Social Welfare Maximization in Smart Grid: Review

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Abstract. The modernized power grid system intelligently integrates various advanced Information and Communication Technologies (ICT’s) with various renewable energy sources. Moreover, recently huge developments are happening in renewable sources, with enhancement in technologies eras, the role of consumers is shifting towards producers so-called "prosumers". Furthermore, main challenges are enlarged energy demands, uncertainty in weather conditions and varied occupant’s behavioural interventions in energy consumption. So, residential user-end is having potential for energy optimization by energy efficiency, conservation, and active participation. Besides, the dynamic fair energy pricing with respect to generation cost and load demands is motivational parameters to users. On the same, this paper focuses on analysing a novel, attractive business model that can actively participate prosumers through dynamic pricing and incentive based demand response programs for the maximization of social welfare. Further this review paper focusses on various optimization models to achieve social welfare maximization. And also bibliometric analysis has been done through the Scopus database.

1. Introduction

The traditional electric grid faces diverse problems such as technical, socio-economical, and environmental. In present scenario, the main challenge like imbalance power supply, due to increase in demand may lead to power outages and blackouts. Moreover, the peak demand management factor is important to maintain grid stability and reliability. In addition to this, many times it requires more generations to fulfil the peak demand. But this extra generation enables us to increase the financial burden on-grid system as shown in Figure 1.

![Figure 1. Major Challenges in Electricity Grid](image)
Thus, there is a need to deal with Social Welfare Maximization (SWM) model, which is a win–win situation for energy provider companies, end-user and environment development. The implementation of SWM majorly depends on optimization in energy, resources and cost. In order to implement SWM model in the existing electricity grid, there is a dire need to upgrade itself with advanced Information and Communication Technologies (ICTs). For the optimization of energy, resources and cost the Renewable Energy Sources (RESs) has to be integrated with Energy Storage System (ESS). Moreover, SWM model also helps to improve the overall grid stability and reliability. So, electricity grid with SWM model is having more diverse aspects, complexity, and huge potential. Hence, all grid systems are going towards modernization, called as "Smart Grid" (SG). The major changes in transformation of existing electricity grid are shown in Figure1. There are four main challenges related to transforming the existing grid namely, regulatory and policy shifts, changing market demand, technology innovation and role of consumer as prosumer [1]. Furthermore, effective smart grid management is essential to obtain SWM model. Figure 2 shows the hierarchy of SG management. According to Figure 2, SG management is broadly divided into two groups one is Supply Side Management (SSM) and other is Demand Side Management (DSM).

![Figure 2. Hierarchy of SG Managements](image)

At the SSM, very little scope to do innovative changes for reducing the imbalance between demand and supply. SSM generally includes the major work like installations of new plants or units which is more time consuming and costly. But at the demand or load side, consumers having huge scope to adjust the load using different load strategies. The major load strategies are load shifting, load curtailments, peak cutting and valley filling and RES generation and storages [2]. So, under DSM, Demand Response (DR) programs are acting significant role to balance the effective demand-supply. In addition to this, reducing the peak with filling the valley is important objective of DSM as shown in Figure 2. The successful implementations of DSM completely depend on the utility's effective DR programs and consumer's active participation into it. Generally, pricing and incentive factors are more influencing for consumers. In DR programs, a variety of programs are offered. In addition to this, a dynamic pricing with proportional or fair pricing is more attractive in DR programs to consumers. The energy fair price rate is a true cost, which is directly linked with production cost and time-varying load demand market situations. Here is a scope to improve the efficiency of resources and energy for SWM [3].

Furthermore, data analytics and computational ability is required to improve the customer services and social welfare in the era of big data. Figure 3 shows the data-driven methodology of DR programs.
First step is to collect the data set as per objective and application. The deployments of Advanced Metering Infrastructure (AMI), Phasor Measurement Unit (PMU) and intelligent advanced technologies are used for monitoring, controlling and data collection purposes. Moreover, the deployed smart meters generate huge amount of data continuously in an average to every 15 minutes. This smart meter data shows the individual end-users energy consumption behaviour. Second step is to perform pre-processing and data visualization on collected data. The data visualization will give the Energy Consumption Curve (ECC) as a consumption pattern. In step three behavioural analysis of end-users using optimization models is performed. Based on the optimization model performance, in step four utility companies can develop the DR programs for effective demand side management. So, the DR programs-based data-driven approach using machine learning and deep learning models will improve the SG's overall efficiency with achieving the maximization of social welfare [3][4].

This paper includes a systematic literature review on data-driven based dynamic pricing schemes for residential end-users to get maximization of social welfare with bibliometric analysis.

1.1 Objectives of the review
There are two main objectives in this review paper. First is to cover the latest existing literature on SWM model in smart grid with critical evaluation and discussion. Second is to perform bibliometric analysis using Scopus database for finding the future directions.

1.2 Organization of paper
The organization of paper includes four sections. Section one is introduction with motivation of SWM. Second section discusses the review of literature on SWM models. Section three includes the Scopus database bibliometric analysis using keyword based search technique. At the end conclusion and discussion is covered under section four.

2. Review of Literature
2.1. Introduction
The smart grid is a broader research area in power grid system. Figure 4 shows the major research areas in a smart grid which includes Distributed Generation (DG), Integration of Renewable Energy Sources (RES) with main grid, Improving grid stability by implementations of heuristic algorithms, Smart Grid (SG) Communications, Power Quality, Demand Side Management (DSM), Cyber Security, Advance Metering Infrastructure (AMI), Restructuring of power System, Power System Isolation Mode (Micro-grid), Deregulation and Creating markets for betterment of grid infrastructure. From the above research areas DSM is considered in this paper. The main objective is to balance the power demand and supply by reducing the peak and filling the valley through active participations of consumers to get SWM. Moreover, the user's satisfaction, comfort ness, minimum energy cost, and fairness are the general properties of DSM algorithms. Under DSM, DR program is considered. The DR is a tool to enhance the
efficiency, reliability, and elasticity of the electricity system by the active participation of users. So, DR is a significant part of a smart grid.

As shown in Figure 4, DR programs are classified based on three parameters such as, control mechanism, offered motivations and decision variables. The first control mechanism DR program includes centralized programs and distributed programs. The second offered motivation consists of price-based and incentive-based DR programs. The third DR program is control variable, which includes task scheduling and energy management [4].

Different optimization methods for DR program in SWM have been disused. The object function considered is nonlinear in terms of the difference between the total profit of utilities minus the total energy price of generations and distribution-transmission networks. Moreover, the smart grid is having multiple and distributed generation sources like renewable energy resources. So additional uncertainties and constraint functions should be defined. Furthermore, various solutions have been proposed for SWM with different optimization methods, objective function, constraint function and design vector that are taken into consideration for problem formulation and for applied pricing scheme. The DR Program (DRP) based optimization methods for the SWM model includes partial Swarm Optimization (PSO), Convex Optimization Problem, Non-linear Programming, Mixed Discrete/Continuous Non-linear Programming, Mixed Integer Non-linear Programming, Game Theory, Markov Decision Problem and other remaining methods as shown in Figure 5 [4].
2.2 Analysis of Latest Work Done
Some of the key findings of DR program with SWM work done in the last few years are discussed in [4]. A new method of pricing scheme with benefits of ToU (Time of Use) and RTP schemes i.e. hybrid price-based demand response method proposed to achieve SWM. Then in Day-Ahead (DA) scheduling of a housing consumer micro-grid, with the uncertainty about decision variables and parameters are implemented. Technical and operational constraints of SWM for consumer and distribution network structure discussed. The effective forecasting generation quantity is based on consumer’s daily consumption profile and weather conditions. Results shows, decrease peak to valley index and coefficient of variation percentage with a raise in social welfare indicator, power sale at peak times, compared to other methods. The rebound effect phenomenon is considered. From results, it shows that if hour's load increases then it fails to give the fair rates [5]. Moreover, the author not included incentive programs to motivate the participants. There is no provision for consumer's privacy and data security. Moreover, centralized method will be impractical on increased number of consumers.

Incentive-based DR program has been proposed in [6]. The users’ decision of participation is analysed in a DA way. The quasi-convex cost function is used for forecasting the base-load price. Based on prices, the user shifts their load, and reduce their energy bills. Furthermore, the user’s energy price is calculated according to the users with a same consumption in a particular period using Game Theory (GT), Expected Utility Theory (EUT) and Prospect Theory (PT). Also formulated a social pricing/billing mechanism for the complete load of the system. No integration of RES, as sur-plus energy may put on the main grid and also use in peak load hour to reduce energy bill. The author [7] addressed the issue of Electric Vehicle’s (EV’s) online charging auction market through DR. The design part protects the privacy issue of seller and buyer of EV’s by using differential privacy-based auction scheme. This scheme includes two parts namely, Laplace based winner determination rule and an exponential-based allocation rule. The results show satisfaction not only for economic and privacy parameters but also to increase social welfare, satisfaction ratio, social efficiency and computational overhead.

The author [8] proposed a new SWM model which involved EV’s. The author initially addressed the optimization problem and then moved into mixed-integer linear programming model. The energy optimization in terms of cost, resources and greenhouse gas emissions by integrating the RES with main grid was discussed. The results were verified using Monte-Carlo Simulation (MCS) tool to check the robustness of proposed model.

2.3 Summary of Analysed Papers
The prosumer's active participation through incentive schemes in DRP is the key to succeed in the model. So, according to the literature, limitations, and scope of DSM in DRP for SWM, many kinds of literature lags to integrate the RES as a green-clean energy alternative source and ESS to maintain the grid stability and elasticity. Furthermore, without considering weather conditions it is difficult to build an effective
forecasting model. Along with this, the pricing should be calculated with respect to production cost by considering the time of demand so-called "fair pricing". Table 1 include the common research gaps in literature. This common gaps are the future directions in smart grid for developing robust SWM model using different optimization algorithms. The optimal approach in SWM model is to integrate the RES with main grid. The RES takes care of optimization of energy, resources, cost and green gas emissions.

Table 1. List of Common Gaps

| Sr. No. | Common Gaps |
|---------|-------------|
| 1       | The weather parameter in load forecasting and load management were missed in [9][10] |
| 2       | The integration of RES with main grid as distributed generations was lagging in [6][9][10] |
| 3       | The energy storage system, which helps to reduce the energy bill and improve the power reliability was not considered in [2][11] |
| 4       | The fair time-varying rates, which mainly includes generation cost and demand quantity was lagging in [5] |
| 5       | Pricing mechanism for all types of end-users was not used in [12] |
| 6       | The Rebound Effect phenomenon in RTP was lagging in [13] |
| 7       | The optimization of energy in cost, resources and CO\textsubscript{2} emissions were missed in [9] |
| 8       | Less considerations of Plug-in Hybrid Electric Vehicles (PHEV) infrastructures in micro-grid in [10] |
| 9       | The various uncertainty like change in loads, weather condition, end-user’s life style etc. was not considered in [10] |
| 10      | Simulated dataset were used and less studies on ground level problems using real dataset were followed in [2][3] |
| 11      | Machine learning and deep learning based models has not taken care of users data security and privacy issues in [3][4][5] |

2.4 Future Scope
The SWM model is the energy optimization model in smart grid. DR is a key element of smart grid which helps to implement the SWM model. Moreover, DR programs can be defined more specifically as modifications in energy practice by occupants from their ordinary utilization curve with respect to variations in energy cost over a time interval, or to encouragement or reward type payments designed to stimulate lesser energy utilize at higher wholesale market costs or when system reliability is in risk [11]. Wide future scope is briefed as follows:

1. Price reduction in occupant’s energy bill with the profit maximization of utility providers by reducing total generation cost [4].
2. Demand reduction through energy optimization and energy efficiency models to maximize the overall power system elasticity, reliability and stability [11].
3. To motivate end-users through incentives and activities to change their consumption habits [12].
4. To give fair dynamic rates which reflect the electricity value and cost at various time slots with improving resource-efficiency [11].
5. Design DR program scheme to participate and attract interest of prosumer (Producer + Consumer) [12].
6. Reduction of demand and total generation with integration of RES with main grid which enables the Energy Service Provider (ESP) to meet their pollution obligations [11].

3. Bibliometric Analysis
The bibliometric analysis is done from the open-source Scopus database. This structural statistical analysis helps to choose less saturated and emerging research area. The bibliometric study has the following main objectives:
• To study the evolution of work done.
• To enlist quality publications, journals, etc.
• To detects the most prolific authors, institutions, affiliations for future collaborative work.
• To study various funding agencies and their hot areas.
• To collect high impact factors, more cited papers from quality journals.
• To identify the change in the boundaries of the disciplines.

The Scopus database [13] was accessed on 24th October 2020 from the www.scopus.com website. Based on keywords as query total, 2874 results found, including open access and others. The detailed process and results are given in the next sub-section.

3.1 Methodology for Bibliometric study
Step I: Search query- "smart grid" or "social welfare maximization" or "SG" or "micro-grid" or "MG" and "Dynamic Pricing" or "RTP" or "real time pricing" or "time-varying pricing" or "Maximization for social welfare" or "Residential" or "Unified consumer" or "prosumers".
Step II: Result Analysis- The key word based search is used to enable the bibliometric analysis. Search query has resulted the following graphs shown in the Figure 6 to Figure 11.

Figure 6 is representing the documents search in recent 10 years and highest publication 395 which is achieved in year the year 2018. Similarly Figure 7 shows country or territory wise published documents, with highest documents 554 by United States, followed by china on second and India on third position. Publications are less in Australia and Canada compared to other countries.

Figure 6. Search Documents by Year

Figure 7. Top Ten Country with Document

Figure 8 represent the statistical analysis of documents published by author across the world using scatter plot. Highest publications of 81 documents has been done by author Javaid N. The highest published documents found under conference paper followed by article type documents as shown in Figure 9. The book and business article types are the least published documents.
A maximum of 98 documents were published by IEEE Transactions on Smart Grid journal of Institute of Electrical and Electronics Engineers Inc. publisher as shown in Figure 10. All ten journals are Scopus indexed in different quartiles. The Figure 11 shows the document search by affiliation with largest 96 affiliations is from COMSATS University Islamabad. The number of affiliations in publication indicates the research culture in the institute.

A total 2874 documents which belong to various subject’s and top ten subject are shown in Table 2. Among all documents engineering subject area is highest by 57% of documents and followed by computer science and energy. Moreover, smart grid belongs to multidisciplinary area having 20 documents. Table 3 is providing the top ten funding sponsor institutes analysis.

The National Natural Science Foundation of China has given highest funding up to 107 documents and National Science Foundation on second rank with 63 documents. It means that China is promoting more in smart grid research and development activities. The funding related documents shows the information on research domain for applying funding proposal. The objective and theme of each funding sponsoring institute of various countries are different.
4. Conclusion and Discussions

SG is an organized incorporation of sophisticated computerization technologies, electric grid, and ICT. Enabling technologies of SG progress synchronized monitoring, controlling and analysis of power systems. The SG allows the bi-directional flow of power and information among the utility and prosumers (producer + consumer). The efficiency, reliability, elasticity, and stability of the smart grid achieved using DSM with DRP as a key element. In incentive-based and price-based DRP, prosumers are actively involved in the smart grid system. So, it reduces various parameters like energy consumption, electricity bill and CO₂ emissions. All this possible due to various activities such as integrating RES with the main grid, participating in peak demand management for maximizing benefits of utility, task scheduling and real-time pricing (fair pricing) DRP at active end-user side.

In this paper, a review and bibliometric analysis using Scopus database done. A methodology on dynamic pricing schemes to prosumers or consumers to obtain social welfare maximization is discussed. This model will help to improve the power imbalance issues and maximization of social welfare through active participation of consumer which forms the main objective of this work. As a future scope data-driven model to maximize social welfare with energy data analytics and prediction model based on interdisciplinary approaches can be done.

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