/ - Multiple load level/
[135]	**5/5.4.** MG	Multiple DG + ESS (Loc. + Type)	Minimize (↓↓): 1. Total operation costs 2. GHG Emissions from DG	1. Power balance 2. DR constraints 3. Power limits 4. Thermal power balance	Typical 24 bus MG	- **2.3.2.** Scheduling (24 h) - **4.1.4.** ESS; 4.1.10. DR, - **4.1.8.** Control (MIP) MGCC - **4.2.1.** Resource Scheduling - **4.2.9.** Demand side sources	- (MO-P)/ - Lexicographic optimization + weighted ε-constraint technique - Fuzzy DM (FDM)	- May 2013/ - Constant load/ - Multiple load level/ - CPLEX solver (GAMS)

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[136]	**5/5.4.** MG	Multiple DG + EV (Type + Size + Loc.)	Minimize objective function: 1. Power loss 2. Voltage deviation along MG buses 3. Line current security margin	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Transformer overloading limit	MV/LV 30 bus MG Model	- **2.3.1b.** Operational (Off-line) planning/ - **4.1.6.** EV - **4.2.(1,6,9)** Ancillary services by MG	- MO + W/ - Exponential weighted method & Compromise programming method/ - Weights by rank order centroid (ROC) method/	- Nov 2013 (2014)/ - Constant power/ - Single load level/ - Weights (1–3): w1 = 0.611, w2 = 0.278, w3 = 0.111.
[137]	**5/5.4.** MG	Multiple DG + ESS (Type + Size + Loc.)	Minimize (↓↓): 1. Investment cost 2. Expected ENS (EENS) 3. Line losses	1. Voltage 2. Power-flow limit 3. Load-flow constraint 4. DG capacity limit 5. Thermal limits 6. P/Q compensation limit	IEEE 33 bus DN - - - - - - - - - - Rural DN	- **2.3.1b.** Operational (Off -line) planning/ - **4.1.1.** PV-Wind-ESS - **4.1.8.** SG control - 6×MG modes (operation)	- (MO-P)/(INSGA-II) - Improved non-sorting genetic algorithm II + - HAC algorithm + - Fuzzy set theory/	- Mar 2014 (2015)/ - Controllable load/ - Controllable load level/
[138]	**5/5.4.** MG	Multiple Protection devices (Type + Loc.)	Minimize (↓↓): 1. SAIFI 2. SAIDI 3. Total cost (Investment + Interruption)	1. Radial DN constraint 2. Reclosers and switches on same section 3. Fuses on laterals	51 Node radial MG	- **2.3.1b.** Operational (off-line) planning/ - **4.1.9.** Advance protection	- (MO-P)/(IB-MOPSO) - Improved binary multi-objectives-PSO - Max-min approach	- Aug 2014 (2015)/ - PLd/ - PLL/
[139]	**5/5.4.** MG	Multiple DG + ST (Type)	Minimize (↓↓): 1. Total operation costsMaximize (↑↑): 2. Availability of resources	1. Power-flow constraint 2. DG Capacity limit 3. Area allocated to PV	DC MG Design Model	- **2.3.1b.** Scenario based off-line planning/ - **4.1.5.** Power electronics (PE) - **4.2.7.** DC supply based MG	- (MO-P)/ - NSGA-II/ - Monte-Carlo (MCS)/ - DM with weights/	- Sep 2014 (2015)/ - Controllable load (CL)/ - Controllable load level (CLL)/
[140]	**5/5.4.** MG	Multiple DG + ESS (Type + Size + Loc.)	OF with weights: 1. Daily fixed cost of investment (DFCI) 2. Load loss probability (LLP) 3. Excess energy rate (EER)	1. DG Capacity limit 2. Number of DG and ESS 3. Battery Limit (charge/dis-charge rate)	LV MG Model	- **2.3.1b.** Operational off-line planning **2.3.b.** Scheduling/ - **4.1.1.** SGCI (REG), - **4.1.4.** ESS - **4.2.1.** Uncertainty	- MO + W/(Upper: 1, Lower: 2) - 1. Hybrid weighted method, - 2. Penalty function method/ - Improved adaptive GA/ - Value function (certainty) - Utility function (uncertainty)	- Sep 2015 (2016)/ - Time varying Load/ - Multiple load Level/ - Weight (1–3): [0.6333, 0.2605, 0.1062] - Hybrid bi-level model
[141]	**5/5.5.** IMG, SA/IDS	Multiple DG + ESS (Type+ Size)	Objective function: 1. Leveled energy cost (LEC) 2. Unmet load fraction (ULF) 3. Wasted renewable energy 4. Fuel consumption	1. Cost constraints 2. Number of DG and ESS 3. Battery Limit (charge/dis-charge rate)	Test SA MG System	- **2.3.1b.** Scenario based off-line planning (design)/ - **4.1.1.** SGCI (REG); - **4.1.4.** ESS	- MO + W/ - Fuzzy TOPSIS technique + - Fuzzy set theory/ - MCDM tool (level diagram)	- Mar 2013/ - Non-Controllable and Controllable Load/

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[142]	**5/5.5.** IMG, SA/IDS	Multiple DG + ESS (Type+ Size)	Minimize objective function: 1. Levelized energy cost (LEC) 2. Life cycle cost (LCC) 3. GHG emissions 4. LEC + LCC5. LEC + GHG emissions	1. Unmet load 2. Battery constraints 3. Meteorological data 4. Electrical. load demand (ELD) 5. Types of load constraint	Test SA MG designed system	- **2.3.1a.** Long-term planning in years/ - **4.1.4.** Power electronics (PE) - **4.2.6.** Market	- MO-P/ - Steady ε-state evolutionary algorithm (EA)/	- Apr. 2013/ - Time varying load/ - Multiple load level/
[143]	**5/5.5.** IDS	Multiple DG + ESS (Type + Size + Loc.)	Minimize objective function: 1. Total generation cost 2. Energy losses 3. GHG emissions	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. P/Q power compensation 5. Limits of power exchanged by each EES system	IDS MV 207 Bus DN	- **2.3.1b.** Scenario-based off-line planning (Design)/ - **4.1.4.** ESS - **4.2/1,6** Management scenarios	- MO-P/ - NSGA-II/ - ST-VP (voltage profile strategy) as best scenario	- May. 2013/ - Time-varying load/ - Multiple load level/
[144]	**5/5.5.** IMG, SA/IDS	Multiple DG + ESS (Type + Size)	Maximize OF: 1. Life cycle cost (LCC) 2. REG penetration	1. DG capacity limit 2. Planning periods 3. Adequacy in each mode 4. High REG penetration 5. REG penetration limit 6. Energy regulation capability	Actual SA MG Dong-fushan Island	- **2.3.1a.** Long-term planning in (20 years)/ - **4.1.1.** SGCI (REG) - **4.1.4.** ESS; - **4.1.5.** PE - **4.2.6.** IMG design	- MO + W/ - GA/ - Verified based on actual data	- Oct 2013 (2014)/ - Constant load/ - Single load level/
[145]	**5/5.5.** IMG, SA/IDS	Multiple DG + ESS (Type + Size)	Minimize objective function: 1. Net present cost (NPC) 2. GHG emissions	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. DG capacity limit 5. Battery constraints	Test SA MG system	- **2.3.1a.** Long-term planning in (20 years)/ - **4.1.1.** SGCI (REG) - **4.1.4.** ESS - **4.1.5.** PE	- MO-P/ - Stochastic CCP - NSGA-II	- Nov 2013 (2014)/ - Probabilistic load (PLd)/ - Probabilistic load level (PLL)/
[146]	**5/5.5.** IDS	Multiple DG + ESS (Type + Size)	1. Net present value (↓↓) 2. HDI (↑↑) 3. Job creation (JC) (↑↑)	1. Cost constraints 2. Number of DG and ESS 3. DG/ESS code	Test SA IDS system	- **2.3.1a.** Long- (5 years) - **4.1.1.** SGCI (REG) - **4.1.(4,5).** ESS; PE	- MO-P/ - Primary: MOEA - Secondary: GA/	- Mar. 2016/ - Time varying load/ - Multiple load level
[147]	**5/5.5.** IMG/IDS	Multiple DG + ESS (Number +Type + Size + Location)	1. Minimize generating cost paid by Distribution Company (DISCO) 2. Maximizing of internal rate of return (IRR)	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Battery constraints 5. Diesel generator constraint	Test SA IMG SAMG Model	- **2.3.1a.** Long-term planning (10 years) - **2.3.1b.** Offline/ - **2.3.2.** Scheduling - **4.1.1.** REG; - **4.1.4.** ESS, - **4.1.8.** Power control	- MO-P/ - NSGA-II	- Sep. 2016/ - Time-varying load/ - Multiple load level

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[148]	**5/5.6.** MMG	Multiple DG + MG + Nodes (Location)	1. MMG (installation and operation) cost (↓↓) 2. Investment deferral (years) 3. Active power loss (↓↓) 4. Emission (GHG) (↓↓) 5. Non distributed energy (NDE) due to MMG	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. DG capacity (P & Q) limit	15 kV urban DN with 35 MGs	- **2.3.1a.** Long-term planning/ - **4.1.2.** Communication - **4.1.8.** Control, - **4.2.1.** DMS (demand side management),	- (MO + W)/ - Multi-criteria decision aid based tradeoff analysis/ - DM: Weight method	- May 2012/ - Time Varying load/ - Active (controllable) load level/
[149]	**5/5.6.** MMG	Multiple DG + ESS (Loc. + Type)	Overall performance index: 1. Electricity Price 2. Environment effects (GHG) 3. Service Quality	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. DG capacity constraint 5. Power capacity constraint of MG	MG Model and MMG Model	- **2.3.2.** Scheduling - **2.3.3.** RT-OP/ - **4.1.7.** Measurement, - **4.1.8.** Control (MAS), - **4.1.10.** DSM/DR, - **4.2.1.** Energy management, - **4.2(1,3).** Forecasting; - **4.2.6.** Market,	- (MO + W)/ - Performance index based weighting method (WSM)	- Nov 2013 (2014) - Time-varying load/ - Multiple load level/
[150]	**5/5.6.** MMG	Multiple DG + ESS + Reactive sources (RS) + Tie and sectionalizing switches (SWs) (Type + Size + Loc.)	Single objective function: 1. Minimize total cost of control & communication.(a) New control centers (V & f controller units)(b) Network switches & routers(c) Communication media 2. Minimize real & reactive power balance and load with in each zones	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Reliability limits 5. P/Q power compensation limit 6. Frequency limit	IEEE PG & E 69-bus DNW - - - - - - - - - - IEEE 123 Bus DNW	- **2.3.1a.** Long-term planning/ - **4.1.2.** Communication - **4.1.3.** ADA - **4.1.4.** ESS - **4.1.8.** Control - **4.1.9.** Protection - **4.2.2.** Power quality	- MO + W/ - Main Algorithm:Tabu search (TS) optimization/ - Sub Algorithm:Graph Theory/ - Load/Power Flow:Newton–Raphson-based probabilistic LF/	- Feb. 2015/ - Time varying load/ - Multiple load level/ - Weights: w1 or K1 = 0.7 w2 or K2 = 0.3
[151]	**5/5.6.** MMG	Multiple leaders + Multiple Consumers	1. Leaders' profit (↑↑) 2. Carbon emissions (↓↓) 3. Consumer bills (↓↓)	1. Demand constraints 2. Cost constraints	Test MMG Market Model	- **2.3.3.** Real-time operational planning/ - **4.2.6.** New (open) market model in MMG	- MO-P/ - Stackelberg game + - BL-HMOEA	- May. 2015/ - Time-varying load/ - Multiple load level/

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[152]	**5/5.2.** LDN/**5/5.6.** MMG	Multiple DG + ESS + MG (Type + Size + Loc.)	**LDN: (Upper Level) OF1:** 1. Power loss (↓↓) 2. Node voltage offset (↓↓) **MMG: (Lower Level)** Minimize objective function 2: 1. Fuel cost 2. Operation & maintenance cost 3. Depreciation cost 4. Environment cost 5. Purchasing/selling cost 6. Wind & solar curtailment cost	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. P/Q power compensation 5. Available dispatch capacity limitation of PCC 6. MG & other output power 7. DG capacity limit 8. Ramp constraint of micro turbine (MT) 9. ESS Constraints	Upper: IEEE 33 Bus LDN/LV MG Model Lower: IEEE 123 Bus ARDN/LV MG Model	- **2.3.1b.** Operational Off-line planning/ - **4.2.6.** Optimal operation of MMG concept - **5/5.1.** ARDN - **5/5.2.** LDN - **5/5.4.** MG - **5/5.6.** MMG	- MO-P/ - Upper-Level Optimization:Self-Adaptive Genetic Algorithm (SAGA) - Lower Level Optimization: - NLP implemented with SUMT - LF by MATPOWER - Fuzzy set theory (DM)	- Sep. 2015 (2016)/ - Time-varying load/ - Multiple load level/
[153]	**5/5.4.** MG/**5/5.7.** VPP	Multiple Grid + DG + ESS + MG (Type + Size + Loc.)	OF1. Profit for energy control coordination center (↑↑) OF2. Line power losses (↓↓) OF3. Voltage stability index (↑↑) OF4. Ordered supplier index (fluctuation index) (↓↓) OF5. Customer order index (↑↑)	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Load flow constraint 5. DG capacity limit 6. Stability limit 7. P/Q power compensation	Test System for VPP --------- 9-Node example system	- **2.3.1b.** Off-line planning/ - **2.3.2.** Scheduling/ - **4.1.10.** DSM; - **4.2.1.** Active management - **4.2/1,3.** Forecasting - **4.2.6.** Electricity market - **4.2.8.** Control coordination	- MO + W/ - Fuzzy Two step MO compromise method (based on interactive satisfaction.) - Satisfaction degrees for DM preferences	- Apr. 2011/ - Controllable load/ - Sensitive load/ - Level 1: OF3, OF2; - Level 2: OF4, OF5; - Level 3: OF1.
[154]	**5/5.7.** VPP	Multiple DER + ESS (Loc. + Type)	Maximize: 1. Satisfactory profit valuesMinimize 2. EENS	1. Supply & demand balance 2. Line flow limits 3. DER capacity limits	Test 3 and 100 nodes VPP Model	- **2.3.2.** Scheduling/ - **4.1/2.** Communication - **4.2/1,6** Centralized and decentralized dispatch	- MO + W/ - Weighting method (AHP)	- Aug. 2013/ - Controllable load/ - Multiple load level/
[155]	**5/5.7.** VPP	Multiple DER + ESS (Loc. + Type)	Maximize: 1. Profit returns from VPP 2. DG penetrations	1. DG penetration limit 2. Minimum load restrictions 3. Dynamic reserve capability of DG units (reserve limit)	Test VPP Model	- **2.3.2.** Scheduling (short term)/ - **4.1.1.** DG Penetration - **4.1.4.** ESS	- MO-P - MOGA - gamultiobj in MATLAB	- Nov. 2013 (2014)/ - Time varying load/ - Multiple load level/
[156]	**5/5.7.** VPP	Multiple DER + DR + ESS (Loc. + Type)	Maximize: 1. VPP BenefitsMinimize: 2. VPP self-supplying cost	1. Lower and upper limits of generation units, 2. Ramps of the units, 3. Regulation reserve needs, 4. Intermittent generation	Test VPP Model	- **2.3.2.** Scheduling/ - **4.1.1.** DER, - **4.1.10.** DR, - **4.2.1.** Management, storage - **4.2.(1,6).** Market management (Emissions)	- (MO-P)/ - CPLEX solver (GAMS) iterative problem/ - ROM in GAMS - CPLEX as solver	- Nov. 2014 (2015)/ - Fuzzy load/ - Multiple load level/

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[157]	**5/5.7.** VPP	Multiple DG (Location)	1. Satisfaction values towards Profits 2. Expected energy not supplied (EENS)	1. Fuzzy chance constraint 2. Power balance constraint 3. Interruptible load limit 4. Max-Min generation limits 5. Ramp-up/down limit 6. Min. up/downtime DG limit	18 bus DN with VPP (Mesh)	- **2.3.2.** Scheduling (short term)/ - **4.1.1.** DG penetration - **4.2.1.** VPP profit (↑↑) - **4.2.7.** VPP	- (MO + W)/ - Fuzzy CCP, MRGA + MCS/ - Weighting method	- Aug. 2015 (2016)/ - Uncertain loads - Controllable loads
[158]	**5/5.7.** VPP	Multiple DG + DR Load (DRL) (Type + Size + Loc.)	MO/criteria function: 1. Overall cost. in VPP (↓↓) **Sensitivity analysis:** 1. DG penetration (↑↑) 2. Voltage stabilization (↑↑) 3. Power loss reduction (↓↓)	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Load flow constraint 5. DG capacity limit 6. Radial constraint	IEEE 33 bus ARDN	- **2.3.1a** Long-term (10 years) planning - **2.3.2.** Scheduling (24 h to 1 year)/ - **4.2.6.** New market model	- MO + W/ - BPSO Algorithm + OPF/ - Sensitivity analysis (for performance evaluation)/	- Sep. 2015 (2016)/ - Constant load/ - Single load level/
[159]	**5/5.8.** SH	Multiple DG + EV + DR load (DRL) (Devices) (Type + Size)	Single objective function: 1. User Priority 2. Flexibility of loads 3. Devices satisfaction index 4. Power similarity for load delay 5. High power consumption with tariff consideration	1. Voltage limits 2. Power-flow limit 3. Feeder (current) capacity 4. Transformer overloading 5. Radial constraint 6. Types of loads 7. Load-flow constraint	LV Test Radial ARDN	- **2.3.3.** RT-OP (5 min)/ - **4.1.8.** Control Application - **4.1.10.** Load control - **4.2.(1,6).** Market pricing	- MO + W/-Multi-objective decision making (MODM)/ - Analysis method with decision making matrix/	- Apr. 2012/ - Time varying load/ - Multiple load level/ - Weights (1–5):[[0.8, 0.5, 0.7, 0.7, 0.9]
[160]	**5/5.8.** SH	Multiple DR + Price Consumer	Objective function to (↓↓) minimize: 1. Retail price (Forecasted) 2. Temperature control	1. Vector constraint 2. Model equality (time) constraint 3. Types of load	Test SHs Model	- **2.3.2.** Scheduling - **2.3.3.** RT-OP (15 min)/ - **4.2.1.** SEMS - **4.2.6.** Energy market	- MO + W/ - ICSP - DM: Weights with min-max to solve MONP	- Dec. 2012 (2013)/ - Fuzzy load/ - Fuzzy load level/
[161]	**5/5.4., 5/5.8., 5/5.9.**, SH, SB, MG	Multiple DG + DR/price + Storage (ESS)	1. Minimize daily energy cost 2. Minimize CO_2 emissions	1. Capacity constraints 2. Energy storage constraints 3. Energy balances 4. Starting and finishing time 5. Peak demand charge 6. Demand charge	MG + smart building of 30 homes	- **2.3.2.** Scheduling/ - **5/5.4.** MG, - **5/5.8.** SH, - **5/5.9.** SB,	- MO-P/ - MOO with ε-constraint/ - MILP model in GAMS using CPLEX solver	- Dec. 2015 (2016)/ - Time-varying load/ - Multiple load level/

Table 3. *Cont.*

Ref.	MDC/SDN	Decision Variables	Considered Objectives/Objective Function (OF)	Major Constraints	Test SDN	Planning Type/SGTF & SGAF/Features	MO Class/MO Optimization Method/Decision Making	Year/Load Model/Load Profile/Others/
[162]	**5/5.9.** SH, SB	Multiple DSM + DR + Devices Consumer	Multi OFs to minimize: 1. Cost of energy 2. Delay time in appliance use for load balancing	1. Vector constraint 2. Types of load	Test SG Model & includes SHs, SBs	- **2.3.2.** Scheduling - **2.3.3.** RT-OP/ - **4.1.10.** DSM and DR	- MO-P - MOEA - Load balancing algorithm (for electrical devices)	- Dec. 2015 (2016)/ - Time-varying load/ - Multiple load level/
[163]	**5/5.9.** SB	Multiple DG + ESS + Devices (Type + Size)	Objective function: 1. Minimize energy cost 2. Improve energy efficiency	1. Power-flow equality 2. Transformer overloading 3. Temperature constraint 4. Device constraint 5. Storage constraint	Test SBs Model	- **2.3.2.** Scheduling - **2.3.3.** RT-OP (1 h)/ - **4.1.8.** Control application - **4.2.1.** SEMS - **5/5.9.** SB	- MO-P/ - Augmented multi-objective particle swarm optimization (AMOPSO)/	- Sep.2014/ - Responsive/ non-responsive Loads
[164]	**5/5.9.** SB	Multiple DG + Storage (ESS) + Devices (Type + Size)	1. Minimize LCEAC 2. Minimize LCEI 3. Minimize LCEAC 4. Minimize NRCED 5. Minimize GHG	1. Power-flow equality 2. Types of loads 3. load-flow constraint 4. DG capacity limit 5. Storage constraint	Portuguese SBs Model	- **2.3.3.** RT-OP/ - **4.2.1.** SEMS - **5/5.9.** SB	- MO-P/ - Multi-objective linear programming (MOLP)/	- Apr. 2015/ - Time varying load/ - Multiple load level/
[165]	**5/5.9.** SB	Multiple DG + Storage (ESS) + Devices (Type + Size)	Framework with OF: 1. Optimize power usage 2. Improve temp. index 3. Improve illumination index 4. Air quality index (GHG) 5. Comfort for consumer	1. Power-flow equality 2. Types of loads 3. load-flow constraint 4. DG capacity limit	Test SBs Model	- **2.3.3.** RT-OP/ - **4.1.8.** Control - **4.2.1.** SEMS - **4.2.10.** Consumer comfort - **5/5.9.** SB	- MO-P/ - MOGA - HMOGA/ - DM: Weighting factor/	- Aug. 2015 (2016)/ - Time varying load/ - Multiple load level/
[166]	**5/5.10.** SC	Multiple DG + Heat Storage (Types+ Size + Loc.)	Minimize : 1. CO_2 Emissions 2. Annual Costs	1. Power-flow constraint 2. Branch/feeder capacity 3. Unique parameter selection 4. Standard component size 5. Stability limit; 6. Heat balance	Aalborg City Den-mark	- **2.3.1a.** Long-term - **2.3.1b.** Operational off-line planning/ - **4.2.7.** Automatic energy design scenario	- MO-P/ - MOEA + EnergyPLAN(Complete framework + Tool for future energy scenarios)/ - Smart cities (SC)	- Dec. 2015 (2016)/ - Time varying load/ - Multiple load level/ - Pilot Projects

Important Terms: BL-HMOEA: Bi-level hybrid multi-objective evolutionary algorithm, **CHP**: Combined heat and power plant, **CCP**: Chance constrained programming; D**M**: Decision maker/making, **FCM**: Fuzzy clustering mechanism, **FDM**: Fuzzy decision making, **GA**: Genetic algorithm, **GAMS**: General algebraic modeling system, **GHG**: Greenhouse gases emission, **HAC**: Hierarchical Agglomerative Clustering, **HDI**: Human development index, **HMOGA**: Hybrid Multi-objective optimization genetic algorithm, **ICSP**: Immune clonal selection programming, **ITLBO**: Improved teaching–learning-based optimization, **LC**: Life cycle; **LCEAC**: LC equivalent annual cost, **LCEI**: LC environmental impact; **LCEAC**: LC annual equivalent cost, **LF**: Load/Power Flow, **MAS**: Multi-agent system infrastructure, **MCS**: Monte-Carlo Simulations, M**ILP**: Mixed integer linear programming, **MOEA**: Multi-objective evolutionary algorithm, **MONP**: Interactive multi-objective non-linear programming, **MOO**: Multi-objective optimization, **MRGA**: Matrix real-coded genetic algorithm, **NLP**: Nonlinear programming, **NRCED**: Nonrenewable cumulative energy demand, **OF**: Objective function, **OPF**: Optimum power flow, **ROM**: Reliability and operation model, **RT-OP**: Real-time operational planning, **SAPMS**: Self-adaptive probabilistic modification strategy, **SEMS**: Smart energy management system, **SUMT**: Sequential unconstrained minimization technique, **TOPSIS**: Technique for Order Preference by Similarity to Ideal Solutions.

7.3. Investigation of MOP Formulations

The MOP formulations usually comprise interaction among inner optimization, outer or main optimization and decision making (DM) methods, respectively. The inner optimization aims at (usually load flow) solution techniques to address system constraints. The main (outer) optimization algorithm aims at finding various solutions of the concerned planning problem. Finally, the DM method sorts out the final trade-off solution, according to the needs of decision makers (or stakeholders).

7.3.1. Inner Optimization (Analytical/Numerical)

The inner optimization techniques in MOP formulations primarily comprises analytical, numerical and meta-heuristic based methods. The main aim of inner optimization is to deal with system constraints. Load/power flows (analytical) and numerical techniques mostly dominate this part, based on the nature of planning problem. Inner optimization solution technique have classified on the basis of formulation type, solver, initialization and interaction among them [167]. The non-linear formulation needs a potential solver that can deal efficiently with varying load scenarios and associated uncertainties. The improved (optimized) starting point (hot start), unlike random or flat starts, can significantly reduce the computation cost of the concerned problem.

a. Analytical Methods

The prominent analytical techniques mainly include conventional load flows and sensitivity-based methods. Newton-Raphson (NR) load flows are prominently employed in interconnected nature (structure) SDNs, as shown in [125,129,150]. Sensitivity analysis methods have also been employed in [127,128,158]; for potential initial solutions.

b. Numerical Methods

The noticeable numerical techniques addressed in the literature (Table 3) include; ε-constraint method [121,135,161]; second order cone programming [124]; lexicographic method [135]; MCS [122,139,157]; OPF [158]; integer programming [85]; graph theory [85,150]; penalty factor (funchion) method [130,140]; CCP [145,157]; compromise method [153]; ICSP [160]; linear programming (LP) [164] and non-linear programming (NLP) [152,160]. Moreover, goal programming (GOP), exhaustive search, sequential quadratic programming (SQP) and dynamic programming methods have sucessfully employed in conventional DN related planning problems [26]. The noticible numerical commercial (OPF) solvers employed include the DICOPT solver in GAMS to solve MINLP problems [121,156] and MILP problem in [161]. In addition, the GUROBI solver is utilized to solve the MISOCP problem in [124].

7.3.2. Outer/Main Optimization (Meta-Heuristics/Artificial Intelligence)

The main optimization techniques in MOP formulations mostly comprise meta-heuristic (MH) and/or artificial intelligence (AI)-based methods. The main aim of the main optimization is to find a potential set of solutions for concerned planning problems. The prominent meta-heuristic techniques addressed in the literature (Table 3) include: genetic algorithm (GA) and associated evolutionary algorithms with various variants as in [122,128,131,137,139,143,147,152,155,157,162,165,166]. Also, PSO with various variants have addressed SDN planning problems as in [125,127,130,132,138,158,163]. Furthermore, an improved variant of the teaching learning algorithm (ITLBO) [133] and bacterial foraging algorithm (MBFO) [134] have been employed for short term MO planning (scheduling) problems, respectively. An improved variant of an evolutionary algorithm, the seeker optimization algorithm (SOA) in [123,126]; and AI-based artificial neural network-based methods (NNE) [86] have been employed to solve offline planning and scheduling (real time) problems, respectively. Also, the tabu search algorithm (TSA) was employed to optimize equipment placement, aiming at long-term SDN planning. In the literature, MOP problems aiming at conventional DN planning have successfully employed MH/AI techniques [26]. The prominent techniques include harmony search (HS), big bang big crunch (BB-BC), artificial bee colony (ABC), immune algorithm (IA), simulated annealing (SA), honey bee mating (HBMO), ant colony optimization (ACO), bat algorithm (BA), differential evolution (DE), gravitational search algorithm (GSA), shuffled frog leaping (SFL) and hybrid algorithms respectively. Hybrid MH/AI methods results in efficient performance towards global solution aiming at complex planning problems [26]. The use of the aforesaid methods, from a future SDN planning viewpoint, offers potential research perspectives.

7.3.3. Decision-Making Methods

The decision making (DM) methods are vital, both as main optimization algorithms and as a means of sorting out a trade-off solutions among a set of multiple conflicting objectives. The prominent DM techniques addressed in the literature (Table 3) include weight methods that include both weighted sum (WSM) and product (WPM) methods, respectively, as in [132,139,140,148,149,157]. The analytical hierarchy process (AHP) has been employed for both long and short term SDN planning, as in [124,154]. Fuzzy decision making (FDM) is among the most popular DM methods and employed in many studies, mainly due to its ability to address varying, uncertain nature and various scenarios of the concerned problem. The FDM aiming at MOP problems has been employed in literature with various variants and associated methods as in [86,125,128,133,135,137,141]. Other multi-criteria decision analysis methods addressed in this study include the min-max approach [123,126,134,138,160]; rank order centroid (ROC) in [136] and TOPSIS in [141], respectively. A detailed account of MCDA methods can be found in [168,169].

7.4. Analysis of Potential Methods in MOP Formulations

The analysis of potential methods in MOP formulation, aiming at optimized SDN planning, are summarized, from the perspective of various performance indicators, in Table 4. The performance indicators include sub-optimizations in MOP formulations, respective execution (implementation and coding), and computation cost, solution quality, initial parameter dependence (tuning complexity) and application. The performance indicators have shown with desired requirements, as best (√), better/average (❈) and poor (×) as indication metrics, respectively.

Table 4. Brief comparison review of the merits and demerits of potential approaches applied for SDN planning.

Methods in MOP Formulation	Execution	Computation Efficiency (↑)	Solution	Parameter (PI)	Application
Sensitively Analysis (A)	Easy (E)	Efficient (less) (√)	Simple (√)	Flat/No (N)	Simple RDN
NR LF (A), OPF Solvers (N)	Easy (E), (A)	High (×)	Better (❈)	Flat/No (N)	Interconnected DN
ε.Const.; GOP; SQP; MILP (N)	Difficult (D)	High (×)	Better (❈)	Flat/No (N)	Linear, Complex (❈)
MCS; OPF; CP; MINLP (N)	Difficult (D)	High (×)	Complex (√)	Flat/No (N)	Non-Linear (√)
[GA; PSO; EA] (**1**), TS (MH/AI)	Easy (E)	High/Code (×)	Better (❈)	N/Y, Y, -, Y	Complex (❈), **LP** (√)
Improved variants (**1**) (MH/AI)	Difficult (D)	High/Code (×)	Complex (√)	Yes (Y)	Complex system (√)
HS; TLA; BB-BC; ABC (MH/AI)	Average (A)	Average (❈)	Better (❈)	-, N, Y, Y	Non-Linear (√)
IA; SA; HBMO; BFO (MH/AI)	D, E, A, A	(×), (×), (❈), (❈)	(❈, √, ❈, ×)	N/Y, N/Y, Y, -	Complex(×, ❈, ❈, ×)
BA; DE; SOA; GSA (MH/AI)	A, A, D, A	(❈), (❈), (×), (❈)	Better (❈)	Y, -, Y, Y	Complex system (❈)
ANN; SFL; Hybrid (MH/AI)	Difficult (D)	High/Code (×)	Complex (√)	Y, -, Y	Complex system (√)
WSM; AHP; FDM; TOPSIS (DM)	E, E, A, A	(√), (√), (❈), (❈)	(×, ❈, √, √)	-, -, -, -	Complex(×, ×, √, √)

Notes: The symbols E, A and D refers to: easy, average and difficult execution of problem with concernec solution technique, respectively. Yes (Y), No (N), and not applicable indicated as "-", best (√), better/average (❈) and poor (×).

8. Challenges and Future Research Directions

The current challenges in SDN planning and possible research directions have arranged from viewpoint of each SGP classification and presented throughout Sections 8.1–8.4, as follows.

8.1. SGTF Perspective

The development in SG technologies and achieving anticipated functionalities are still facing various challenges and issues, which serves as a motivation for future research directions as follows:

8.1.1. Options in SGET

SGCI:	Barriers in SG component integration due to a limitation in available infrastructure.
ICT:	Privacy, cryptographic algorithms for cyber security (data) in AMI and re-routing designs.
ADA:	Proposing techniques, enabling ADA, aiming at realizing interconnected SDN.
EST:	Need for improved storage technology aiming at minimizing battery failure and cost.
PE:	Harmonics, saturation, losses, waveform distortions and reactive power pricing in the market.
EV:	Optimized storage operation and cost with new techniques for EV applications.
SMMT:	Complexities due to a large number of measurement devices and fault detection methods.
CT:	MAS application, the trade-off between centralized and decentralized control.
APS:	Modified protection techniques to enable bi-directional power flow and ensure reliability.
DSM:	Real-time pricing (RTP) instead of average, integration of ICT infrastructure, efficient weather/load forecasting models, interoperability (among stakeholders), scalability issues (increased consumers and requirements), new scheme and predicting consumer response.

8.1.2. Options in SGAF

$\acute{\eta}$ & EM:	New forecasting methods, cloud-based control, and efficient management strategies.
PQS:	Modern control, ADA and PE, to house high DER penetration, aiming at PQS (V & f) issues.
ARTM:	Huge storage memory requirements with over data and privacy issues with visualization.
Rel.:	Evaluation of new consumption models from reliability perspective and cost of reliability.
S & P:	Need for improved cyber security and privacy protection algorithms in SH and SB.
NMOM:	Addressing complexity issues in new market model, devices, and management techniques.
INC & P:	Exploring interconnected topology based MDCs with new performance indicators.
DIDS:	Compatibility of intelligent devices, DM, and perspective aware interoperability platform.
SGCIR:	New simulators and solvers (for various scenarios), pilot projects and support tools.
FoC:	Proposing consumer-centered schemes for active participation (DM) in grid operations.

8.2. MDC Perspective

The futuristic SDN planning, like traditional counterpart, can be addressed as an expansion and new planning development. The MDCs is envisioned as being intelligent in nature, interconnected in structure and capable of accommodating bidirectional power (& communication) flows.

8.2.1. Expansion/Modification-Based SDN Planning

- Candidate SDNs: Modification of RDN (ARDN) to LDN and/or MDN with SGTF support.
- Motivation: Maximum objective attainment (multi-objective optimization).
- Likely features: ADA, ICT, MAS (advance control) and advanced protection schemes.

8.2.2. Emerging Concepts-Based New SDN Planning

- Candidate SDNs: MG and MMG concepts mainly center on the innovations in enabling SG hardware (EST, EV, PE, etc.). The SH, SB, VPP and SC, on the other hand, depends on main innovations in automation, ICT, and control technologies, respectively.
- Motivation: Develop new specified standards, formulation of new tools and techniques.
- Likely features: Still gray research areas in MOP under SGTF from a MDC perspective. The possible research-worthy areas include power quality, stability, reliability and DER housing.

8.2.3. Futuristic SDN Planning Based on Scaling Approach

The limitations in current standards and guidelines result in a variety of MDCs, complex variations and definitions across the globe. Unlike hierarchal TGs, SG and associated concepts must be differentiated on a distinct scale of implementation, which includes geographical and electrical boundaries, respectively. The proposed primitive architecture of SDN planning based on distinct scaling approach is illustrated in Figure 9. The approach indicates the scale of implementation of each MDC concept on the basis of geographical area, starting from small scale (such as SH, SB, and MG) to medium scale (MG, LDN/MDN, MMG, and VPP) and finally large scale (LDN, MMG, VPP and SC). Among six scale levels (SL), SL1 indicates the small SL and covers MDCs like SH and SB on the consumer side of the smart meter. The SL1 has briefly discussed in following Section 8.2.3.1 and shown with the dotted box in Figure 9. The medium scale level (SL2) covers MG. Medium/large scale level covers SL3 (MG, LDN), SL4 (LDN, MDN, and MMG) and SL5 indicated a variant of medium/large scale level covers VPP. Finally, SL6 indicates SC that covers all the MDC on the utility's end and is briefly discussed in the following Section 8.2.3.2 and shown with composite boxes in Figure 9, respectively.

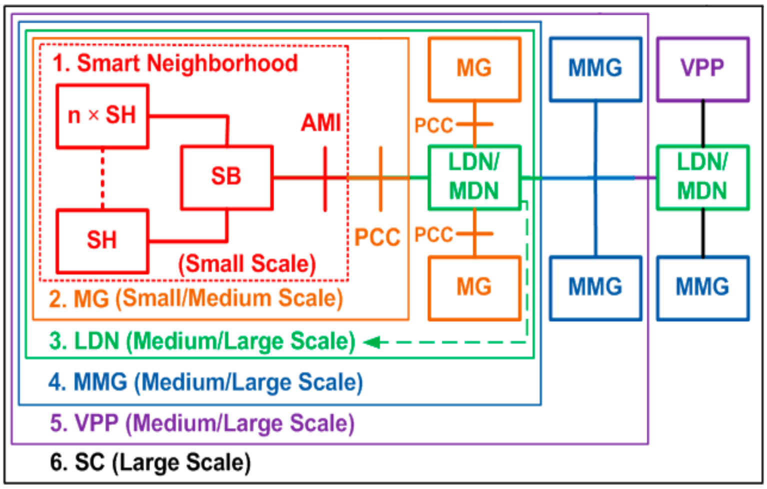


Figure 9. Scale-based planning architecture of SDNs, varying from small (SH) to large level (SC).

8.2.3.1. Future SDN Planning (Small Scale at the Consumer's End)

- Candidate SDNs: SH, SB and smart neighborhood are MDC concepts on consumer (AMI) side.
- Motivation: Realization relies on ICT, cloud and new integrated forecasting techniques.
- Potential Issues: The potential issues of rebound peaks, misalignment among REGs and consumer load patterns, irregular human factors, security and privacy issues, and difficulty due to a limitation in existing infrastructure, needs to be further explored.
- Likely features: Technical, economic and environmental/social objectives-based approaches must be introduced in HEMS to enable and serve consumers towards efficient scheduling of available resources. Also, flexible home automation systems (for consumer interaction in real-time) need further consideration.
- The scale of implementation:
  - ○ Small Scale Level-SL1: The possible scale-based planning approach starts from consumer level MDC (SH and SB) at smart meter side (of consumers).

8.2.3.2. Future SDN Planning (Medium-Large Scale at the Utility End)

- Candidate SDNs: The MDCs on the utility side such as MG, LDN, MDN, MMG, VPP, and SC.

- Motivation: Medium to large scale approach incorporating all the aforementioned MDCs.
- Likely features: The possible new architectures, planning tools, together with SGTF, modern integrated planning methods and interaction among interconnected MDC concepts; serves as a worthy research area.
- The scale of Implementation:
  - Medium-SL2: MG equipped with PCC, is capable of islanding and grid connection.
  - Medium/Large-SL3, SL4: The MG connects with modified (upgraded) LDN/MDN, which can house several MGs, hence realizing MMG concept.
  - Medium/Large-SL5: Several MG, LDN/MDN, and MMG; can cluster together in a grid connected VPP configuration, on the basis of deregulated market environment.
  - Large-SL6: SC houses all MDC on large (city) scale, as shown in Figures 7b and 9, respectively.

8.3. PWP Perspective

The SDN concept (MDC) realization have motivated stakeholders such as many countries (regions), leading policy makers, research institutes, and researchers, towards efforts from various perspectives, as shown in Table 5, since the cost is a vital factor (constraint) in traditional planning. However, the SDN development under the SG paradigm need to compromise cost constraints to a certain level. The pilot projects and policies around the world offer valuable experience that can help stakeholders to utilize maximum key enabler (SGTF) potential in mature SDN planning strategies. Technical and other objectives need to be prioritized in DM and the cost impact needs to be considered over a certain planning horizon. The prominent SDN motivations around the globe, with possible key enablers (SGTF), prominent stakeholders and focused objectives are presented in Table 5.

Table 5. The PWP perspective of SDN planning.

SDN Motivation	Possible Key Enablers in SG	Stakeholders	Focused (Aimed) Objectives
5. (5.1–5.10) New distribution concepts (MDC)	**4.1.1.** SGCI (DER/DG/REG); **4.1.2.** ICT (AMI); **4.1.3.** ADA; **4.1.4.** EST/Storage (ST); **4.1.5.** Power Electronics (PE); **4.1.6.** EV integration; **4.1.8.** CT; **4.1.9.** Smart protection (APS); **4.1.10.** DR/DSM; **6.** Test/pilot projects.	1. Research groups; 2. Organizations; 3. Academia; 4. Countries; 5. Investors; 6. Utilities 7. Consumers	- V & f deviations (↓↓) - Voltage stability (↑↑) - DER penetration (↑↑) - Reliability (↑↑) - Power Quality (↑↑) - System losses (↓↓) - System congestion (↓↓)
Enabled stability and robustness	**4.1.1.** SGCI (DER) integration; **4.1.2.** ICT (AMI); **4.1.3.** ADA; **4.1.4.** EST; **4.1.5.** PE (FACTS); **4.1.6.** EV integration; **4.1.9.** APS; **4.2.8.** Interoperability; **4.2.8.** New and up to date standards; **6.** Test/pilot projects, test beds.	1. Grid investigation groups; 2. Consumer societies; 3. Related companies; 4. Utilities (DSO);	- Power Quality (↑↑) - Power Security (↑↑) - V & f deviations (↓↓) - Reliability (↑↑) - Efficiency (Peak demand) (↑↑) - REG penetration (↑↑) - Voltage stability (↑↑)
New technology adoption to meet limitations in existing systems	**4.1.1.–4.1.10.** **4.2.1.** Investment in Infrastructure; **4.2.1.–4.2.10.** **6.** Test/pilot projects, test beds.	1. Service providers; 2. Utilities (DSO); 3. Consumers;	- Optimize asset utilization (↑↑) - Power Quality & security (↑↑) - Reliability (↑↑) - Consumer participation (↑↑)

Table 5. *Cont.*

SDN Motivation	Possible Key Enablers in SG	Stakeholders	Focused (Aimed) Objectives
Increase in % of REG in energy mix (reduce fossil fuels ↓↓)	**4.1.1.–4.1.10.** Up to date technology innovations and applications, e.g., ST, EV, SGUI (REG), etc. **4.2.1.** Support by carbon crediting (Kyoto protocol).	1. Companies (Device makers, Technology innovators, etc.) 2. Policymakers	- REG penetration (↑↑) - Fossil fuel consumption (↓↓) - Associated risks (↓↓) - Power Quality (↑↑)
ICT adoption by utilities	**4.1.2.** ICT support; **4.1.3.** ADA; **4.1.7.** Sensor Networks; **4.1.10.** DSM/DR; **5/5.8.** SHs; **5/5.9.** SBs.	1. Utilities (DSO) 2. Consumers	- Consumer awareness (↑↑) - Consumer participation (↑↑) - Consumer satisfaction (↑↑)
Sustainability/ Environment	**4.1.1.** SGCI (REG); **4.1.3.** ADA; **4.1.4.** EST; **4.1.5.** FACTS devices; **4.1.6.** EV.	1. Regulation authorities 2. Policy makers	- REG integration (↑↑) - GHG emission—Associated risks (↓↓) (↓↓)
Deregulated market structures	**4.2.6.** New market models; **4.2.7.** Market support tools, etc.	1. New market participants	- Profits for utilities (↑↑) - Benefit to cost ratio (↑↑)
Regulation for low energy costs	**4.1.1.–4.1.10.** Compliance with up-to-date technology innovations and applications (**4.2.1–4.2.10**); **4.2.1.** Investment in Infrastructure;	1. Country work-maps 2. Policymakers 3. Regulation authorities	- Social Objectives (↑↑) - Economic Growth (↑↑) - Consumer (↑↑) - Investor benefit (↑↑)
New investment opportunities (profit oriented)	**4.2.6.** Investment friendly policies; **4.2.10.** Consumer friendly policies.	1. Investors in SG paradigm 2. Market participants	- Investor benefit (↑↑) - Profits for utilities (↑↑) - Consumer participation (↑↑)
New/Multiple Infrastructure based planning In SG environment	**4.1.1.** SGCI (DER) Integration; **4.1.3.** ADA; **4.1.8.** Enhanced controls; **4.1.9.** Upgraded protection (APS); **4.1.10.** DSM/DR; **5.1–5.10.** Establish new and modified performance indices; and smart devices (innovations and applications); **7/7.1.** New planning tools; **7/7.2.** MO Decision support.	1. New grid planners 2. Grid Managers 3. Device makers 4. Technology innovators 5. Policymakers 6. Regulation Authorities 7. Utilities (DSO) 8. Consumers	- V & f deviations (↓↓) - Voltage stability (↑↑) - DER penetration (↑↑) - Reliability (↑↑) - Power Quality (↑↑) - System losses (↓↓) - System congestion (↓↓) - Optimize asset utilization (↑↑) - System losses (↓↓) - Defer new installations (↓↓) - Coordinated development (↑↑)

8.4. RWO Perspective

In this paper, MOP problems have been reviewed as RWO problems. However, the literature review indicates that there are several notable potential research areas for SDN planning, as follows:

8.4.1. APM for SDN Planning

The three stages-based deeper and wider optimization model needs to explore various aspects of SDN (MDC) planning. The proposed model includes long-term (off-line/scenario), followed by medium-term scheduling and finally short term RT-OP. The model includes three approaches as shown in Figure 8. The model needs consideration, aiming at planning strategies of different MDCs, for optimal planning solution on a long-term basis.

8.4.2. Power Flow

The development in two-way power flow optimization needs due consideration. The NR method, besides computer tools, was normally utilized for looped bi-directional power flows in various studies.

However, SDNs have expected to be interconnected in nature and complex in operation, hence, traditional power/load flow methods may not be applicable.

8.4.3. Optimized Initial Parameters Setting

The optimized initial parameterization can help both inner and outer optimization, in finding a global optimal solution at less computation cost and time, respectively. Simply, optimize initial parameters, speed-up the whole optimization process.

8.4.4. New Methods and Tools

Still various AI and hybrid techniques have not yet employed in finding a global optimal solution for SDN planning perspective. Despite comparatively highly efficient, they are difficult to code and few examples are available in the literature. Hence, the limitation serves as a likely research area to exploit various SGTF options in SDN planning.

8.4.5. Prioritization of Objectives in DM

The optimal weight allocation in DM can provide a feasible trade-off solution and can avoid surpassing technically (reliable/feasible) solutions in comparison with a cost effective oriented solution. SDN simulators and pilot projects can provide an opportunity for finding optimal objective weights to speed-up the DM process.

9. Conclusions

In this paper, the smart distribution network (SDN) as a SG modernization concept has presented from a planning perspective. SDN planning has motivated by various key enabling technologies and features under the SG paradigm that was limited in traditional planning (TDP). Since SDN will be capable of accommodating bi-directional power flow and is interconnected in nature and operation, as a consequence, traditional planning techniques and tools may not remain relevant.

The requirement of smooth SDN evolution needs roadmaps (plans and policies) for building new consumption models (MDC) either from the start or intelligently expands the traditional RDN. Thus, the SDN concept has presented via SGP, which includes SGTF, MDC, PWP, and RWO, respectively. The SGTF have been reviewed on the basis of their literature, limitations, applications, associated technologies, and benefits towards the realization of SDN concepts. Similarly, the expected SGAF have been reviewed by means of objective attainment, concept realization features, limitations, and SGET, which can be helpful in optimal SDN planning and operation. The new consumption models or MDC have been reviewed as potential SDN candidates, primarily by concepts, architecture, literature, prominent features, requirements, associated SGTF and research directions, respectively.

The SG policies of seven leading countries (and regions) with key guidelines, major policy objectives and core motivation (focus) with respective SGTF have been summarized in Table 1. Also, the fifteen notable SDN projects with associated details, related SGET, aimed SGAF and required objectives in the form of indicators (OI) have been presented in Table 2.

The real world optimization (RWO) planning problems, due to the involvement of a large number of stakeholders, are multi-objective (MO) in nature. MOP tools can provide trade-off solutions of the concerned problem among contradictory objectives and satisfy multiple stakeholders. The MOP problems aiming at SDN (MDC) have emphasized the need to address as aggregated planning model (APM). The main aim of the APM is to ensure the long-term success of MDC under SDN, on both technical and economic basis.

The current status of MOP-based literature works associated with SDN has been thoroughly reviewed and arranged in Table 3. Moreover, MOP formulations have been investigated on the basis of their structure, such as interaction between initialization, inner and outer optimization, decision-making procedures and respective solution techniques, respectively. It has been found that analytical and numerical techniques constitute the maximum portion of the inner optimization. MH/AI makes a large portion of outer optimization (for a set of feasible solutions) and MCDA methods represent a prominent portion of DM solutions. A brief comparison of MOO-based solution techniques applied for SDN planning, on the basis of merits and demerits, has illustrated in Table 4.

The challenges in SDN planning, possible research directions for their solutions and research motivations have arranged according to each classification in SGP. The research options in SGET have been presented as infrastructure limitations, need for improved methods and issues in the existing phase of respective technology. Similarly, SGAF was reviewed on the basis of operational issues, performance indication and limitation in addressing techniques.

The futuristic SDN planning has been addressed, as proposed primitive architecture on a distinct scale of implementation, including both electrical and geographical boundaries. The scaling approaches have two categories: the first corresponds to small scale MDC (such as SH, SB, and MG) on the consumer side and the rest of MDC on the utility side of the smart meter, respectively. In addition, the prominent SDN motivations around the globe were presented in Table 5, with possible key enablers (SGTF), prominent stakeholders and focused objectives.

Finally, integrated planning approaches and new power flow models should be further explored, aiming at efficient SDN planning. Also, artificial intelligence (AI) and hybrid techniques need to be employed for MOP problems in finding global optimal solutions. Still, limitations in new planning tools, hot (optimally predefined parameters) initialization methods, improved solution techniques and prioritization of decision objectives weights serves as a prospective research area to exploit various SDN planning options.

Acknowledgments: This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No. R0113-15-0002, Automotive ICT based e-Call standardization and after-market device development).

Author Contributions: Syed Ali Abbas Kazmi (first and corresponding author), Muhammad Khuram Shahzad (second author), Akif Zia Khan (third author) and Dong Ryeol Shin (main corresponding author) provide a composite review in the field of smart distribution networks. In particular, review of modern distribution concepts with key enablers is provided, based on literature work in top notch journals. The authors provided a critical assessment of different smart grid techniques, anticipated functionalities, modern distribution concepts, policies in leading countries and multi-objective as real-world optimization problem. In addition, challenges and future research directions for engineers, researchers, and planners; have also presented.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations have used in this paper:

ή	Efficiency
A/D/E	Average/Difficult/Easy
V	Voltage
f	Frequency
(√)/(❄)/(×)	Best/better or average/poor
ABC	Artificial bee colony
AC/DC	Alternating current/Direct current
ADA	Advanced distribution automation
ADN	Active distribution network
AHP	Analytical hierarchal process
AI	Artificial intelligence
ANM	Active network management
AMI	Advance metering infrastructure
APDS	Advanced power distribution system
APM	Aggregated planning model
ARDN	Active radial distribution network
ARTM	Advanced real time monitoring

AεCM	Augmented ε constrained method
BL-HMOEA	Bi-level hybrid MO evolutionary algorithm
CCP	Chance constrained programming
CHP	Combined heat and power plant
CIS	Customer information system
CMG	Clustered micro grids
CT	Control technologies
DCC	Distribution control centers
DER	Distributed energy resources
DG	Distributed generation
DM	Decision making
DR/DRP	Demand response/Demand response provider
DIDS	Distributed intelligence decision support
DSM	Demand side management
DSO	Distribution system operator
DSS/BSS	Distributed storage system/Battery storage system
EM/EMS	Energy management/Energy management system
ESS/EST	Energy storage systems/Energy storage technology
EV	Electrical vehicle
FCM	Fuzzy clustering mechanism
FoC	Freedom of choices
GAMS	General algebraic modeling system
GIS	Global information system
HAC	Hierarchical agglomerative clustering
HAN	Home area network
HDI	Human development index
HMOGA	Hybrid multi-objective optimization genetic algorithm
INC & P	Implementation of new concepts and paradigms
ICSP	Immune clonal selection programming
ICT	Information and communication technologies
IDS	Isolated (off-grid) distribution system
LC	Load controller
LCEAC	Life cycle equivalent annual cost
LCEI	Life cycle environmental impact
LDN	Loop distribution network
LL	Load level
MAS	Multi-agent system (infrastructure)
MC	Micro source controller
MCC	Main control center
MCDA	Multi-criteria decision analysis
MCS	Monte Carlo Simulations
MDC	Modern distribution concepts
MDN	Mesh distribution network
MG/MGCC	Micro grid/Micro grid central controller
MH	Meta-Heuristics
MINLP	Mixed integer nonlinear programming
MISOCP	Mixed integer second order cone programming
MMG	Multi-micro grids
MONP	Multi-objective (Interactive) non-linear programming
MO/MOO	Multi-objective/Multi-objective optimization
MOP	Multi-objective planning
MRGA	Matrix real-coded genetic algorithm
MV/LV	Medium voltage/Low voltage
NMOM	New market models, opportunities and management
NR	Newton Raphson (power flow method)

NRCED	Nonrenewable cumulative energy demand
OF/OI	Objective function/Objective index
OPF	Optimum power flow
PCC	Point of common coupling
PE	Power electronics
PI	Parameters initialization (and tuning)
PQS	Power quality and stability
PSO	Particle swarm optimization
PV	Photovoltaic (systems)
PWP	Policies, work maps and pilot projects
RDN	Radial distribution network
REG	Renewable energy generation
Rel.	Reliability
ROM	Reliability and operation model
RT	Real time
RT-OP	Real time operational planning
RWO	Real world optimization (problem)
RT-OP	Real-time operational planning
S & P	Security and privacy
SAPMS	Self-adaptive probabilistic modification strategy
SB/SC	Smart Building/Smart City
SDN	Smart distribution network
SEMS	Smart energy management system
SGCI	Smart grid components integration
SGCIR	Smart grid components integration realization
SGP	Smart grid package
SGTF	Smart grid package with technologies and functionalities.
SGAF	Smart grid anticipated functionalities
SGET	Smart grid enabling technologies
SH/SL	Smart home/Scale level
SoA	Service oriented architecture
SS	Sectionalized–switches
SMMT	Sensing, measurement, and monitoring technologies
SUMT	Sequential unconstrained minimization technique
TCC	Transmission control centers
TOPSIS	Technique for order preference by similarity to ideal solutions
TS	Tie-switches
VPP	Virtual power plant
WAN	Wide area network
WPM/WSM	Weighted product model/Weighted sum model
(Y)/(N)	Yes/No

References

1. Farhangi, H. The path of the smart grid power energy. *IEEE Mag.* **2010**, *8*, 18–28.
2. Lueken, C.; Carvalho, P.M.S.; Apt, J. Distribution grid reconfiguration reduces power losses and helps integrate renewables. *Energy Policy* **2012**, *48*, 260–273. [CrossRef]
3. Sultanaa, U.; Khairuddin, A.B.; Aman, M.M.; Mokhtara, A.S.; Zareen, N. A review of optimum DG placement based on minimization of power losses and voltage stability enhancement of distribution system. *Renew. Sustain. Energy Rev.* **2016**, *63*, 363–378. [CrossRef]
4. Yun, S.Y.; Chu, C.M.; Kwon, S.C.; Song, I.K.; Choi, J.H. The Development and Empirical Evaluation of the Korean Smart Distribution Management System. *Energies* **2014**, *7*, 1332–1362. [CrossRef]
5. Fang, X.; Misra, S.; Xue, G.; Yang, D. Smart grid—The new and improved power grid: A survey. *IEEE Commun. Surv. Tutor.* **2012**, *14*, 944–980. [CrossRef]

6. Jiang, Y.; Liu, C.C.; Xu, Y. Smart Distribution Systems. *Energies* **2016**, *9*, 297. [CrossRef]
7. Tuballa, M.L.; Abundo, M.L. A review of the development of Smart Grid technologies. *Renew. Sustain. Energy Rev.* **2016**, *59*, 710–725. [CrossRef]
8. El-Hawary, M.E. The Smart Grid—State-of-the-art and Future Trends. *Electr. Power Compon. Syst.* **2014**, *42*, 239–250. [CrossRef]
9. Khator, S.K.; Leung, L.C. Power distribution planning: A review of models and issues. *IEEE Trans. Power Syst.* **1997**, *12*, 1151–1159. [CrossRef]
10. Georgilakis, P.S.; Hatziargyriou, N.D. A review of Power distribution planning in the modern power systems era: Models, methods, and future research. *Electr. Power Syst. Res.* **2015**, *121*, 89–100. [CrossRef]
11. Jahromi, S.N.; Rashidinejad, M.; Abdollahi, A. Multistage distribution network expansion planning under smart grids environment. *Electr. Power Energy Syst.* **2015**, *71*, 222–230. [CrossRef]
12. Georgilakis, P.S.; Hatziargyriou, N.D. Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research. *IEEE Trans. Power Syst.* **2013**, *28*, 3420–3428. [CrossRef]
13. Kim, J.C.; Cho, S.M.; Shin, H.S. Advanced Power Distribution System Configuration for Smart Grids. *IEEE Trans. Smart Grid* **2013**, *4*, 353–358. [CrossRef]
14. Murty, V.V.S.N.; Kumar, A. Mesh distribution system analysis in presence of distributed generation with time varying load model. *Electr. Power Energy Syst.* **2014**, *62*, 836–854. [CrossRef]
15. Gamarra, C.; Guerrero, J.M. Computational optimization techniques applied to microgrids planning: A review. *Renew. Sustain. Energy Rev.* **2015**, *48*, 413–424. [CrossRef]
16. Siddaiah, R.; Saini, R.P. A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications. *Renew. Sustain. Energy Rev.* **2016**, *58*, 376–396. [CrossRef]
17. Nosratabadi, S.M.; Hooshmand, R.A.; Gholipour, E. A Comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resource scheduling in power systems. *Renew. Sustain. Energy Rev.* **2017**, *67*, 341–363. [CrossRef]
18. Lobaccaro, G.; Carlucci, S.; Löfström, E. A Review of Systems and Technologies for Smart Homes and Smart Grids. *Energies Rev.* **2016**, *9*, 348. [CrossRef]
19. Zhou, B.; Li, W.; Chan, K.W.; Cao, Y.; Kuang, Y.; Liu, X.; Wang, X. Smart home energy management systems: Concept, configurations, and scheduling strategies. *Renew. Sustain. Energy Rev.* **2016**, *61*, 30–40. [CrossRef]
20. Calvillo, C.F.; Miralles, A.S.; Villar, J. Energy management and planning in smart cities. *Renew. Sustain. Energy Rev.* **2016**, *55*, 273–287. [CrossRef]
21. International Energy Agency. Technology Road Map Smart Grids. April 2011. Available online: http://www.iea.org/publications/freepublications/publication/smartgrids_roadmap.pdf (accessed on 16 August 2016).
22. Rodriguez, A.A.; Ault, G.; Galloway, S. Multi-Objective planning of distributed energy resources: A review of the state-of-the-art. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1353–1366. [CrossRef]
23. Keane, A.; Ochoa, L.F.; Borges, C.L.T.; Ault, G.W.; Alarcon-Rodriguez, A.D.; Currie, R.; Pilo, F.; Dent, C.; Harrison, G.P. State-of-the-art techniques and challenges ahead for distributed generation planning and optimization. *IEEE Trans. Power Syst.* **2013**, *28*, 1493–1502. [CrossRef]
24. Shen, X.; Shahidehpour, M.; Han, Y.; Zhu, S.; Zheng, J. Expansion Planning of Active Distribution Networks with Centralized and Distributed Energy Storage Systems. *IEEE Trans. Sustain. Energy* **2017**, *8*, 126–134. [CrossRef]
25. Konstantelos, I.; Giannelos, S.; Strbac, G. Strategic Valuation of Smart Grid Technology Options in Distribution Networks. *IEEE Trans. Power Syst.* **2017**, *32*, 1293–1303. [CrossRef]
26. Kazmi, A.A.; Shahzad, M.K.; Shin, D.R. Multi-Objective Planning Techniques in Distribution Networks: A composite Review. *Energies* **2017**, *10*, 208. [CrossRef]
27. Hossain, M.S.; Madlool, N.A.; Rahim, N.A.; Selvaraj, J.; Pandey, A.K.; Khan, A.F. Role of smart grid in renewable energy: An overview. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1168–1184. [CrossRef]
28. Viral, R.; Khatod, D.K. Optimal planning of distributed generation systems in distribution system: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 5146–5165. [CrossRef]
29. Tan, W.S.; Hassan, M.Y.; Majid, M.S.; Rahman, H.A. Optimal distributed renewable generation planning: A review of different approaches. *Renew. Sustain. Energy Rev.* **2013**, *18*, 626–645. [CrossRef]

30. Strasser, T.; Andrén, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitão, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; et al. A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems. *IEEE Trans. Ind. Electr.* **2015**, *62*, 2424–2438. [CrossRef]
31. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. A Survey on Smart Grid Potential Applications and Communication Requirements. *IEEE Trans. Ind. Inform.* **2013**, *9*, 28–42. [CrossRef]
32. Nikos Komninos, N.; Eleni Philippou, E.; Pitsillides, A. Survey in Smart Grid and Smart Home Security: Issues, Challenges and Countermeasures. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1933–1954. [CrossRef]
33. Li, W.; Zhang, X. Simulation of the smart grid communications: challenges, techniques, and future trends. *Comput. Electr. Eng.* **2014**, *40*, 270–288. [CrossRef]
34. Madani, V.; Das, R.; Aminifar, F.; McDonald, J.; Venkata, S.S.; Novosel, D.; Bose, A.; Shahidehpour, M. Distribution Automation Strategies Challenges and Opportunities in a Changing Landscape. *IEEE Trans. Smart Grid* **2015**, *6*, 2157–2165. [CrossRef]
35. Das, R.; Madani, V.; Aminifar, F.; McDonald, J.; Venkata, S.S.; Novosel, D.; Bose, A.; Shahidehpour, M. Distributed Automation strategies: Evolution of Technologies and the business case. *IEEE Trans. Smart Grid* **2015**, *6*, 2166–2175. [CrossRef]
36. Barsali, S.; Ceraolo, M.; Giglioli, R.; Poli, D. Storage applications for Smartgrids. *Electr. Power Syst. Res.* **2015**, *120*, 109–117. [CrossRef]
37. Erdinc, O.; Paterakis, N.G.; Pappi, I.N.; Bakirtzis, A.G.; Catalao, J.P.S. A new perspective for sizing of distributed generation and energy storage for smart house holds under demand response. *Appl. Energy* **2015**, *143*, 26–37. [CrossRef]
38. Sbordone, D.A.; Martirano, L.; Falvo, M.C.; Chiavaroli, L.; Pietra, B.D.; Bertini, I. Reactive power control for an energy storage system: A real implementation in a Micro-Grid. *Netw. Comput. Appl.* **2015**, *59*, 250–263. [CrossRef]
39. Hemmati, R.; Saboori, H.; Saboori, S. Assessing wind uncertainty impact on short term operation scheduling of coordinated energy storage systems and thermal units. *Renew. Energy* **2016**, *95*, 74–84. [CrossRef]
40. Debnath, U.K.; Ahmad, I.; Habibi, D.; Saber, A.Y. Energy storage model with gridable vehicles for economic load dispatch in smart grid. *Electr. Power Energy Syst.* **2015**, *64*, 1017–1024. [CrossRef]
41. Colak, I.; Kabalci, E.; Fulli, G.; Lazarou, S. A survey on the contributions of power electronics to smart grid systems. *Renew. Sustain. Energy Rev.* **2015**, *47*, 562–579. [CrossRef]
42. Jian, L.; Zheng, Y.; Xiao, X.; Chan, C.C. Optimal scheduling for vehicle-to-grid operation with stochastic connection of plug-in electrical vehicles to smart grid. *Appl. Energy* **2015**, *146*, 150–161. [CrossRef]
43. Shaaban, M.F.; Eajal, A.A.; El-Saadany, E.F. Coordinated charging of plug-in hybrid electrical vehicles in smart hybrid AC/DC distribution systems. *Renew. Energy* **2015**, *82*, 92–99. [CrossRef]
44. Liu, L.; Fong, F.; Liu, X.; Peng, Y.; Wang, Q. A review on electric vehicles interacting with renewable energy in smart grid. *Renew. Sustain. Energy Rev.* **2015**, *51*, 648–661. [CrossRef]
45. Yong, J.Y.; Ramachandaramurthy, V.K.; Tan, K.M.; Mithulananthan, N. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renew. Sustain. Energy Rev.* **2015**, *49*, 365–385. [CrossRef]
46. Tan, K.M.; Ramachandaramurthy, V.K.; Yong, J.Y. Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques. *Renew. Sustain. Energy Rev.* **2016**, *53*, 720–732. [CrossRef]
47. Hare, J.; Shi, X.; Gupta, S.; Bazzi, A. Fault diagnostics in smart micro-grids: A survey. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1114–1124. [CrossRef]
48. Kamel, R.M.; Alsaffar, M.A.; Habib, M.K. Noval and simple scheme for Micro-Grid Protection by connecting its loads neutral points: A review on Micro-Grid Protection techniques. *Renew. Sustain. Energy Rev.* **2016**, *58*, 931–942. [CrossRef]
49. Mirsaeidi, S.; Said, D.M.; Mustafa, M.W.; Habibuddin, M.H.; Ghaffari, K. Fault location and isolation in micro-grids using a digital central protection unit. *Renew. Sustain. Energy Rev.* **2016**, *56*, 1–17. [CrossRef]
50. Khan, A.R.; Mahmood, A.; Safdar, A.; Khan, Z.A.; Khan, N.A. Load forecasting, dynamic pricing and DSM in smart grid: A review 2016. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1311–1322. [CrossRef]
51. Logenthiran, T.; Srinivasan, D.; Shun, T.Z. Demand side management in smart grid using heuristic optimization. *IEEE Trans. Smart Grid* **2012**, *3*, 1244–1252. [CrossRef]

52. Gelazanskas, L.; Gamage, K.A.A. Demand side management in smart grid: A review and proposals for future direction. *Sustain. Cities Soc.* **2014**, *11*, 22–30. [CrossRef]
53. Siano, P. Demand response and smart grids—A survey. *Renew. Sustain. Energy Rev.* **2014**, *30*, 461–478. [CrossRef]
54. Evangelopoulos, V.A.; Georgilakis, P.S.; Hatziargyriou, N.D. Optimal operation of smart distribution networks: A review of models, methods and future research 2016. *Electr. Power Syst. Res.* **2016**, *140*, 95–106. [CrossRef]
55. Wright, P.S.; Christensen, A.E.; Davis, P.N.; Larson, B.; Lippert, T.; Patel, P. Power Quality Propagation Measurements in Smart Grids. In Proceedings of the IEEE Conference on Precision Electromagnetic Measurements, Ottawa, ON, Canada, 10–15 July 2016; pp. 1–2.
56. Wang, P.; Liang, D.H.; Yi, J.; Lyons, P.F.; Davison, P.J.; Taylor, P.C. Integrating electrical energy storage into coordinated voltage control schemes for distribution networks 2014. *IEEE Trans. Smart Grid* **2014**, *5*, 1018–1032. [CrossRef]
57. Pathirikkat, G.; Reddy, M.J.B.; Mohanta, D. Stability concerns in smart grid with emerging renewable energy technologies. *Electr. Power Comput. Syst.* **2014**, *42*, 418–425.
58. Hasanvand, S.; Nayeripour, M.; Waffenschmidt, E.; Abarghouei, H.F. A new approach to transform an existing distribution network into a set of micro-grids for enhancing reliability and sustainability. *Appl. Soft Comput.* **2017**, *52*, 120–134. [CrossRef]
59. Depuru, S.S.S.R.; Wang, L.; Devabhaktuni, V. Smart Meters for Power Grid: Challenges, Issues, Advantages and Status. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2736–2742. [CrossRef]
60. Yang, Q.; Barria, J.A.; Green, T.C. Communication infrastructures for distributed control of power distribution networks. *IEEE Trans. Ind. Inform.* **2011**, *7*, 316–327. [CrossRef]
61. Ting, L.; Yanan, S.; Yang, L.; Yuhong, Z.; Yucheng, D.; Wang, C.S. Abnormal traffic-indexed state estimation: A cyber–physical fusion approach for smart grid attack detection. *Future Gener. Comput. Syst.* **2015**, *49*, 94–103.
62. Fan, X.; Gong, G. Security challenges in smart-grid metering and control systems. *Technol. Innov. Manag. Rev.* **2013**, *3*, 42–49.
63. Yu, X.; Xue, Y. Smart Grids: A Cyber–Physical Systems Perspective. *Proc. IEEE* **2016**, *104*, 1058–1070. [CrossRef]
64. Divshali, P.H.; Choi, B.J. Electrical Market Management Considering Power System Constraints in Smart Distribution Grids. *Energies* **2016**, *9*, 405. [CrossRef]
65. Tafreshi, S.M.M.; Lahiji, A.S. Long-term market equilibrium in smart grid paradigm with introducing demand response provider in competition. *IEEE Trans. Smart Grid* **2015**, *6*, 2794–2806. [CrossRef]
66. Safdarian, A.; Firuzabad, M.F.; Lehtonen, M. Benefits of Demand Response on Operation of Distribution Networks: A Case Study. *IEEE Syst. J.* **2016**, *10*, 189–197. [CrossRef]
67. Kalambe, S.; Agnihotri, G. Loss minimization techniques used in distribution network: bibliographical survey. *Renew. Sustain. Energy Rev.* **2014**, *29*, 184–200. [CrossRef]
68. Chen, T.H.; Huang, W.T.; Gu, J.C.; Pu, G.C.; Hsu, Y.F.; Guo, T.Y. Feasibility study of upgrading primary feeders from radial and open loop to normally closed-loop arrangement. *IEEE Trans. Power Syst.* **2004**, *19*, 1308–1316. [CrossRef]
69. Simanjorang, R.; Miura, Y.; Ise, T. Controlling voltage profile in loop distribution system with Distributed Generation using series type BTB converter. In Proceedings of the 7th International Conference on Power Electronics, Daegu, Korea, 22–26 October 2007; pp. 1167–1172.
70. Jeong, B.S.; Chun, Y.H. Feeder Loop Line Control for the Voltage Stabilization of Distribution Network with Distributed Generators. *J. Electr. Eng. Technol.* **2014**, *9*, 1–5. [CrossRef]
71. Sayed, M.A.; Takeshita, T. Line Loss Minimization in Isolated Substations and Multiple Loop Distribution Systems Using the UPFC 2014. *IEEE Trans. Power Electron.* **2014**, *29*, 5813–5822. [CrossRef]
72. Kazmi, S.A.A.; Shahzad, M.K.; Shin, D.R. Voltage stability index for Distribution Network connected in Loop Configuration. *IETE J. Res. Taylor Francis* **2017**, *63*, 1–13. [CrossRef]
73. Kazmi, S.A.A.; Hasan, S.F.; Shin, D.R. Multi criteria decision analysis for optimum DG placement in smart grids. In Proceedings of the 2015 IEEE Innovative Smart Grid Technologies—Asia (ISGT ASIA), Bangkok, Thailand, 3–6 November 2015; pp. 1–5.
74. Roy, N.K.; Pota, H.R. Current Status and Issues of Concern for the Integration of Distributed Generation into Electricity Networks. *IEEE Syst. J.* **2015**, *9*, 933–944. [CrossRef]

75. Herault, M.C.A.; Doye, N.N.; Gandioli, C.; Hadjsaid, N.; Tixador, P. Meshed distribution network vs. reinforcement to increase the distributed generation connection. *Sustain. Energy Grids Netw.* **2015**, *1*, 20–27. [CrossRef]
76. Hadjsaid, N.; Alvarez-Hérault, M.C.; Caire, R.; Raison, B.; Descloux, J.; Bienia, W. Novel architectures and operation modes of Distribution Network to increase DG integration. In Proceedings of the 2010 IEEE Power and Energy Society General Meeting, Minneapolis, MN, USA, 25–29 July 2010; pp. 1–6.
77. Sharma, S.; Abhyankar, A. Loss Allocation for Weakly Meshed Distribution System using Analytical Formulation of Shapley Value. *IEEE Trans. Power Syst.* **2017**, *32*, 1369–1377. [CrossRef]
78. Akorede, M.F.; Hizam, H.; Aris, I.; Ab-Kadir, M.Z.A. Effective method for optimal allocation of distributed generation units in meshed electric power systems. *IET Gener. Transm. Distrib.* **2011**, *5*, 276–287. [CrossRef]
79. Lasseter, R.H.; Paigi, P. Microgrid: A Conceptual Solution. In Proceedings of the IEEE 35th Annual Power Electronics Specialists Conference (PESC'04), Aachen, Germany, 20–25 June 2004; pp. 4285–4290.
80. Guerrero, J.M.; Chandorkar, M.; Lee, T.L.; Loh, P.C. Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control. *IEEE Trans. Ind. Electron.* **2013**, *60*, 1254–1262. [CrossRef]
81. Guerrero, J.M.; Loh, P.C.; Lee, T.L.; Chandorkar, M. Advanced Control Architectures for Intelligent Microgrids—Part II: Power Quality, Energy Storage, and AC/DC Microgrids. *IEEE Trans. Ind. Electron.* **2013**, *60*, 1263–1270. [CrossRef]
82. Che, L.; Khodayar, M.; Shahidehpour, M. Only connect: Microgrids for distribution system restoration. *IEEE Power Energy Mag.* **2014**, *12*, 70–81.
83. Kazmi, S.A.A.; Hasan, S.F.; Shin, D.R. Analyzing the integration of Distributed Generation into smart grids. In Proceedings of the IEEE 10th Conference Industrial Electronics and Applications (ICIEA), Auckland, New Zealand, 15–17 June 2015; pp. 1–5.
84. IEEE Std. 1547.4. IEEE Guide for Design, Operation and Integration of Distributed Resource Island Systems with Electric Power Systems. 2011. Available online: www.seari-nc.com/iec/2012828152334.pdf (accessed on 14 August 2016).
85. Che, L.; Zhang, X.; Shahidehpour, M.; Alabdulwahab, A.; Al-Turki, Y. Optimal planning of Loop-Based Microgrid Topology. *IEEE Trans. Smart Grid* **2016**, *99*, 1–11. [CrossRef]
86. Chaouachi, A.; Kamel, R.M.; Andoulsi, R.; Nagasaka, K. Multiobjective Intelligent Energy Management for a Microgrid. *IEEE Trans. Ind. Electron.* **2013**, *60*, 1688–1699. [CrossRef]
87. Lasseter, R.H.; Eto, J.H.; Schenkman, B.; Stevens, J.; Vollkommer, H.; Klapp, D.; Linton, E.; Hurtado, H.; Roy, J. CERTS Microgrid Laboratory Test Bed. *IEEE Trans. Power Deliv.* **2011**, *26*, 325–332. [CrossRef]
88. Mandelli, S.; Barbieri, J.; Mereu, R.; Colombo, E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1621–1646. [CrossRef]
89. Vasiljevska, J.; Lopes, J.A.P.; Matos, M.A. Integrated micro-generation, load and energy storage control functionality under the multi micro-grid concept. *Electr. Power Syst. Res.* **2013**, *95*, 292–301. [CrossRef]
90. Asmus, P. Microgrids, virtual power plants and our distributed energy future. *Electr. J.* **2010**, *23*, 72–82. [CrossRef]
91. Mancarella, P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy* **2014**, *65*, 1–17. [CrossRef]
92. Peik-Herfeh, M.; Seifi, H.; Sheikh-El-Eslami, M.K. Decision making of a virtual power plant under uncertainties for bidding in a day-ahead market using point estimate method. *Electr. Power Energy Syst.* **2013**, *44*, 88–98. [CrossRef]
93. Saponara, S.; Bacchillone, T. Network architecture, security issues, and hardware implementation of a home area network for smart grid. *J. Comput. Netw. Commun.* **2012**, *2012*, 5345121. [CrossRef]
94. Zhang, D.; Shah, N.; Papageorgiou, L.G. Efficient energy consumption and operation management in a smart building with microgrid. *Energy Convers. Manag.* **2013**, *74*, 209–222. [CrossRef]
95. Wang, Z.; Wang, L.; Dounis, A.I.; Yang, R. Integration of plug-in hybrid electric vehicles into energy and comfort management for smart building. *Energy Build.* **2012**, *47*, 260–266. [CrossRef]
96. Romero, S.R.; Santos, A.C.; Pérez, F.M.; Rey, A.L. Integration of distributed generation in the power distribution network: The need for smart grid control systems, communication and equipment for a smart city—Use cases. *Renew. Sustain. Energy Rev.* **2014**, *38*, 223–234. [CrossRef]

97. European Commission. European Smart Grids technology platform, vision and strategy for Europe's electricity. 2006. Available online: http://ec.europa.eu/research/energy/smart-grid (accessed on 14 September 2016).
98. Gangale, F.; Mengolini, A.; Onyeji, I. Consumer engagement: An insight from smart grid projects in Europe. *Energy Policy* **2013**, *60*, 621–628. [CrossRef]
99. IqtiyaniIlham, N.; Hasanuzzaman, M.; Hosenuzzaman, M. European smart grid prospects, policies, and challenges. *Renew. Sustain. Energy Rev.* **2017**, *67*, 776–790. [CrossRef]
100. Brown, R.E. Impact of Smart Grid on Distribution System Design. In Proceedigns of the 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008; pp. 1–4.
101. *Smart Energy Reference Architecture SERA*; Microsoft: Redmond, WA, USA, 2009.
102. *NIST Special Publication 1108 NIST Framework and Roadmap for Smart Grid Interoperability Standards*; NIST: Gaithersburg, MD, USA, 2010.
103. Zhao, X.; Yusheng, X.; Po, W.K. Recent advancements on smart grids in China. *Electr. Power Comput. Syst.* **2014**, *42*, 251–261.
104. *The Strategic Energy Plan of Japan*; Summary; Ministry of Economy Trade and Industry Japan: Tokyo, Japan, 2010.
105. Korean Smart Grid Institute. 2016. Available online: http://www.smartgrid.or.kr/eng.html (accessed on 16 August 2016).
106. Kim, S.T.; Lim, B.I.; Park, W.K.; Kim, M.K.; Son, S.Y. An analysis on the effectiveness of a smart grid test-bed project: The Korean case. *Renew. Sustain. Energy Rev.* **2016**, *59*, 868–875. [CrossRef]
107. Smart Grid Australia. Available online: http://www.smartgridsmartcity.com.au (accessed on 20 August 2016).
108. Haidar, A.M.A.; Muttaqi, K.; Sutanto, D. Smart Grid and its future perspectives in Australia. *Renew. Sustain. Energy Rev.* **2015**, *51*, 1375–1389. [CrossRef]
109. Selvam, M.M.; Gnanadass, R.; Padhy, N.P. Initiatives and technical challenges in smart distribution grid. *Renew. Sustain. Energy Rev.* **2016**, *58*, 911–917. [CrossRef]
110. Durieux, O.; Wilde, V.D.; Lambin, J.J.; Otjacques, S.; Lefort, M. Smart Grid Technologies Feasibility Study: Increasing Decentralized Generation Power Injection Using Global Active Network Management. In Proceedings of the CIRED 21st International Conference on Electricity Distribution Frankfurt, Frankfurt, Germany, 6–9 June 2011; pp. 1–6.
111. International Energy Commission (IEA). How2Guide for Smart Grids in Distribution Networks, Roadmap Development and Implementation. 2016. Available online: http://cluergal.org/media/zinnia/files/Smart_Grids_in_DistributionNetorks.pdf (accessed on 25 December 2016).
112. Lawrence Berkeley National Laboratory. CERTS Microgrid Laboratory Test Bed. Available online: http://certs.lbl.gov/pdf/certs-mgtb-app-o.pdf (accessed on 29 December 2016).
113. DER IREC 22@Microgrid Project (n.d.). Available online: der-microgrid.gtd.es (accessed on 26 December 2016).
114. Enrich, R.; Skovron, P.; Tolos, M.; Moreno, M.T. Microgrid Management Based on Economic and Technical Criteria. In Proceedings of the IEEE International Energy Conference and Exhibition (ENERGYCON), Florence, Italy, 9–12 September 2012; pp. 551–556.
115. Jayawarna, N.; Jenkins, N.; Barnes, M.; Lorentzou, M.; Papthanassiou, S.; Hatziagyriou, N. Safety Analysis of a MicroGrid. In Proceedings of the 2005 International Conference on Future Power Systems (FPS), Amsterdam, The Netherlands, 16–18 November 2005; pp. 1–7.
116. Warmer, C.J.; Hommelberg, M.P.F.; Roossien, B.; Kok, J.K.; Turkstra, J.W. A field test using agents for coordination of residential micro-chip. In Proceedings of the 2007 International Conference on Intelligent Systems Applications to Power Systems, Kaohsiung, Taiwan, 5–8 November 2007; pp. 1–4.
117. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergüt, S.; Buccella, C.; Cecati, C.; Hancke, G.P. Smart Grid and Smart Homes: Key Players and Pilot Projects. *IEEE Ind. Electron. Mag.* **2012**, *6*, 18–34. [CrossRef]
118. Kohno, M.; Masuyama, Y.; Kato, N.; Tobe, A. Hitachi's Smart City Solutions for New Era of Urban Development.pdf. pp. 79–88. Available online: http://www.hitachi.com/rev/pdf/2011/r2011_02_101.pdf (accessed on 25 August 2016).
119. Yamagata, Y.; Seya, H. Proposal for a local electricity-sharing system: A case study of Yokohama city, Japan. *IET Intell. Transp. Syst.* **2015**, *9*, 38–49. [CrossRef]

120. Izadian, A.; Girrens, N.; Khayyer, P. Renewable Energy Policies, a Brief Review of the Latest U.S. and E.U. Policies. *IEEE Ind. Electron. Mag.* **2013**, *7*, 21–34. [CrossRef]
121. Zakariazadeh, A.R.; Jadid, S.; Siano, P. Stochastic multi-objective operational planning of smart distribution systems considering demand response programs. *Electr. Power Syst. Res.* **2014**, *111*, 156–168. [CrossRef]
122. Mena, M.; Hennebel, Y.F.; Li, C.; Ruiz, E.Z. A risk-based simulation and multi-objective optimization framework for the integration of distributed renewable generation and storage. *Renew. Sustain. Energy Rev.* **2014**, *37*, 778–793. [CrossRef]
123. Kumar, D.; Samantaray, S.R. Design of an advanced electric power distribution systems using seeker optimization algorithm. *Electr. Power Energy Syst.* **2014**, *63*, 196–217. [CrossRef]
124. Nick, M.; Cherkaoui, R.; Paolone, M. Optimal Allocation of Dispersed Energy Storage Systems in Active Distribution Networks for Energy Balance and Grid Support 2014. *IEEE Trans. Power Syst.* **2014**, *29*, 2300–2310.
125. Kayal, P.; Chanda, C.K. A multi-objective approach to integrate solar and wind energy sources with electrical distribution network. *Sol. Energy* **2015**, *112*, 397–410.
126. Kumar, D.; Samantaray, S.R. Implementation of multi-objective seeker-optimization-algorithm for optimal planning of primary distribution systems including DSTATCOM. *Electr. Power Energy Syst.* **2016**, *77*, 439–449.
127. Arasteha, H.; Sepasiana, M.S.; Vahidinasab, V.; Siano, P. SoS-based multiobjective distribution system expansion planning. *Electr. Power Syst. Res.* **2016**, *141*, 392–406. [CrossRef]
128. Buayai, K.; Ongsaku, W.; Mithulananthan, N. Multi-objective micro-grid planning by NSGA-II in primary distribution system. *Eur. Trans. Electr. Power* **2012**, *22*, 170–187.
129. Chen, T.H.; Lin, E.H.; Yang, N.C.; Hsieh, T.Y. Multi-objective optimization for upgrading primary feeders with distributed generators from normally closed loop to mesh arrangement. *Electr. Power Energy Syst.* **2012**, *45*, 413–419. [CrossRef]
130. Ganguly, S.; Sahoo, N.C.; Das, D. A novel multi-objective PSO for electrical distribution system planning incorporating distributed generation. *Energy Syst.* **2010**, *1*, 291–337. [CrossRef]
131. Sanseverino, E.R.; Di Silvestre, M.L.; Ippolito, M.G.; Re, G.L. An execution, monitoring and replanning approach for optimal energy management in microgrids. *Energy* **2011**, *36*, 3429–3436.
132. Moghaddam, A.A.; Seifi, A.; Niknam, T.; Pahlavani, M.R.A. Multi-objective operation management of a renewable MG (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source. *Energy* **2011**, *36*, 6490–6507. [CrossRef]
133. Niknam, T.; Abarghooee, R.A.; Narimani, M.R. An efficient scenario-based stochastic programming framework for multi-objective optimal micro-grid operation. *Appl. Energy* **2012**, *99*, 455–470. [CrossRef]
134. Motevasel, M.; Seifi, A.R.; Niknam, T. Multi-objective energy management of CHP (combined heat and power)-based micro-grid. *Energy* **2013**, *51*, 123–136. [CrossRef]
135. Aghaei, J.; Alizadeh, M.I. Multi-objective self-scheduling of CHP (combined heat and power)-based microgrids considering demand response programs and ESSs (energy storage systems). *Energy* **2013**, *55*, 1044–1054. [CrossRef]
136. Carpinelli, G.; Caramia, P.; Mottola, F.; Proto, D. Exponential weighted method and a compromise programming method for multi-objective operation of plug-in vehicle aggregators in microgrids. *Electr. Power Energy Syst.* **2014**, *56*, 374–384. [CrossRef]
137. Sheng, W.; Liu, K.; Meng, X.; Ye, X.; Liu, Y. Research and practice on typical modes and optimal allocation method for PV-Wind-ES in Microgrid. *Electr. Power Syst. Res.* **2015**, *120*, 242–255. [CrossRef]
138. Prommee, W.; Ongsakul, W. Multi-objective optimal placement of protective devices on microgrid using improved binary multi-objective PSO. *Int. Trans. Electr. Energy Syst.* **2015**, *25*, 2621–2638. [CrossRef]
139. Shadmand, M.B.; Balog, R.S. Multi-Objective Optimization and Design of Photovoltaic-Wind Hybrid System for Community Smart DC Microgrid. *IEEE Trans. Smart Grid* **2014**, *5*, 2635–2643. [CrossRef]
140. Wu, H.; Zhuang, H.; Zhang, W.; Ding, M. Optimal allocation of microgrid considering economic dispatch based on hybrid weighted bilevel planning method and algorithm improvement. *Electr Power Energy Syst.* **2016**, *75*, 28–37. [CrossRef]
141. Perera, A.T.D.; Attalage, R.A.; Perera, K.K.C.K.; Dassanayake, V.P.C. A hybrid tool to combine multi-objective optimization and multi-criterion decision making in designing standalone hybrid energy systems. *Appl. Energy* **2013**, *107*, 412–425. [CrossRef]

142. Perera, A.T.D.; Attalage, R.A.; Perera, K.K.C.K.; Dassanayake, V.P.C. Designing standalone hybrid energy systems minimizing initial investment, life cycle cost and pollutant emission. *Appl. Energy* **2013**, *107*, 220–230. [CrossRef]
143. Ippolito, M.G.; Silvestre, M.L.D.; Sanseverino, E.R.; Zizzo, G.; Graditi, G. Multi-objective optimized management of electrical energy storage systems in an islanded network with renewable energy sources under different design scenarios. *Energy* **2014**, *64*, 648–662. [CrossRef]
144. Zhao, B.; Zhang, X.; Li, P.; Wang, K.; Xue, M.; Wang, C. Optimal sizing, operating strategy and operational experience of a stand-alone microgrid on Dongfushan Island. *Appl. Energy* **2014**, *113*, 1656–1666. [CrossRef]
145. Guo, L.; Liu, W.; Jiao, B.; Hong, B.; Wang, C. Multi-objective stochastic optimal planning method for stand-alone microgrid system. *IET Gener. Transm. Distrib.* **2014**, *8*, 1263–1273. [CrossRef]
146. Lopez, R.D.; Monreal, I.R.C.; Yusta, J.M. Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation. *Renew. Energy* **2016**, *94*, 280–293. [CrossRef]
147. Guo, L.; Wang, N.; Lu, H.; Li, X.; Wang, C. Multi-objective optimal planning of the stand-alone microgrid system based on different benefit subjects. *Energy* **2016**, *116*, 353–363. [CrossRef]
148. Vasiljevska, J.; Pecas, J.A.; Lopes, J.A.; Matos, M.A. Evaluating the impacts of the multi microgrid concept using multicriteria decision aid. *Electr. Power Syst. Res.* **2012**, *91*, 44–51. [CrossRef]
149. Zhang, L.; Gari, N.; Hmurcik, L.V. Energy management in a microgrid with distributed energy resources 2014. *Energy Convers. Manag.* **2014**, *78*, 297–305. [CrossRef]
150. Arefifar, S.A.; Mohamed, Y.A.R.I.; El-Fouly, T. Optimized Multiple Microgrid-Based Clustering of Active Distribution Systems Considering Communication and Control Requirements 2015. *IEEE Trans. Ind. Electron.* **2015**, *62*, 711–723. [CrossRef]
151. Belgana, A.; Rimal, B.P.; Maier, M. Open Energy Market Strategies in Microgrids: A Stackelberg Game Approach Based on a Hybrid Multiobjective Evolutionary Algorithm. *IEEE Trans. Smart Grid* **2015**, *6*, 1243–1252. [CrossRef]
152. Lv, T.; Ai, Q.; Zhao, Y. A bi-level multi-objective optimal operation of grid-connected microgrids. *Electr. Power Syst. Res.* **2016**, *131*, 60–70. [CrossRef]
153. Gong, J.; Xie, D.; Jiang, C.; Zhang, Y. Multiple Objective Compromised Method for Power Management in Virtual Power Plants. *Energies* **2011**, *4*, 700–716. [CrossRef]
154. Yang, H.; Yi, D.; Zhao, J.; Dong, Z.Y. Distributed Optimal Dispatch of Virtual Power Plant via Limited Communication. *IEEE Trans. Power Syst.* **2013**, *28*, 3511–3512. [CrossRef]
155. Papaefthymiou, S.V.; Papathanassiou, S.A. Optimum sizing of wind-pumped-storage hybrid power stations in island systems. *Renew. Energy* **2013**, *64*, 187–196. [CrossRef]
156. Dietrich, K.; Latorre, J.M.; Olmos, L.; Ramos, A. Modelling and assessing the impacts of self supply and market-revenue driven Virtual Power Plants. *Electr. Power Syst. Res.* **2015**, *119*, 462–470. [CrossRef]
157. Songli, F.; Qian, A.; Longjian, P. Fuzzy day-ahead scheduling of virtual power plant with optimal confidence level. *IET Gener. Transm. Distrib.* **2016**, *10*, 205–212.
158. Nosratabadi, S.M.; Hooshmand, R.A.; Gholipour, E.; Parastegari, M. A new simultaneous placement of distributed generation and demand response resources to determine virtual power plant. *Trans. Electr. Energy Syst.* **2016**, *26*, 1103–1120. [CrossRef]
159. Shahnia, F.; Wishart, M.T.; Ghosh, A.; Ledwich, G.; Zare, F. Smart demand side management of low-voltage distribution networks using multi-objective decision making. *IET Gener. Transm. Distrib.* **2012**, *6*, 986–1000. [CrossRef]
160. Hong, Y.Y.; Lin, J.K.; Wu, C.P.; Chuang, C.C. Multi-Objective Air-Conditioning Control Considering Fuzzy Parameters Using Immune Clonal Selection Programming 2012. *IEEE Trans. Smart Grid* **2012**, *3*, 1603–1610. [CrossRef]
161. Zhang, D.; Evangelisti, S.; Lettieri, P.; Papageorgiou, L.G. Economic and environmental scheduling of smart homes with microgrid: DER operation and electrical tasks. *Energy Convers. Manag.* **2016**, *110*, 113–124. [CrossRef]
162. Muralitharan, K.; Sakthivel, R.; Shi, Y. Multiobjective optimization technique for demand side management with load balancing approach in smart grid. *Neurocomputing* **2016**, *177*, 110–119. [CrossRef]
163. Hu, M.; Weir, J.D.; Wu, T. An augmented multi-objective particle swarm optimizer for building cluster operation decisions. *Appl. Soft Comput.* **2014**, *25*, 347–359. [CrossRef]

164. Safaei, A.; Freire, F.; Antunes, C.H. A life cycle multi-objective economic and environmental assessment of distributed generation in buildings. *Energy Convers. Manag.* **2015**, *97*, 420–427. [CrossRef]
165. Shaikh, P.H.; Nor, N.B.M.; Nallagownden, P.; Elamvazuthi, I.; Ibrahim, T. Intelligent multi-objective control and management for smart energy efficient buildings. *Electr. Power Energy Syst.* **2016**, *74*, 403–409. [CrossRef]
166. Mahbub, M.S.; Cozzini, M.; Ostergaard, P.A.; Alberti, F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. *Appl. Energy* **2016**, *164*, 140–151. [CrossRef]
167. Castillo, A.; ONeill, R.P. Computational Performance of Solution Techniques Applied to the ACOPF. 2013. Available online: http://www.ferc.gov/industries/electric/indus-act/market-planning/opf-papers/acopf-5-computational-testing.pdf (accessed on 27 December 2016).
168. Wang, J.J.; Jing, Y.Y.; Zhang, C.F.; Zhao, J.H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278. [CrossRef]
169. Kumar, K.; Sah, B.; Singh, A.R.; Deng, Y.; He, X.; Kumar, P.; Bansal, R.C. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renew. Sustain. Energy Rev.* **2017**, *69*, 596–609. [CrossRef]