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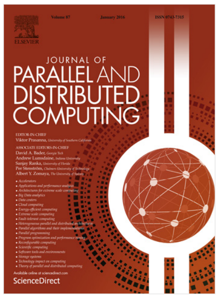

SDN-based energy management scheme for sustainability of data centers: An analysis on renewable energy sources and electric vehicles participation

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*Highlights (for review)

Following are the highlights of the paper.

1. Control plane learning scheme has been designed for energy management of cloud data centers.
2. an energy trading and reward point scheme is designed to attract the EVs to participate in the energy management at the data centers
3. The charging discharging strategy for electric vehicles participation has been designed to remove the intermittency issues of renewable energy sources.

SDN-based Energy Management Scheme for Sustainability of Data Centers: An Analysis on Renewable Energy Sources and Electric Vehicles Participation

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Abstract

Energy management is becoming one of the major issues from last many years due to an exponential increase in the smart devices users for accessing various services from the geo-distributed cloud data centers (DCs) using Internet. During this time, there is an emergence of new technology called as cloud computing which provides on-demand pay-per-use services such as storage, computation, and network to the end users. These services are provided to the end users by various geographically located DCs which are hosted by different service providers such as-Microsoft, Amazon, IBM etc. With an increase in dependence of end users, DCs have expanded both in size and number. With such an expansion, these DCs consume huge amount of energy to accomplish their routine tasks. Such an increase in energy consumption generates a lot of load on the power grid. Moreover, the carbon emissions from these DCs has a global impact on the environment. To mitigate these issues, the integration of DCs with renewable energy sources (RES) can be helpful to reduce the carbon emissions and to ease the load on the power grid. For this purpose, a SDN-based energy management scheme for sustainability of DCs is proposed using RES in this paper[1]. **To achieve the aforementioned objectives, an energy-efficient flow scheduling algorithm is proposed using SDN. Moreover, a charging-discharging scheme for**

[1]This paper is an extended version of paper entitled "SDN-Based Data Center Energy Management System Using RES and Electric Vehicles" presented in IEEE Global Communications Conference (GLOBECOM), 2016, 4-8 December 2016 at Washington D.C.

penetration of electric vehicles (EVs) is also presented to manage the intermittency of renewable energy. An energy trading and reward point scheme is designed to attract the EVs to participate in the proposed energy management scheme. The efficacy of the proposed scheme is proved using realistic weather traces. The results obtained clearly show the effectiveness of the proposed scheme for sustainability of DCs.

Keywords: Data centers, Electric vehicles, Energy management, Renewable energy, Sustainability.

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1. Introduction

Cloud computing (CC) has emerged as one of the most powerful technologies from past few years in which end users access various services from the service providers as per the their demands on pay per basis concept. In CC using virtualization, multiple slices of virtualized resources are created over physical servers [1]. Such a virtualized environment and resources are hosted at large geo-distributed, service-oriented, and critical computing infrastructure known as data centers (DCs). The increasing demand of data-oriented computing, storage, and processing has made way for creation of massive DCs. Over 12 million servers are installed in nearly 3 million DCs to manage the on-line activities such as email, social media, and e-commerce across US only [2]. Moreover, with an exponential growth of 566%, every second 2.5 billion people are on-line all over the world including 70% Internet users. Nearly, 204 million email messages are exchanged, 5 million Google searches are made, 1.8 million users make likes on Facebook, 350,000 tweets are made, $ 272,000 amount is spent on Amazon for purchases, 15,000 tracks are downloaded through i-tunes on daily basis [2]. DCs act as backbone to handle all such on-line activities. For this reason, DCs have emerged as crucial promoter for growing IT sector with a global market size of $ 152 billion by 2016 [3]. The rapid growth in users demand for more data and high-bandwidth resources is fueling the surge for drastic expansion of DCs.

However, there is an operational cost associated to serve such a large number of requests from different geographically separated DCs. Among various factors contributing to the operational cost of these DCs, energy is one of the major concerns for management of routine activities of DCs. With an increase in size of DCs, their energy consumption has increased drastically which results in a overall high operational cost. For example, a typical server room in single DC consume energy equivalent to energy required to power 180 thousand homes. According to New York times (2012), DCs consumed energy equal to generation of 30 nuclear plants [4]. According to National resources defense council (2013), DCs consumed nearly 91 billion kWh of energy in US only. Moreover, the energy consumption of US DCs is projected at a growth of 53%, i.e., 140 billion kWh till 2020 which is equal to $13 billion annually. The aforementioned facts reveal that it requires 34 power plants capable of generating 500 MW of energy to power DCs in US only. According to the forecasting [2], by 2020, US will need 17 more power plants to meet the energy demand of DCs. The use of fossil fuels to power such a huge demand of DCs results in an increase in carbon emissions. Moreover, 97 million MT of harmful emissions were released in 2013 and are projected to reach 147 million MT by 2020 [2]. For this reason, DCs are projected as the biggest contributors to carbon footprints. However, with projection of renewable energy sources (RES), the annual growth rate of CO_2 emissions has significantly dropped globally. Hence, RES can be adopted as an alternative for traditional energy sources to power DCs. Such an alternative could not only minimize the carbon emissions but also ease the load of power grid. However, the intermittent nature of RES is one of the biggest challenges for sustaining the energy consumption of DCs [5]. Hence to overcome such a challenge, novel mechanism for participation of both RES and EVs is required for DCs sustainability.

1.1. Motivation

After analyzing the above facts, it is clear that energy demand of DCs will increase drastically in the coming years. Hence, to meet such a huge demand, the energy generation sector has to expand many folds. This expansion will lead to development of more power plants which are already biggest contributors toward carbon emissions. On the other hand, RES could be an attractive alternative for DCs sustainability. Also, the conflux of DCs with RES may reduce the additional load on grid and carbon emissions. However, the intermittent nature is a challenge towards suatianabilty of energy consumption of DCs using RES. However, with an increase in popularity of EVs in recent times, by using the charging-discharging capabilities of these EVs, we can mitigate the intermittent nature of renewable energy. With such a conflux of DCs with RES and EVs, the flexibility and scalability of underlying networks need to be managed effectively. Hence, to reduce the complexity of underlying network, a SDN-based architecture can be a viable option to design an effective solution for sustainability of communication-sensitive DCs.

1.2. Organization

The rest of this paper is organized as follows. Section 2 describes the literature review. System model is illustrated in Section 3. In Section 4, the problem is formulated. Section 5, the proposed scheme for energy management using SDN is presented. In Section 6, the proposed reward point scheme and energy trading scheme is presented. In Section 7, the performance evaluation of the proposed scheme is presented. Finally, Section 8 provides the conclusion.

2. Literature Review

Many existing research proposals have explored energy management of DCs with respect to issues such as-cost minimization, energy-efficiency, and uncertainty of demand. For example, Qiu *et al.* [6] proposed a cost minimization scheme based on dynamic migration of user requests among geo-distributed DCs. Li *et al.* [7] proposed an electricity demand management scheme for price-sensitive batch computing workload with an aim of energy cost minimization. Rao *et al.* [8] focused on minimization of risk due to uncertainty in deregulated energy markets while maintaining performance of DCs. Tran *et al.* [9] proposed a Stackelberg game for demand response management between DCs and grid. The proposed scheme uses dynamic server allocation and workload shifting among DCs with an aim to minimize the operational cost. Polverini *et al.* [10] proposed a thermal-aware scheduling of batch jobs in geo-distributed DCs for energy cost minimization. Further, Buyya *et al.* [11] defined an energy minimization scheme by continuous consolidation of virtual machines (VMs) with respect to the current utilization of resources. In a related work, Dai *et al.* [12] designed fast algorithms to place an energy-efficient virtual clusters, into VMs with a focus on providing energy-efficient Quality of Service (QoS). Wang *et al.* [13] proposed an optimization scheme for minimization of energy along with QoS guarantee for data-intensive services. All the above discussed proposals focused on energy/cost minimization by optimal scheduling of workload among geo-distributed DCs with respect to dynamic pricing offered by smart grid.

2.1. Participation of RES for Energy Management of DCs

However, none of the above proposals have focused on integration of RES with DCs for minimizing the carbon emissions to ease the load on power grid. Some of the research proposals have utilized RES to manage the energy consumption of DCs to some extent. In this context, Yu *et al.* [14] designed an optimization technique for energy management system to deal with power outages using RES, backup generators, and battery management. Paul *et al.* [15] proposed a scheme for demand response using energy-efficient resource scheduling with integration of RES. In a similar work, Bose *et al.* [16] also proposed an energy-efficiency scheme for load distribution and energy price control using RES. Chen *et al.* [17] proposed a scheme for operational cost minimization in DCs using renewables. In this direction, Kaewpuang *et al.* [18] proposed a cooperative game to minimize operational cost of DCs using fair allocation scheme for VM management using RES. Wang *et al.* [19] formulated an energy-efficient game-theoretic scheme between cloud and DC controllers using dynamic pricing of SG with integration of renewables. In an another work, Erol-Kantarci and Mouftah [20] suggested that utilization of RES to power DCs could be an effective solution to cost minimization of DCs while reducing harmful carbon emissions.

All the above discussed research proposals utilized RES as an additional source of energy for DCs. However, these proposals have not focused on sustainability of DCs using RES. Aforementioned proposals have used utility grid as a major source of energy to power DCs. The intermittent and variable nature of renewable energy poses a challenge to manage the energy consumption of DCs. In this direction, Guo *et al.* [21] proposed an energy and network aware workload management scheme for sustainable DCs using thermal storage. The authors targeted the opportunities offered by the geographical load balancing and opportunistic scheduling of delay-tolerant workloads using thermal storage to manage the intermittency of RES. In a similar work, Chen *et al.* [22] proposed a workload and energy management scheme for sustainability of DCs. The authors highlighted the need of energy efficient and sustainable DCs to tackle the growing energy demand of the massive data processing infrastructure. The authors presented a framework for integration of RES, distributed storage units, and colling facilities in DCs. They presented an optimization problem for resource allocation to manage with the intermittency of RES. In an another work, Aujla *et al.* [23] presented a Stakelberg game for energy-aware workload scheduling scheme for sustainability of DCs using RES.

2.2. Participation of EVs for Energy Management

However, none of the existing proposals have utilized the charging and discharging capability of EVs to manage the intermittency of RES for sustainability of DCs. Various existing research proposals presented the penetration of EVs to tackle the intermittency of RES. In this context, Milano and Hersent [24] proposed an optimal load management scheme for grid using EVs. Kaur *et al.* [25] utilized fleet of EVs for frequency support through a load management scheme using an aggregator. Druitt *et al.* [26] proposed a flexible demand management model to cope with the variability of wind power. In another work, Freire *et al.* [27] proposed a scheme for load balancing of grid using RES and EVs. Further, Saber *et al.* [28] presented a scheme for maximum utilization of EVs and RES for cost and emission reductions. The authors suggested that the penetration of EVs to tackle the intermittency of RES could be attractive and economical. Hence, after analyzing the aforementioned research proposals, it is evident that EVs could be utilized to manage the intermittent nature of RES effectively. Such an integration would be environment friendly and cost effective solution to manage the load of DCs.

2.3. Evolution of SDN

With an integration of RES and EVs with DCs, a huge amount of load on the network would be generated due to numerous requests flow across different DCs. For this purpose, there is a requirement of an effective, programmatically configured, scalable, flexible, and adaptable underlying network backbone. In this context, an emerging architecture such as software-defined networks (SDN) can make network management as energy-efficient and effective. In SDN, the underlying internal infrastructure is abstracted from the applications and network control functions. The OpenFlow (OF) [29] protocol used in SDN for designing solutions is directly programmable and centrally managed. Moreover, SDN is agile, programmatically configured, open standards based, and vendor neutral, which makes it best suited to address the challenges faced by DCs. Such a platform not only improves the network performance, but it can also manage the network load efficiently. **Table 1 shows the charactersistics of traditional network and SDN [30, 31]. In SDN-based systems, the control flow management can be programmed according to the user's requirements. But, in traditional networks, the control flow is fixed and cannot be programmed. Due to this reason, unutilized switches and links consume huge amount**

of energy. But, energy consumption of such networks can be minimized by managing the control flow.

Table 1: Traditional Networks vs SDN-based Networks

Parameters	**SDN**	**Traditional Networks**
Methodology	Centralized protocol	Dedicated protocol for each problem
Configuration	Automated and programmable	Manual and error-prone
Control	Cross layer and dynamic	Single layer and static
Implementation	Software-based environment	Hardware-based environment
Architecture	Decoupled layers (Data, control, and application)	Coupled layers
Extensibility	Open to new innovations due to software-based implementation	Limited implementation of new innovations due to hardware limitations
Forwarding	Flow-based	Routing table based
Control flow	Programmable and reconfigurable	Uses traditional protocols
Hardware	Vendor independent	Vendor dependent
Virtualization	Network and server	Not available
Network segmentation	Easy	Complicated
Data flow	Multiple paths for same flow	Fixed path

In this direction, various existing proposals have highlighted the benefits of SDN with respect to DCs. For example, Tu *et al.* [32] highlighted that SDN-controlled scheme is quite effective for communication-sensitive DCs. Further, Truncer *et al.* [33] suggested that SDN can handle heterogeneous applications, equipments and controls effectively. In a recent work, Aujla *et al.* [34] proposed an SDN-based energy management scheme for renewable-powered DCs with participation of EVs. Xu *et al.* [35] highlighted the importance of SDN for implementation of various network services such as, routing, flow management, QoS, bandwidth management in context of designing more deterministic, scalable, and energy-efficient DCs. Moreover, Vishwanath *et al.* [36] highlighted the fact that network devices and efficient network has a huge impact on energy consumption of DCs. Hence, energy-aware flow scheduling and routing with SDN in DC networks could minimize the energy consumption and control the communication-sensitive conflux of RES and EVs. Hence, SDN could be an attractive platform towards designing sustainable DCs using RES and EVs.

2.4. Comparison with Existing Proposals

After analysis of various existing techniques, a comparative analysis of proposed scheme with respect to different evaluation criterias and parameters is presented in Table 2.

Table 2: Comparison with Existing Proposals

Existing techniques	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Qiu *et al.* [6]	✓	✓	×	×	✓	×	×	×	×	×	×	×
Li *et al.* [7]	✓	✓	✓	×	✓	×	×	✓	×	×	×	×
Tran *et al.* [9]	✓	✓	×	×	✓	×	×	✓	✓	×	×	×
Polverini *et al.* [10]	✓	✓	×	✓	✓	×	×	✓	×	×	×	×
Paul *et al.* [15]	×	×	✓	✓	✓	×	×	✓	×	✓	×	×
Chen *et al.* [17]	×	×	✓	✓	✓	×	×	×	×	×	×	×
Kaewpuang *et al.* [18]	✓	✓	✓	✓	✓	×	×	✓	×	✓	×	×
Wang *et al.* [19]	✓	✓	✓	×	✓	×	×	✓	✓	✓	×	×
Guo *et al.* [21]	✓	×	×	×	×	×	×	×	×	✓	✓	×
Chen *et al.* [22]	✓	×	×	×	×	×	×	×	×	✓	✓	×
Aujla *et al.* [23]	×	✓	×	×	✓	✓	×	×	×	✓	✓	✓
Aujla *et al.* [34]	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	×
Xu *et al.* [35]	×	×	✓	✓	✓	✓	✓	×	×	×	×	×
Proposed scheme	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note- 1: Geo-distributed DCs, 2: Heterogeneous servers, 3: Energy efficiency, 4: Resource utilization, 5: Cost savings, 6: SDN, 7:Flow scheduling algorithm, 8: SG Dynamic pricing, 9: Stackelberg game, 10: RES, 11: Sustainability, 12: EV participation

Notations-✓: considered, and ×: not-considered

2.5. Contributions

Based upon the above discussion, the major contributions of this work are as given below.

- An SDN-based energy management scheme is designed to sustain the energy consumption of DCs using renewable energy. For this purpose, an energy-aware flow scheduling scheme is designed for SDN controller.
- An efficient charging-discharging control scheme is proposed to manage the intermittent nature of renewable energy using EVs. In this context, a reward point mechanism is formulated to attract the participation of EVs for charging-discharging at DC.
- A single-leader multi-follower Stackelberg game is proposed for energy trading between EVs and charging station (CS) located at DC. Moreover, an energy trading scheme between grid and DC is also presented.

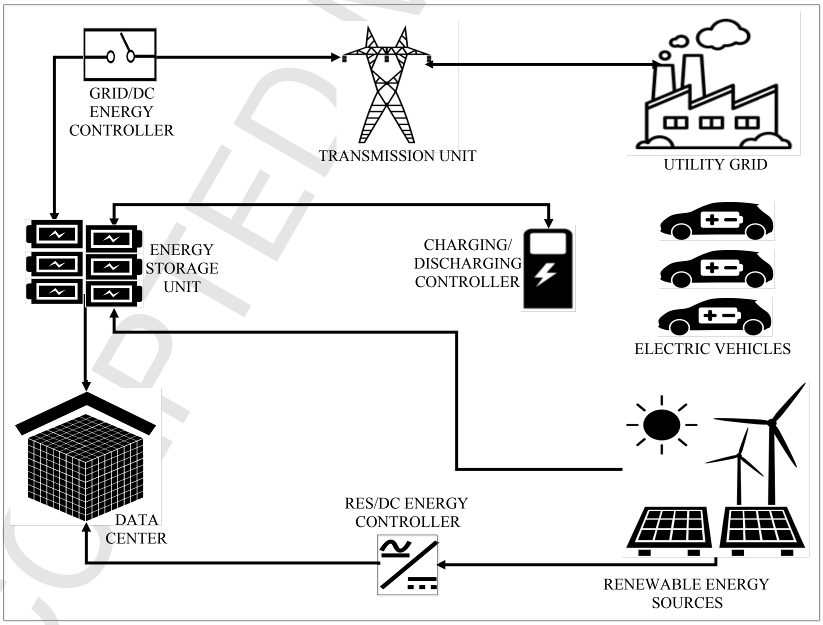


Figure 1: System model for proposed scheme

3. System Model

Fig. 1 shows the system model of the proposed scheme comprising of a typical DC connected to an energy storage unit (ESU) and three different sources of energy (RES, EVs, and utility grid). A typical DC consist of servers, memory, storage, and network devices which are utilized to accomplish the routine jobs based on end user requests. The DC consumes large amount of energy while accomplishing these routine jobs based on end user requests. Traditionally, a DC is connected to utility grid to meet its energy demand. However, in proposed scheme, the DC is connected to three sources of energy to manage its power demand. The three energy sources and ESU that are connected to DC are discussed in the subsequent sub-sections.

3.1. Renewable energy sources

The primary source of energy considered in the proposed work is RES which consist of solar and wind energy. **Solar and wind energy are one of the most popular RES which could be deployed in-house for energy management. However, the proposed scheme for energy management of DCs is extensible to other RES also.** The energy generated (E_{dc}^{ren}) by RES is utilized by DC directly. However, when the energy generation by RES is higher than the consumption of DC then it is stored in energy storage unit (ESU) connected to DC. The energy generated (E_{dc}^{ren}) by RES is given as below.

$$E_{dc}^{ren} = E_{dc}^{pv} + E_{dc}^{wn} \tag{1}$$

where, E_{dc}^{pv} is the energy generated by PV panels and E_{dc}^{wn} is the energy generated by wind turbines.

The two most popular RES that are used in the proposed work are discussed as below.

3.1.1. Solar energy

The most popular alternative for traditional non-renewable energy sources is Solar energy. The photovoltaics (PV) panels are used to capture radiant heat and convert it into solar energy. However, solar energy generated by PV panels is variable and depends on various factors such as solar radiations (ɽ), conversion efficiency of panel (η), radiation angle of Sunlight ($cos\ \alpha$), size of panel (S_{dc}^{pv}), and temperature exedence loss (L_{pv}^{temp}). The ratio of energy received from solar radiations and amount of energy generated is known as conversion efficiency. The radiant angle of solar radiations on PV panel depends on the angular deviation (α) of sunlight. The temperature exedence loss occurs due to cold weather. The energy (E_{dc}^{pv}) generated by capturing Sunlight using PV panels is given as below [37].

$$E_{dc}^{pv} = \left(1 - L_{pv}^{temp}\right)\ \eta\ S_{dc}^{pv}\ cos(\alpha)\ \varsigma \tag{2}$$

3.1.2. Wind energy

Apart from solar energy, wind is one of the widely used renewable source of energy which use wind turbines to generate wind energy. The energy (E_{dc}^{wn}) generated by a typical wind turbine is given as below [38].

$$E_{dc}^{wn} = \frac{1}{2}\ \left[\text{Ç}\ \rho\ \hat{a}\ \nu^3\right]\ L_{wn}^{temp} \tag{3}$$

where, Ç is the rotar efficiency, ρ is the air density, $\hat{a}$ is the area swept by rotar blades, ν is the wind speed, and L_{pv}^{temp} is the temperature exedence loss.

3.2. Electric Vehicles

The secondary source of energy are i EVs which can charge/discharge the energy through a CS located at DC. This CS also act as charging/discharging controller to manage the inflow/outflow of energy to/from EVs. The energy stored in i^{th} EVs battery is given as below.

$$E_i^{avl} = V\ E_i^{rat}\ SoC_i^{inl} \tag{4}$$

where, V is the voltage, E_i^{rat} is the rated capacity of i^th EVs battery, and SoC_i^{inl} is the initial state of charge (SoC) of i^th EVs battery.

The energy available (E_{dc}^{ev}) with all the EVs connected to DC is given as below.

$$E_{dc}^{ev} = \sum_{i=0}^{n} \left(V\ E_i^{rat}\ SoC_i^{prs}\right) \tag{5}$$

3.3. Utility grid

The utility grid acts as last energy source and is connected to DC with a switch managed by a controller. The supply of energy from grid to DC is switched ON by the controller when there is deficit in energy supply from RES and EVs. The energy is supplied from DC to grid when it has excess energy supply from RES and EV which cannot be stored in ESU. The DC and grid trade for the energy with respect to excess and deficit of energy at DC. The DC supplies excess energy to grid and in turn gets back the energy whenever it requires from grid. The utility grid collects the excess energy from DC to ease the load of its traditional customers. However, it have to return back the amount of energy it has been supplied along with an advance credit of energy if required by DC. Such an advance energy received from grid is supplied back to it when DC has excess of energy available with it. The energy (E_{dc}^{grid}) available at utility grid that can be drawn to power the DC is given as below.

$$E_{dc}^{grid} = E_{dc}^{drawn} - E_{dc}^{sup} \tag{6}$$

where, E_{dc}^{drawn} is the energy drawn from DC and E_{dc}^{sup} is the energy supplied to DC.

3.4. Energy storage unit

The RES are intermittent in nature due to variability of sunshine in a day and wind speed [5]. Hence, at some period of time, the energy generated by RES may not meet the energy consumption of DC. However, at other period of time, the energy generated by RES could be excess with respect to energy demand of DC. Hence at such times the excess energy is stored in ESU connected to DC. Hence, to effectively map the excess/deficit of energy generated by RES with energy demand of DC, an RES/DC energy controller is used. Further, there may be a situation when the energy demand of DC is not meet by energy stored in ESU also. To deal with such situation, energy stored in batteries of EVs is utilized by DC. In such case, the charging/discharging of energy from/to EVs in ESU is controlled by a charging/discharging controller located at CS. Finally, if the energy generated by RES and energy charged from EVs is excess with respect to energy demand of DC and storage capacity of ESU, then the excess energy could be supplied to utility grid from ESU. Fo this purpose a DC/grid energy controller is used. To manage all the above mentioned situation of excess and deficit of energy from various sources and to control the inflow/outflow of energy from/to various sources, an ESU has an important role to play. Further, due to real-time execution of various jobs at DC, the continuous power connectivity is essential.

ESU consists of various batteries which can be modeled similar to [39]. The advantages and disadvantages of energy storage techniques are given below in Table 3 [40].

Table 3: Advantages and disadvantages of energy storage techniques

Advantages	
Utility viewpoint	• *Time-Shifting:* Energy storage can be used to reduce the generation cost by storing energy at off-peak times and utilize the same energy at peak times to stabilize energy price. • *Power Quality:* Energy storage techniques can be adopted to improve the quality of power by maintaining the power voltage and frequency within tolerance. This can be achieved by deploying energy storage units at the end of highly loaded lines to improve the voltage drops. • *Efficient use of network:* Large-scale batteries can be deployed at appropriate substations to mitigate the congestion in network due to high power demand. • *Isolated grids:* Within an isolated power network (for example, island, DCs, etc), the energy generated by renewable energy sources or generators, that is used to meet the power demand can be stabilized using energy storage. • *Emergency power supply:* To provide reliable power supply in emergency conditions, use of energy storage can be beneficial.
Consumer viewpoint	• *Cost saving:* Energy storage can be beneficial to save costs by storing energy at off-peak times and utilizing the same energy at peak times. • *Electric Vehicles:* EVs are expected to be utilized to power in-house and small industries in combination with solar energy and fuel cells. • *Emergency power supply:* To provide reliable power supply to consumer appliances that need continuous supply, in emergency conditions use of energy storage can be beneficial.
Renewable energy generators viewpoint	• *Time shifting:* When RES generate excess energy, the poor may be shifted to energy storage units to effectively utilize at later time in energy deficit. • *Connection to grid:* EVs are expected to be utilized to power in-house and small industries in combination with solar energy and fuel cells.
Disadvantages	
General viewpoint	• One of the major disadvantages is the self-discharge rate of batteries which may vary with respect to different composition of batteries. • Battery container temperature exedence loss due to cold weather. • Battery degradation is dependent on to number of cycles (use).

The classification of various types of energy storage systems is shown in Table 4 as below [40, 41].

Table 4: Classification of various energy storage systems

Energy storage systems	
Mechanical	• *Pumped hydroelectric storage:* – Advantages: Involved in energy management in the fields of time shifting, frequency control, supply reserve, etc. – Disadvantages: Long construction time and high capital investment. • *Compressed air energy storage:* – Advantages: Beneficial in load shifting, peak shaving, frequency/voltage control, and renewable energy applications. – Disadvantages: Low round trip efficiency and investment cost depends on geographical location. • *Flywheel energy storage:* – Advantages: High cycle efficiency and power density, no depth-of-discharge effects, and easy maintenance. – Disadvantages: Idling loss during time when flywheel is on standby, ie., high discharge rate, upto 20%.
Electrochemical	• *Battery energy storage (Lead acid, NiCd, NiMh, Nas):* – Advantages: Short construction period, flexibly, in-house deployment. – Disadvantages: Low cycling time, and high maintenance costs. • *Flow battery energy storage (Redox flow, Hybrid flow):* – Advantages: Power is independent of storage capacity, low self-discharge rate – Disadvantages: High manufacturing costs, non-uniform pressure drops, highly complicated system requirement.
Chemical	• *Hydrogen (Electrolyser, Fuel cell, SNG):* – Advantages: Quieter, lower pollution, high efficiency and scalability – Disadvantages: Cost reduction and durability verification required for deployment in large-scale applications
Electrical	• *Double-layer capacitor:* – Advantages: High power density & response time, high cycle efficiency. – Disadvantages: High capital cost, high self-discharge rate, and negative environment impact. • *Superconducting magnetic coil:* – Advantages: High power density and shorter charging time. – Disadvantages: Limited capacity, low energy density, and high self-discharge rate.
Thermal storage	• *Sensible heat storage:* – Advantages: Low self-discharge rate & capital cost, high storage density. – Disadvantages: Low cycle efficiency.

The energy stored in the ESU depends on the terminal voltage (V_t), and capacity (E_{bat}) of the battery,

$$E_{cap}^{esu} = V_t E_{bat} SoC_{ch} \tag{7}$$

where. E_{cap}^{esu} is the energy stored in the battery of ESU, and SoC_{ch} is the SoC required for charging of a battery.

The energy stored in the battery is dependent on the number of cycles used. As the number of cycles increases, the energy capacity of battery decreases. So, the efficiency of the battery (δ) depends on the battery cycles and is given as below [39].

$$\delta = d \times \frac{N_t - N_c}{N_t} \tag{8}$$

where, N_c is the number of full cycles, N_t depict the life cycle of a battery, and d is the constant parameter for battery degradation.

However, a self-discharge loss which is almost 1-5 % per hour occurs at ESU [42]. So, the energy stored (E_{dc}^{esu}) in ESU at any instant is given as below.

$$E_{dc}^{esu}(t) = \left(E_{dc}^{esu}(t-1) + E_{dc}^{ren} \mp E_{dc}^{ev} - E_{dc}^{cons}\right) L_{dc}^{esu} \tag{9}$$

where, L_{dc}^{esu} is the self-discharge rate of ESU and E_{dc}^{cons} is the energy consumed by DC from ESU.

4. Problem Formulation

A typical DC consisting of k servers consumes some energy (E_{dc}) to accomplish its routine job execution. The energy consumption of DC depends directly on the amount of utilization of servers. The energy consumed (E_{dc}^k) by k^{th} server of a DC is given below [17].

$$E_{dc}^k = E_{idl}^k + (E_{mx}^k - E_{idl}^k)\, U_{dc}^k \tag{10}$$

where, E_{idl}^k , E_{mx}^k, U_{dc}^k denotes the energy consumed by k^{th} idle server of DC, maximum energy consumed by k^{th} server of DC, and utilization level of k^{th} server of DC, respectively.

The utilization level of k^{th} server of a DC is given as below.

$$U_{dc}^k = \left(\frac{R_t^k}{R_{mx}^k}\right) \times 100 \tag{11}$$

where, R_t^k is the status of resource utilization at time t and R_{mx}^k is the capacity of resources at k^{th} server of DC.

Apart from servers, the second most energy consuming infrastructure based on computing are network devices. The network devices consisting of switch and ports consume energy with respect to the traffic load. However, the network devices consumes energy in two parts, i.e., fixed part (energy consumed by working switch components such as fan, chassis, and switching fabric) and dynamic part (energy consumed by working ports). The total energy consumption of network devices in a DC is given as below.

$$E_{dc}^n = E_{sw}^n + E_{port}^n \tag{12}$$

where, E_{sw}^n, and E_{port}^n is the energy consumed by network switches and ports, respectively in a DC.

The energy consumed by the network infrastructure in a DC depends upon the working time of the network devices.

$$E_{dc}^n = \sum_{q \in S} P_q \times T_q + \sum_{r \in Pq} P_r^q \times T_r^q \tag{13}$$

where, S and P_q are set of switches and set of ports in switch q, respectively. P_q, T_q, P_r^q, and T_r^q is the fixed power consumed by q^{th} switch, working time of q^{th} switch, dynamic power consumed by r^{th} port of q^{th} switch, and working time of r^{th} port of q^{th} switch.

The energy consumption in a typical DC depends on servers, cooling, and various other activities. The overall energy consumption of typical DC is given as below.

$$E_{dc} = \sum_{k} E_{dc}^k + E_{dc}^n + E_{dc}^c + E_{dc}^o \tag{14}$$

where, E_{dc}^c, E_{dc}^c, and E_{dc}^o is the energy consumed by network devices, cooling infrastructure and other activities, respectively in a DC.

A typical DC draws energy from grid to which it is connected. But, the proposed work aims to draw energy form RES (solar and wind) to power a DC. However, the intermittent nature of RES pose a serious threat to achieve this objective. Hence, to manage the intermittency of RES and make DCs environment friendly, EVs are used. In this context, the energy consumption of a DC using RES and bi-directional EVs is given as below.

$$E_{dc} = E_{dc}^{ren} \pm E_{dc}^{ev} \tag{15}$$

Hence, after equating Eq. 14 and 15, we get following scenario.

$$\sum_{k} E_{dc}^{k} + E_{dc}^{n} + E_{dc}^{c} + E_{dc}^{o} = E_{dc}^{ren} \pm E_{dc}^{ev} \tag{16}$$

After analyzing above aspects two different cases arise in context of energy consumption of DCs.
Case 1: If $E_{dc}^{ren} > E_{dc}$, then the excess energy (E_{ex}) generated by RES is stored in ESU for future use and is given as below.

$$E_{ex} = E_{dc}^{ren} - E_{dc} \tag{17}$$

However, if $E_{ex} > E_{mx}^{esu}$, then the excess energy is supplied to EVs for charging and is given as below.

$$E_{sup}^{ev} = E_{ex} - E_{mx}^{esu} \tag{18}$$

where, E_{mx}^{esu} is the maximum storage capacity of ESU.

The EVs have to pay a price (P_{dc}^{ev}) to charge for the energy. For this purpose, the DC have to fix an optimal price to attract EVs to charge from DC rather than any other CS. Further, if there are no EVs to charge the excess energy of their is still some energy available after all EVs charge, then the excess energy is supplied to grid and is given as below.

$$E_{dc}^{drawn} = E_{ex} - E_{mx}^{esu} - E_{sup}^{ev} \tag{19}$$

The DC will charge a price (P_{dc}^{grid}) to supply the excess amount of energy to grid.
Case 2: If $E_{dc}^{ren} < E_{dc}$, then the required energy (E_{req}) is drawn from ESU and EVs. The required energy is given as below.

$$E_{req} = E_{dc} - E_{dc}^{ren} \tag{20}$$

After drawing energy from ESU, if energy is still required by DC then it is drawn from EVs. The energy drawn from EVs is stored in ESU and is supplied to DC to fulfill the energy deficit of DC. The required energy is given as below.

$$E_{req}^{ev} = E_{dc} - E_{dc}^{ren} - E_{dc}^{esu} \tag{21}$$

The EVs supply the energy required to DC in proportion to some price (P_{ev}^{dc}) or reward point (RP_{ev}^{dc}) benefits. However, at some instant, the energy required may not be available with EVs. Hence, in such case, an energy deficit (E_{def}) is drawn from grid to which DC is connected and is given as below.

$$E_{def} = E^{ev}_{req} - E^{ev}_{drw} \tag{22}$$

where, E^{ev}_{drw} is the energy drawn from EVs to ESU for powering DC.

Case 3: If $E^{ren}_{dc} = E_{dc}$, then the required energy (E_{req}) is sustained by the energy available with RES (E^{ren}_{dc}). In this case, neither deficit nor excess of energy exists. So, this case is considered as an expected sustainable case.

Hence, using the aforementioned aspects, the objective function of the proposed scheme for sustainability of DCs using RES and EVs for each time instant t is illustrated as below.

$$E_{obj} = min\left(E_{dc}(t) - E^{ren}_{dc}(t) \mp E^{ev}_{dc}\right) : \forall t \tag{23}$$

subject to following constraints

$$E^{ren}_{dc}(t) > 0 : \forall t \tag{24}$$

$$E_{dc} \; > \; 0 : \forall t \tag{25}$$

$$E^{ev}_{dc}(t) > 0 : \forall t \tag{26}$$

$$0 < E^{ren}_{dc}(t) < E^{rren}_{dc}(t) : \forall t \tag{27}$$

$$0 < E^{avl}_{i}(t) < E^{rated}_{i}(t) : \forall i, t \tag{28}$$

$$E^{esu}_{mn}(t) < E^{esu}(t) < E^{esu}_{mx}(t) : \forall t \tag{29}$$

$$P^{ev}_{dc}(t) > P^{dc}_{ev}(t) : \forall t \tag{30}$$

where, E^{rren}_{dc} is the rated power of RES, E^{esu}_{mn} is minimum capacity of ESU, **P^{ev}_{dc} is the price charged by DC to supply energy to EVs, and P^{dc}_{ev} is the price charged by EVs to supply energy to DC.**

In the next Section, the proposed scheme for sustainability of DC is illustrated along with all its components.

5. Proposed Scheme

In this paper, a SDN-based renewable energy and network aware framework for for sustainability of DCs using RES and EVs is proposed. The proposed scheme is divided into various sub-systems which are elaborated in the subsequent sub-sections.

5.1. SDN-based Control Framework

In the proposed SDN-based control framework, the underlying infrastructure and the network control services are separated using various planes such as, data plane, control plane, and application plane. The proposed SDN-based framework is shown in Fig. 2. All the communication infrastructure in the proposed framework is SDN-enabled using Open flow protocol [43]. The underlying network devices follow the proposed control algorithm to automatically configure itself as per various situations. For better insight of the proposed scheme, three planes of the proposed SDN-based scheme are described as below.

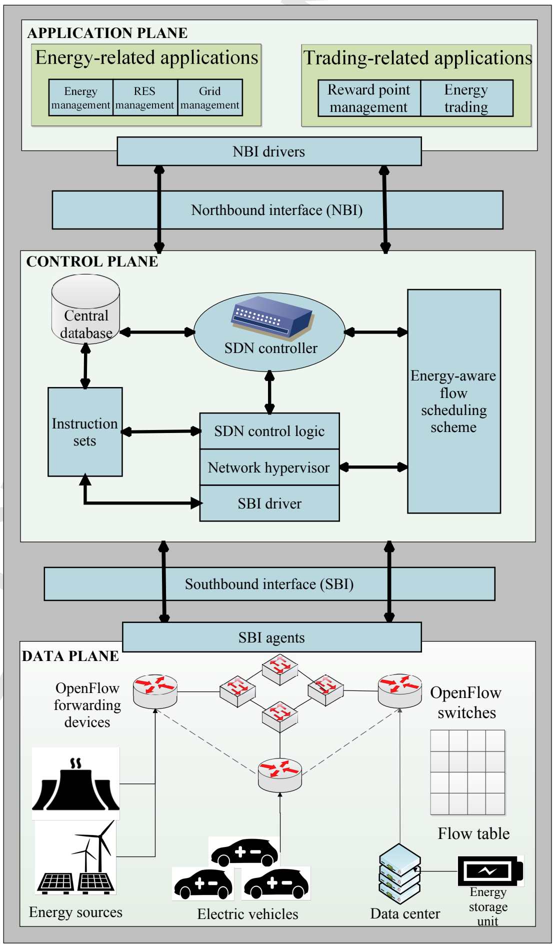


Figure 2: SDN-based control framework of the proposed scheme

Data plane: The data plane consist of various sources such as DC, ESU, EVs, and energy sources (RES and grid) which are connected using various forwarding devices such as Openflow physical switches, Openflow virtual switches, Openflow routers, and Openflow gateways. The data generated from the various sources is routed over the energy-aware path using forwarding tables based on the policy prescribed by SDN controller. A list of forwarding tables and group table linked by a pipeline are available with each forwarding device. The flow table available with the forwarding devices is small in size in order to keep the SDN architecture simple and consistent. Based on the programmable logic of SDN controller, an instruction set containing the forwarding decisions is installed on the forwarding devices. The instruction set installed at the forwarding devices is mapped with the list of flow tables and forwarding decision is taken accordingly. In the proposed SDN-based framework, an energy-aware flow scheduling algorithm is proposed to make various flow related decisions. The data acquired from all these sources is used by the proposed scheme to make decisions and computations in the control plane. The DC consists of heterogeneous servers, network devices, and various other equipments. Further, the ESU is associated with data related to storage of energy, inflow/outflow of energy to/fro various sources such as EVs, RES, grid. The data acquired from EVs comprise of battery capacity, state of charge (SoC) and other related data. The energy sources are responsible for data related to energy generated from renewables and price of energy at grid at a particular instance.

Control Plane: The control plane is the decision making plane where the SDN controller is located and is also known as the brain of network. SDN controller resides in a centralized server located at this plane with a network operating system installed in it. The basic objective of this plane is to enable the control commands on various forwarding devices and manage the information related to all the SDN applications residing at the application plane. The control plane is also responsible for receiving the feedback from various forwarding devices. The network policies are decided at this plane which are implemented at other two planes. The data acquired from various sources and equipments is used by control algorithms at this plane for decisions making and trade-offs. The control plane makes various decisions with respect to various applications related to ESU, RES, EVs charging-discharging, grid, and energy trading.

Application plane: The application plane consists of various end user applications. All the SDN applications run on the application plane. The proposed scheme comprise of various applications related to RES, EVs, DC, ESU, and grid as shown in Fig. 2. The EVs owners utilize this platform to interact with DC form charging-discharging purpose. The access to reward point scheme for EVs is also through application plane.

The proposed energy-aware flow scheduling scheme for the SDN controller is described as below.

5.2. Energy-aware Flow Scheduling Scheme

The proposed SDN-based scheme take various flow scheduling decisions related to the data generated from various sources using an energy-aware flow scheduling algorithm. The proposed algorithm 1 is designed with focus on improving network performance and minimizing the energy consumption of network devices. In the system model, the SDN controller schedules traffic flows. **The traffic flow is divided into three types on the basis of their status as-active, queued, and suspended. The traffic flow required to be scheduled is put in a specific queue. The flow is considered as active only when a valid path is available for it without any other flows. The flow becomes active when it reaches to the top of the queue. Otherwise, it is suspended when no valid path is available. In order to make the flow scheduling process energy-efficient, ports on an inactive link are put into sleep mode. Moreover, when all ports of a specific switch are in sleep mode, then the concerned switch is also put into sleep mode. This action is performed to minimize the energy consumption of unused ports and switches [35]. In order to synchronize the shifting of switch into sleep mode, a decision variable (d_{syn}, $\forall t$) is defined as below.**

$$d_{syn} = \begin{cases} 1 & \textbf{for} \quad active \\ 0 & \textbf{for} \quad idle \end{cases} \tag{31}$$

If ($d_{syn} = 0$), then the switch shifts to sleep mode. For this purpose, a threshold time (t_{thr}) is considered. The value of d_{syn} become 0 only if the switch is idle for the threshold time (t_{thr}). The switch shifts back to active mode if the value of d_{syn} becomes 1. The working of proposed algorithm 1 is shown as below.

Consider a flow (f_p) having size (s_p) with a release time (T_p^r), and deadline time (T_p^d) which is to be scheduled. The flow (f_p) will be scheduled to links with minimal energy consumption and satisfying deadline time. A guaranteed flow rate (g_p) is calculated for the incoming flow (f_p) (line 1). Now, the first step is to search for a valid path with respect to network topology (G), active flow (F_{act}), queued flows (F_{que}), suspended flows (F_{sus}), incoming traffic flow (f_p), and guaranteed flow rate (g_p) (line 2). If a valid path exists, then the incoming flow could be scheduled over a link with minimal energy consumption. For this purpose, each flow available is divided into set of flows. Once the flow set is available, the active time (T_{act}) of each flow set element (F_{set}) is calculated. The energy consumed by link is calculated using Eq. 13. Now, the incoming flow is scheduled for the flow set element with minimum active time and energy consumption. The flow is entered into top of the queue and becomes active to be scheduled. Otherwise, the incoming flow is suspended (line 3-18). However, if the path do not exist, the incoming flow is suspended directly (line 19-22). Now, once the scheduled flow is finished, the flow is removed from active flows and the next scheduled flow is brought to the front of the queues in active status.

Algorithm 1 Energy-aware flow scheduling algorithm

Input: F, f_p, s_p, T_p^d, T_p^r, G, F_{act}, F_{que}, and F_{sus}

Output: *path* p, g_p

1: Calculate guaranteed flow rate ($g_p = \frac{s_p}{T_p^d - T_p^r}$)
2: p ← *FindPath*(G, F_{act}, F_{que}, F_{sus}, f_p, g_p)
3: **if** path p exists **then**
4:     Schedule f_p over path p with minimum energy consumption
5:     **for** Each flow in F **do**
6:         Divide each flow in F into flow sets F_{set} with no shared links
7:         **for** $F_{set} \in$ F **do**
8:             Calculate $T_{act} = activetime(F_{set})$
9:             Compute energy consumed using Eq. (13)
10:             **if** (T_{act} is minimum) **then**
11:                 $F_{que} \leftarrow F_{que} + f_p$
12:                 Schedule flow f_p
13:             **else**
14:                 Suspend f_p
15:                 $F_{sus} \leftarrow F_{sus} + f_p$
16:             **end if**
17:         **end for**
18:     **end for**
19: **else**
20:     Suspend f_p
21:     $F_{sus} \leftarrow F_{sus} + f_p$
22: **end if**
23: **if** flow f_p finishes **then**
24:     $F_{act} \leftarrow F_{act}$ - f_p
25:     Move f_{p-1} to front of queue
26:     $f_{p-1} \leftarrow$ Active
27: **end if**

5.2.1. Compelxity Analysis

Time Complexity: In this algorithm, line 2 (*findpath*) is a linear search and takes $O(n)$ time. After this, the loop (line 7-17) takes $O(n)$ time in worst case. The loop (line 5-19) takes $O(n^2)$ time. Rest of all the operations take linear time as they are just assignment, calculation, or scheduling operations which takes $O(1)$ time. So, the overall time complexity (TC) is given as below.

$$\begin{aligned} \Rightarrow TC = O(n) + O(n^2) + O(1) \\ \Rightarrow TC = O(n^2) \end{aligned} \tag{32}$$

Space Complexity: : In the proposed algorithm, all input variable can not exceed *n*, i.e., takes $O(n)$ space. Both the loops consumes $O(n)$ space. All assignments and calculations take unit space $O(1)$. Hence, space complexity (SC) is given as below.

$$\begin{aligned} \Rightarrow SC = O(n) + O(n) + O(1) \\ \Rightarrow SC = O(n) \end{aligned} \tag{33}$$

5.3. Energy Management Scheme

An energy management scheme is proposed to control the energy generated from various sources such as RES, EVs, and grid. The major aim of the proposed scheme is to sustain the energy consumption od DC using RES. However, due to intermittent nature of RES, the energy deficit is managed using EVs. The grid is used as a back-up for worst case scenario. The proposed scheme intend to supply excess generated energy to grid using an energy trading scheme. The proposed algorithm 2 for energy management scheme is given as below.

The energy required by DC to accomplish its routine jobs is calculated using Eq. (14) and energy generated by RES is calculated using Eq. (1) (line 1-2). If the energy consumption of DC is greater than energy generated by RES, then calculate (E_{req}) using Eq. (20). Further, if (E_{req}) is less than energy available with ESU (E_{dc}^{esu}), then charge the required energy from ESU (line 3-6). Otherwise, the energy is discharged from EVs. For this purpose, calculate energy required from EVs (E_{req}^{ev}) using Eq. (21) (line 7-8). The energy available with each EV is calculated using Eq. (37). Further, the total energy available with all EVs is calculated using Eq. (5). The required energy is discharged from EVs proportionately using Eq. (38) and it is stored in ESU for use by DC (line 9-14). Now, if energy available with all EVs is less than energy required from EVs, then deficit energy (E_{def}) calculated using Eq. (22) is drawn from grid after paying price (P^{dc}_{grid}) (line 15-17). Otherwise, store excess energy in ESU for use by DC (line 18-22).

Algorithm 2 DC energy management algorithm

Input: E^{esu}_{mx}, P^{dc}_{grid}, P^{dc}_{grid}, E^{rated}_{dc}

Output: E_{dc}, E^{ren}_{dc}, E_{req}, E^{ev}_{req}, $\hat{E}_{req}$, E^{avl}_{i}, E^{avl}_{dc}, E_{def}, E_{ex}

1: Calculate (E_{dc}) using Eq. (14)
2: Calculate (E^{ren}_{dc}) using Eq. (1)
3: **if** ($E_{dc} > E^{ren}_{dc}$) **then**
4:     Calculate (E_{req}) using Eq. (20)
5:     **if** ($E_{req} < E^{esu}_{dc}$) **then**
6:         Charge (E_{req}) from ESU
7:     **else**
8:         Calculate the (E^{ev}_{req}) using Eq. (21)
9:         **for** (i=1; i $\leq$ n; i++) **do** $\triangleright$ $i \leftarrow$ Number of EVs
10:             Calculate (E^{avl}_{i}) using Eq. (37)
11:             Calculate (E^{avl}_{dc}) using Eq. (5)
12:             Charge (E^{ev}_{req}) from i EVs proportionately using Eq. (38)
13:             Store energy charged from EVs in ESU for supply to DC
14:         **end for**
15:         **if** ($E^{avl}_{dc} < E^{ev}_{req}$) **then**
16:             Calculate (E_{def}) using Eq. (22)
17:             Draw (E_{def}) from grid at a price (P^{dc}_{grid})
18:             Update the energy credit account with grid
19:         **else**
20:             Store excess available energy in ESU
21:         **end if**
22:     **end if**
23: **else**
24:     Calculate (E_{ex}) using Eq. (17)
25:     Store (E_{ex}) in ESU
26:     **if** ($E_{ex} > E^{esu}_{mx}$) **then**
27:         Supply energy to EVs proportionately using Eq. (41)
28:     **else if** ($E_{ex} > E^{rated}_{dc}$) **then**
29:         Supply excess energy to grid at price (P^{grid}_{dc})
30:         Update the the energy credit account with grid
31:     **end if**
32: **end if**

If the energy consumption of DC is less than energy generated by RES, then calculate (E_{ex}) using Eq. (17). This excess energy is stored in ESU till it reaches the maximum capacity of ESU. If the excess energy is more than the maximum capacity of ESU, then it is supplied to EVs proportionately using Eq. (41). However, if there are no EVs available to charge energy, then the excess energy is supplied to grid at a price (P^{grid}_{dc}) (line 23-30).

5.3.1. Compelxity Analysis

Time Complexity: In this algorithm, lines 9-14 takes $O(n)$ time. Rest of all the operations take linear time as they are just assignment, calculation, or scheduling operations which takes $O(1)$ time. So, the overall time complexity (TC) is given as below.

$$\begin{aligned} \Rightarrow TC = O(n) + O(1) \\ \Rightarrow TC = O(n) \end{aligned} \quad (34)$$

Space Complexity: : In the proposed algorithm, all input variable can not exceed *n*, i.e., takes $O(n)$ space. The loop consumes $O(n)$ space. All assignments and calculations take unit space $O(1)$. Hence, the space complexity (SC) is given as below.

$$\begin{aligned} \Rightarrow SC = O(n) + O(n) + O(1) \\ \Rightarrow SC = O(n) \end{aligned} \quad (35)$$

5.4. EV charging-discharging management scheme

In the proposed scheme, EVs are used to tackle the intermittent nature of RES. In a situation when energy generation from RES is low, then the EVs discharge the required energy. Further, at times when generation is high, then EVs are charged. In this regard, it is assumed that there are two categories of EVs that charge-discharge at CS located at DC. The first category consist of i EVs which are reward point member such as DC employees and regular customers. The second category is of j EVs which take part in the energy trading scheme to charge and discharge energy on the basis of price computed using time-of-use (TOU) scheme. The working of charging-discharging system is elaborated as below.

5.4.1. EV discharging

The energy stored in EVs battery is used to support the intermittency of RES connected to DC. For this purpose, EVs joining this scheme decide a threshold SoC (SoC_i^{thr}) which they definitely require once they depart from the DC. The SoC (SoC_i^{avl}) available with i^{th} EV to discharge is given as below.

$$SoC_i^{avl} = SoC_i^{inl} - SoC_i^{thr} \quad (36)$$

Further, the energy available with i^{th} EV to discharge is given as below.

$$E_i^{avl} = \left(SoC_i^{inl} - SoC_i^{thr}\right) E_i^{rat} \tag{37}$$

The energy required by DC from EVs (E_{req}^{ev}) is drawn from EVs in proportion to the energy available with each participating EV and is given as below.

$$E_i^{drw} = \left(\frac{SoC_i^{avl}}{\sum_i (SoC_i^{avl})}\right) E_{req}^{ev} \tag{38}$$

5.4.2. EV charging

The EVs charge from CS located at DC to acquire the pre-decided threshold level of SoC if they are part of the reward point scheme. Other EVs can also charge the required energy from DC after paying price calculated using energy trading scheme. The energy that i^{th} EV (part of reward point scheme) can charge from DC is given as below.

$$E_i^{ch} = (SoC_i^{mx} - SoC_i^{up})\, E_i^{rat} \tag{39}$$

where, SoC_i^{mx} is the maximum SoC that i^{th} EV can achieve, SoC_i^{up} is the updated SoC of i^{th} EV after discharging the energy to DC.

The SoC (SoC_i^{gvn}) that must be given to i^{th} EV (part of reward point scheme) to reach its threshold SoC is given as below.

$$SoC_i^{gvn} = SoC_i^{thr} - SoC_i^{up} \tag{40}$$

Using the above equation, the energy (E_i^{gvn}) is given proportionately to all the participating EVs as given below.

$$E_i^{gvn} = \left(\frac{SoC_i^{gvn}}{\sum_i (SoC_i^{gvn})}\right) E_{ex} \tag{41}$$

After the threshold SoC is achieved by EVs and the excess energy if still available with DC is supplied to them till they achieve maximum level of SoC. The EVs will have to pay for energy they charge above the SoC that they had before they joined the reward point scheme. The energy (E_i^{ex}) for which EVs have to pay is given as below.

$$E_i^{ex} = \left(SoC_i^{f} - SoC_i^{inl}\right) E_i^{rat} \tag{42}$$

where, SoC_i^f is the final SoC that i^{th} EV achieve after charging.

The EVs that are not a part of reward point scheme can charge from DC using excess energy is available after meeting the demand of participating EVs by paying some price. The excess energy (E_j^{ex}) available to charge EVs that are not a part of reward point scheme is given as below.

$$E_j^{ex} = E_{ex} - \sum_i E_i^{gvn} - \sum_i E_i^{ex} \tag{43}$$

The energy that j^{th} EV (not a part of reward point scheme) can charge from DC is given as below.

$$E_j^{ch} = \left(SoC_j^{mx} - SoC_j^{inl}\right) E_j^{rat} \tag{44}$$

Such EVs trade for energy with DC using single-leader multi-follower Stackelberg game which is described in next section.

The proposed charging-discharging scheme is shown in the Algorithm 3. In this algorithm, the initial SoC (SoC_i^{inl}) of i EVs participating in reward point scheme is checked. If the initial SoC is greater than threshold SoC (SoC_i^{thr}), then SoC available (SoC_i^{avl}), then the EVs can discharge energy available with them. For this purpose, SoC and energy available with each EV is calculated using using Eq. (36) and Eq. (37) respectively. The available energy with each EV is supplied to DC and stored in ESU proportionately using Eq. (38) and the SoC for each EV is updated accordingly (line 1-10). However, if initial SoC of EVs is less than the threshold SoC, then the energy is charged by EVs from CS connected to DC. For this purpose, SoC and energy given by each EV is calculated using using Eq. (40) and Eq. (40) respectively. The energy is supplied to EVs till they achieve their threshold SoC. After this, the excess available energy (E_i^{ex}) is calculated using Eq. (42). If excess energy is still available, then it is supplied to participating EVs till they reach the desired SoC or maximum SoC (line 11-20). Now, if still there is excess energy available with ESU, then is is supplied to non-participating j EVs using energy trading scheme as per algorithm 4 (line 21-28).

5.4.3. Compelxity Analysis

Time Complexity: In this algorithm, both the loops (line 1-28 and line 21-26) takes $O(n)$ time. So, both take $O(n^2)$ time. Rest all the operations take linear time as they are just assignment,

Algorithm 3 EV charging-discharging algorithm

Input: SoC_i^{inl}, E_i^{rated}

Output:

for (i=1; i ≤ n; i++) **do** ▷ $i \leftarrow$ Number of reward point member EVs
  Check (SoC_i^{inl})
  if ($SoC_i^{inl} > SoC_i^{thr}$) **then**
    Calculate (SoC_i^{avl}) using Eq. (36)
    Calculate (E_i^{avl}) using Eq. (37)
    while ($SoC_i^{avl} > SoC_i^{thr}$) **do**
      Draw (E_i^{drw}) proportionately from EVs
      Supply (E_i^{drw}) to ESU
      Calculate (SoC_i^{upd})
    end while
  else
    Calculate (SoC_i^{gvn}) using Eq. (40)
    Calculate (E_i^{gvn}) using Eq. (41)
    while ($SoC_i^{upd} < SoC_i^{thr}$) **do**
      Supply (E_i^{gvn}) proportionately to EVs
    end while
    Calculate (E_i^{ex}) using Eq. (42)
    while ($SoC_i^{thr} < SoC_i^{mx}$) **do**
      Supply (E_i^{ex}) to EVs
    end while
    for (j=1; j ≤ n; j++) **do** ▷ $j \leftarrow$ Number of other EVs
      Calculate (E_j^{ex}) using Eq. (43)
      while ($SoC_j^{inl} < SoC_j^{mx}$) **do**
        Supply (E_j^{ex}) to j EVs using Algorithm 4
      end while
    end for
  end if
end for

calculation, or scheduling operations which takes $O(1)$ time. So, the overall time complexity (TC) is given as below.

$$\Rightarrow TC = O(n^2) + O(1)$$
$$\Rightarrow TC = O(n^2) \quad (45)$$

Space Complexity: : In the proposed algorithm, every input variable can not exceed n, i.e., takes $O(n)$ space. The loops consumes $O(n)$ space. All assignments and calculations take unit space $O(1)$. Hence, the space complexity (SC) is given as below.

$$\Rightarrow SC = O(n) + O(n) + O(1)$$
$$\Rightarrow SC = O(n) \quad (46)$$

6. Reward-Point Management and Energy Trading Scheme

In this section, a reward point management mechanism and a single-leader multi-follower Stackelberg game for energy trading is designed. The first case is designed for EVs which agree to participate in reward point mechanism. The second case is designed to decide price of energy to be charged from DC by requesting EVs other than the reward point members. The reward point management scheme and an energy trading scheme is described in detail in subsequent sections given below.

6.1. EV reward point management

The reward point management mechanism is designed to attract EVs to be a part of charging-discharging scheme for managing the intermittent nature of RES. The employees of DC and other offices located near DC are attracted by giving luring offers using the proposed scheme. Each participating member has to register using SDN-based on-line user interface. Once an EV becomes member of the scheme, it agrees to park at the DC and supply energy available with it to DC whenever required. Apart from providing free parking facility, DC ensures (RP) to the EVs which could be redeemed whenever required to access cloud services, food in cafeteria, money, etc. The (RP) are updated into the account of EV whenever it charge or discharge from the DC. The RP earned (RP_i^{ern}) by i^{th} EV varies with respect to the initial SoC and final SoC and is given as below.

$$RP_i^{ern} = \begin{cases} \beta^n & \text{for} \quad SoC_i^{fnl} = SoC_i^{thr} \\ \beta & \text{for} \quad SoC_i^{thr} < SoC_i^{fnl} \leq SoC_i^{inl} \\ 0 & \text{for} \quad SoC_i^{fnl} > SoC_i^{inl} \end{cases} \tag{47}$$

where, SoC_i^{fnl} is the level of energy with i^{th} EV when it departs from DC.

The value of n varies with respect to the maximum discharging capacity (D_{dis}^{max}), (SoC_i^{inl}), and (SoC_i^{fnl}) and is given as below.

$$n = 1 + \left(\frac{1}{D_{dis}^{max}}\right)\left(SoC_i^{fnl} - SoC_i^{inl}\right) \tag{48}$$

These RPs could be utilized by EVs to charge from DC at later stage. The RPs utilized (RP_i^{utl}) by i^{th} EV to charge at DC is given as below.

$$RP_i^{utl} = \begin{cases} \beta^m & \text{for} \quad SoC_i^{inl} = SoC_i^{mx} \\ \beta & \text{for} \quad SoC_i^{inl} < SoC_i^{mx} \end{cases} \tag{49}$$

The value of m varies with respect to the maximum charging capacity (D_{ch}^{max}), (SoC_i^{inl}), and (SoC_i^{fnl}) and is given as below.

$$m = 1 + \left(\frac{1}{D_{ch}^{max}}\right)\left(SoC_i^{fnl} - SoC_i^{inl}\right) \tag{50}$$

After the EV charges or discharges from CS located at DC, the RP earned by EV owner are updated accordingly as shown below.

$$RP = RP_i^{inl} + RP_i^{ern} - RP_i^{utl} \tag{51}$$

where, RP_i^{inl} is the initial value, RP_i^{ern} is the earned value, and RP_i^{utl} is the utilized value of RPs.

Algorithm 4 EV reward point management algorithm

Input: RP_i^{inl}, SoC_i^{inl}, SoC_i^{fnl}, SoC_i^{thr}

Output: RP_i^{ern}, RP_i^{utl}, RP

1: **for** (i=1; i $\leq$ n; i++) **do** $\triangleright$ $i \leftarrow$ Number of reward point member EVs
2: Check (RP_i^{inl})
3: **if** $(SoC_i^{fnl} == SoC_i^{thr})$ **then**
4: $(RP_i^{ern} == \beta^n)$
5: **else if** $(SoC_i^{thr} < SoC_i^{fnl} < SoC_i^{inl})$ **then**
6: $(RP_i^{ern} == \beta)$
7: **else**
8: $(RP_i^{ern} == 0)$
9: Calculate (RP_i^{utl}) using Eq. (49)
10: Update RP using Eq. (51)
11: **end if**
12: **end for**

The proposed RP scheme is shown in the Algorithm 4. This algorithm is meant for only i EVs who are participating in RP scheme. The initial value of RP's (RP_i^{inl}) is check for i EVs (line1-2). If the final SoC (SoC_i^{fnl}) of EVs is equal to threshold SoC (SoC_i^{thr}), then β^n RP's are earned which are updated in the account of concerned EV (line 3-4). However, if the final SoC (SoC_i^{fnl}) of EVs is greater than threshold SoC (SoC_i^{thr}) but less than initial SoC (SoC_i^{inl}), then β RP's are earned which are updated in the account of concerned EV (line 5-6). Further, no reward point is given if the final SoC (SoC_i^{fnl}) of EVs is greater than the initial SoC (SoC_i^{inl}) (line 7-8). Similarly, the RP's utilized by EVs is calculated using Eq. (49). Finally, the reward points earned or utilized are updated in the user account using Eq. (51) (line 9-12).

6.1.1. Compelxity Analysis

Time Complexity: In this algorithm, the loop takes $O(n)$ time. Rest of all the operations take linear time. Hence, the time complexity (TC) is given as below.

$$\begin{aligned} \Rightarrow TC &= O(n) + O(1) \\ \Rightarrow TC &= O(n) \end{aligned} \tag{52}$$

Space Complexity: : In the proposed algorithm, the size of these variable can not exceed n, i.e., number of EVs. So, algorithm takes minimum space complexity of $O(n)$. Rest of the algorithm uses assignment, calculation, and scheduling steps which takes $O(1)$ space. Hence, the space complexity (SC) is given as below.

$$\begin{aligned} \Rightarrow SC &= O(n) + O(1) \\ \Rightarrow TC &= O(n) \end{aligned} \tag{53}$$

6.2. Energy trading

In this section, a single-leader multi-follower Stackelberg game for energy trading is formulated. The CS located at DC act as single-leader and EVs act as multi-followers. The CS is connected to ESU to supply energy to EVs. The CSs supply the energy (E_j^{req}) to EVs at a price (P_{dc}^{ev}) calculated using TOU pricing scheme. An user interface such as Plug Share is designed to facilitate EVs to trade for energy [44]. CS decides the price for energy at a particular time slot. EVs that wants to charge for energy check for the announced price. If the announced price suite the requirement of EVs, they decide the energy demand. EVs announce the energy demand to CS which supply the required energy once the price is received.

The energy available (E_{cs}^{avl}) at CS connected to DC that can be supplied to EVs depends upon energy consumption of DC (E_{dc}), energy stored in ESU (E_{dc}^{esu}), and energy generated by RES (E_{dc}^{ren}). The energy available with CS is given as below.

$$E_{cs}^{avl} = E_{dc}^{esu} + E_{dc}^{ev} + E_{dc}^{ren} - E_{dc} \tag{54}$$

In general, the trading of energy between EVs and CSs occurs in sequential way. Hence, the Stackelberg game is the most suited technique which follows the similar movement trend. Further, it is a two period game which involves a leader and follower [45]. The leader has preference to announce its move before follower. The follower can opt out of the competition while the leader cannot back-out from it. So, The leader initiates the game with best move which the follower reply with best response [46]. The aim of leader and follower is to maximize their profit, i.e., utility of players. Moreover, the players in Stackelberg game define their strategies aimed at economic benefit. The various aspects related to the proposed Stackelberg game are given as below.

- **Players:** In this scheme, j EVs (where $j \in \hat{J}$) and single CS is considered.
- **Strategy:** The strategy profile for EVs is given as $S_{ev} = \{CS, j \in \hat{J}\}$. For EVs, the strategy is to decide the amount of energy to be charged from CS which maximizes its utility. For CSs, the strategy is to decide the optimal price of energy using TOU which maximizes its utility.
- **Payoff:** Both EVs and CSs decide their strategies on the basis of the payoffs they receive. The payoff or utility is described on the basis of three entities; price, cost, and revenue. These three entities are used to design the utility functions of EVs and CS. In this context, price is refered as the amount of money charged to sell a energy, revenue is used for the amount of money collected after selling energy, and cost is refered as the amount money incurred on purchase or generation of energy. After incorporating the above entities, the utility functions for EVs and CSs are defined as below.
    1. **Utility function of EV:** The utility of EVs represents the gain or profit achieved after charging required amount of energy from CS. A positive concave function R_j^{ev} is considered as revenue available with j^{th} EV in terms of energy. EVs pay a certain amount of money (P_{dc}^{ev}) to charge the required amount of energy from CS. Hence, the utility function (U_j^{ev}) of j^{th} EV is given as below.
    $$U_j^{ev} = R_j^{ev} - P_{dc}^{ev} \tag{55}$$
    2. **Utility function of CS:** The utility of CS represents the profit or gain achieved after selling energy to EVs. The revenue generated by a CS after selling energy to j^{th} EV is given by R_j^{cs} as follows.
    $$R_j^{cs} = \sum_{j=o}^{m} P_{dc}^{ev} \tag{56}$$

The total cost (C_{dc}^{tot}) of energy comprise of cost incurred on generation (C_{dc}^{ren}) and maintenance of energy (C_{dc}^{mn}) and is given as below.

$$C_{dc}^{tot} = C_{dc}^{ren} + C_{dc}^{mn} \sum_{j=0}^{n} E_j^{ch}. \tag{57}$$

Hence, using the revenue and cost, the utility function (U_{dc}^{cs}) of CS is given below.

$$U_{dc}^{cs} = R_j^{cs} - C_{dc}^{tot} \tag{58}$$

The price of energy varies with respect to time [47]. Hence, using fixed price for energy may not suite every EV. So, the price based on TOU is considered in the proposed energy trading scheme. The TOU is divided into *peak time* and *off-peak time* on the basis of energy available with the CS and the energy being charged by EVs at present time slot. For this purpose, a threshold limit (E_{dc}^{thr}) is considered by CS to differentiate between both the times. The threshold limit (E_{dc}^{thr}) is calculated as given below.

$$E_{dc}^{thr} = E_{dc}^{esu}/j \tag{59}$$

With an increase in the number of EVs charging from CS and decrease in generation of energy by RES, the energy availability at CS is low. If the energy available at CS is less than threshold limit, then it is *off-peak time*. Otherwise, it is *peak time* [48]. The price (P_{dc}^{ev}) of energy decided using TOU is given as follows.

$$P_{dc}^{ev} = \begin{cases} P_p & \text{for} \quad E_{dc}^{avl} \leq E_{dc}^{thr} \\ P_{op} & \text{for} \quad E_{dc}^{avl} > E_{dc}^{thr} \end{cases} \tag{60}$$

The price (P_p) of energy during peak time is given as below.

$$P_p = \zeta E_j^{ch}/E_{cs}^{avl} \tag{61}$$

where, ζ is the constant decided by DC which is used to decide the price of energy during peak time.

The price (P_{op}) of energy during off-peak time is given as below.

$$P_{op} = E_j^{ch}/E_{cs}^{avl} \tag{62}$$

The proposed single-leader multi-follower Stackelberg game for energy trading is described in Algorithm 5. In this algorithm, initially the number of EVs requesting for energy are calculated (line 1). Further, energy available (E_{dc}^{avl}) is calculated using Eq. (37). On the basis of energy available and number of requesting EVs, the threshold value (E_{dc}^{thr}) is calculated using Eq. (59) (line 2-3). Now, if TOU is peak, then calculate price P_p using Eq. (61). But, if TOU is off-peak, then calculate price P_{op} using Eq. (62) (line 4-8). Once price is decided, the CS connected to DC check its utility using using Eq. (58). If the utility is more as compared to utility at previous instance, then announce price. Otherwise, recompute price till the utility shows growth (line 9-13). Once the price is announced, the requesting EVs calculate the energy required from CS using Eq. (44). Using price and energy, EVs calculate their utility using Eq. (55). If the utility is more than the utility at previous instance, then announced price is accepted. The EVs pay the accepted price and charge the required energy. Otherwise, wait for next announcement of price or recompute the energy requirement and check the utility again (line 14-22).

Algorithm 5 Stackelberg game-based energy trading algorithm

Input: j

Output: E_{dc}^{avl}, E_{dc}^{thr}, P_p, P_{op}, U_j^{ev}, U_{dc}^{cs}, E_i^{ch}

1: Check for number of requesting EVs ▷ Leaders move (CS)
2: Calculate (E_{dc}^{avl}) using Eq. (37)
3: Calculate threshold value (E_{dc}^{thr}) using Eq. (59)
4: **if** time-of-use == peak **then**
5:     Calculate P_p using Eq. (61)
6: **else**
7:     Calculate P_{op} using Eq. (62)
8: **end if**
9: **if** ($U_j^{ev}(t) \geq U_i^{ev}(t-1)$) **then**
10:     Announce price to EVs
11: **else**
12:     Recompute price
13: **end if**
14: **for** (j=1; j≤n; j++) **do**
15:     Calculate E_i^{ch} using Eq. (44) ▷ Followers move (EVs)
16:     Calculate utility of all EVs using price announced
17:     **if** ($U_{dc}^{cs}(t) \geq U_{dc}^{cs}(t-1)$) **then**
18:         Accept and pay price, charge for required energy ▷ Nash equilibrium
19:     **else**
20:         Wait for next announcement
21:     **end if**
22: **end for**

6.2.1. Compelxity Analysis

Time Complexity: In this algorithm, loop (lines 14-22), takes $O(n)$ time. Other operations takes linear time, $O(1)$. So, the time complexity (TC) is given below.

$$\Rightarrow TC = O(n) + O(1)$$
$$\Rightarrow TC = O(n) \tag{63}$$

Space Complexity: : In this algorithm, the total number of EVs are *n*. So, it takes minimum space complexity of $O(n)$. Rest of the algorithm uses assignment, calculation, etc which takes $O(1)$ space. Hence, the space complexity (SC) is given as below.

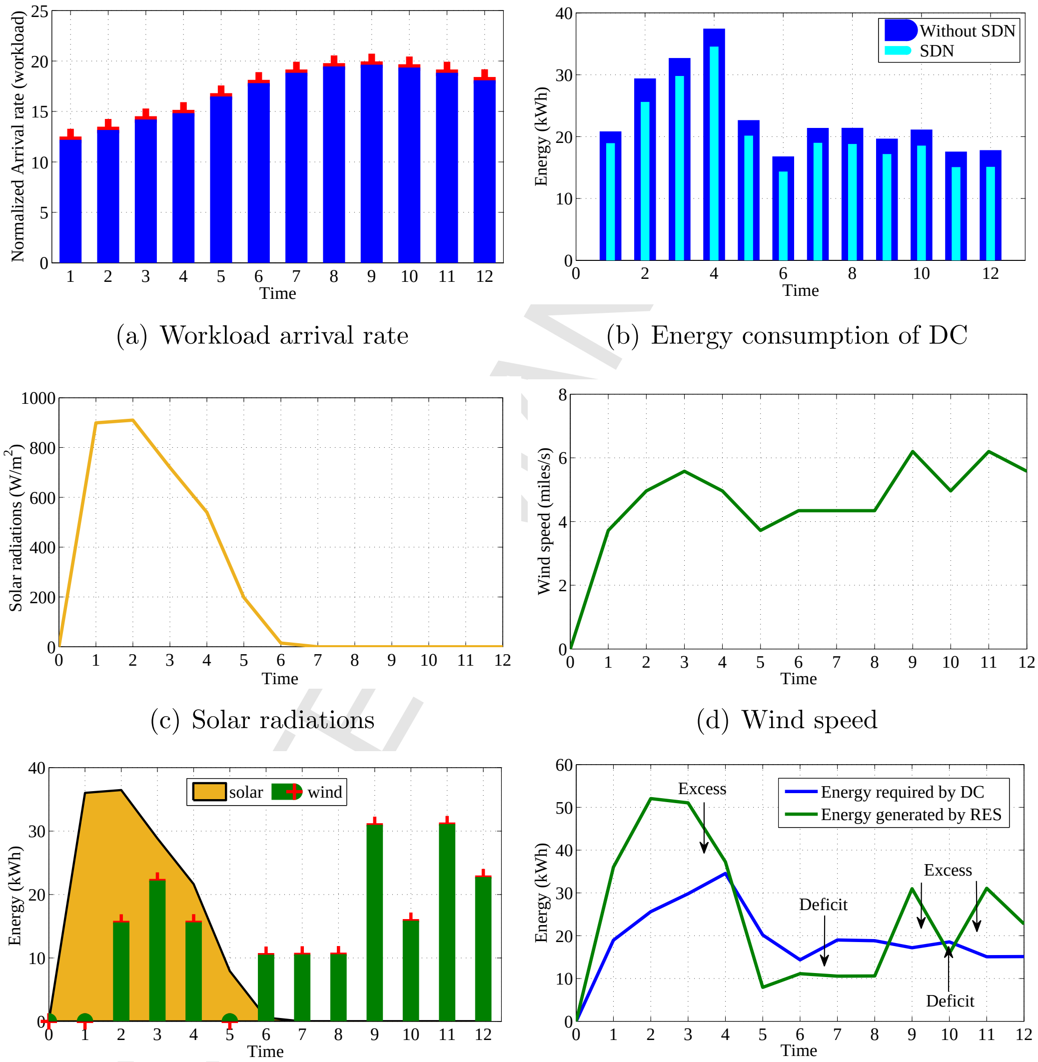
$$\Rightarrow TC = O(n) + O(1)$$
$$\Rightarrow TC = O(n) \tag{64}$$

7. Evaluation and Results

In this section, the proposed scheme and algorithms are simulated using the workload for a DC located in Mohali (Punjab), India having 100 heterogeneous servers. The heterogeneous physical servers considered for the purpose of evaluation are categorized as, HP ProLiant DL380 G7 X5690 Hexacore 3.46 GHz (180 W), and HP ProLiant DL80 Gen9 Hexacore E5-2630 v3 (220 W). Each heterogeneous server considered in the proposed evaluation setup has different configuration and energy consumption properties. The proposed scheme is not limited to a single DC, type of servers, input parameters, and hardware configuration as per requirement. The input parameters considered for calculations are given in Table 5.

Table 5: Pre-defined input parameters

Parameter	Value	Parameter	Value	Parameter	Value
η	0.7	L_{pv}^{temp}	0.25	SoC_{thr}	40%
S_{dc}^{pv}	3271 m^2	L_{wn}^{temp}	0.25	SoC^{mx}	100%
$cos(\alpha)$	0.07	L_{dc}^{esu}	0.5	D_{dis}^{max}	75%
$\rho\ (av)$	1.146732	E_{mx}^{esu}	50 kWh	D_{dis}^{min}	10%
Ç	0.5	E^{rat}	16 & 12	β	10
$\hat{a}$	1800 m^2	$\zeta\ (op\ time)$	10	$\zeta\ (p\ time)$	20



(a) Workload arrival rate
(b) Energy consumption of DC
(c) Solar radiations
(d) Wind speed
(e) Energy generated by RES
(f) Mapping of energy

Figure 3: Results for energy consumption and generation at DC

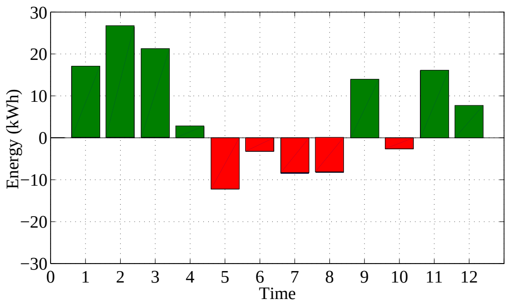
The interactive workload traces having arrival rate as shown in Fig. 3(a) are rescaled from real traffic from Wikipedia [22]. Using the proposed scheme, the energy consumption of DC is shown in Fig. 3(b). The result shows that the energy consumption of DC is less when the proposed SDN-based energy-aware flow scheduling scheme is used. The major reason for the above result is the optimal use of network infrastructure. The use of SDN-based model results in almost 11.38% lesser energy consumption by DC.

7.1. Energy genration by RES

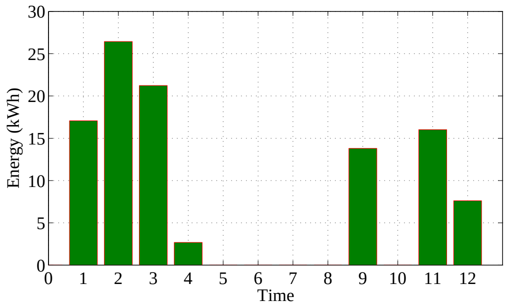
The major objective of this work is to sustain the energy consumption of DCs using RES. For this purpose, the energy generated by each DC is computed using weather traces. The DC is connected to in-house renewable energy generation sources, i.e, PV panels and wind turbines. To evaluate the proposed scheme, solar radiations [49] and wind speed [50] at DC are considered for 12-hours as shown in Fig. 3(c) and Fig. 3(d). The energy generated by PV panels and wind turbines deployed at DC is shown in Fig. 3(e). The energy generation by PV panels is high from 1300 hrs to 1400 hrs. After 1400 hrs, the energy generation goes down steeply and it becomes nil after 1800 hrs. However, the energy generation by wind turbines is variable throughout the time frame. The wind energy is almost negligible at 1300 hrs and 1700 hrs. The wind energy is maximum from 2100 hrs to 2400 hrs. It is clearly evident that the energy generation by both RES is highly intermittent during 12 hours.

7.2. Analysis of energy management scheme

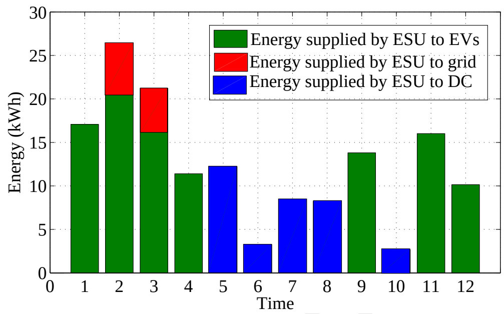
Due to intermittent nature of RES, the energy required by DC is different from the energy generation patterns. Fig. 3(f) shows the mapping of energy required by DC at each time slot with respect to energy generated by RES. The result shows that the energy generation by RES is in excess till 1600 hrs. After 1600 hrs, the energy generated by RES is not sufficient to power the DC. Fig. 3(f) shows that the energy generation and requirement shows similar mismatch patterns for further time slots also. In this regard, the proposed energy management scheme is used to supply sufficient amount of energy required to power the DC using ESU, EVs, and grid. Fig. 4(a) shows the excess and deficit in energy to power the DC. To map the energy requirement of the DC, the excess energy generated by RES is supplied to ESU. The excess energy drawn by ESU from RES to maintain its maximum



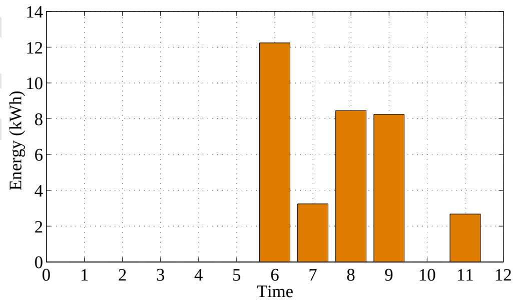
(a) Excess and deficit of energy



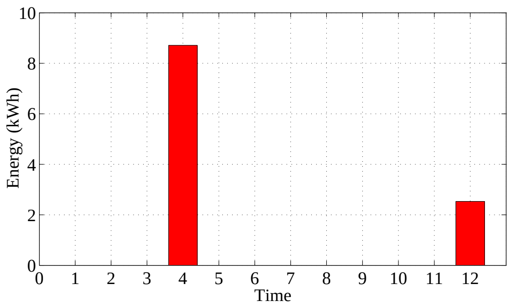
(b) Energy drawn by ESU from RES



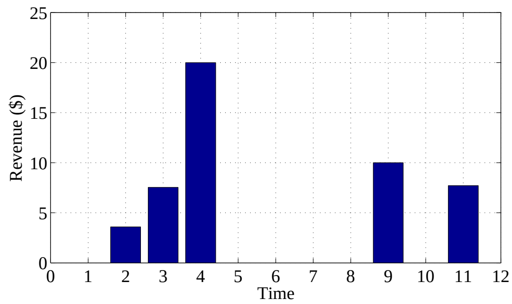
(c) Energy supplied by ESU



(d) Energy drawn by ESU from EVs



(e) Energy drawn by ESU from grid



(f) Revenue generated

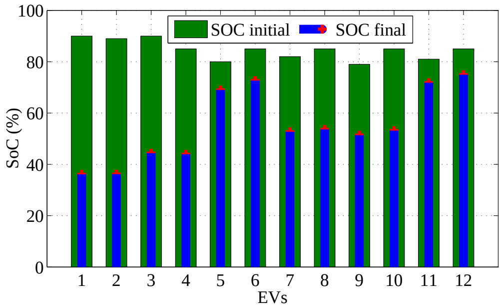
Figure 4: Results for analysis of energy management scheme

capacity is shown in Fig. 4(b). Once the ESU reaches its maximum capacity, the excess energy is either supplied to EVs or grid. The ESU supplies the stored energy to power DC at times when there is deficit of generation by RES. The energy supplied by ESU to various sources is shown in Fig. 4(c). Further, whenever the ESU is below the maximum capacity then, it draws energy from EVs and grid. The energy supplied to grid is taken back from it whenever it is required. The result shows that energy is supplied to grid at 1200 hrs and 2300 hrs. This energy supplied to grid is taken back by ESU at 1400 hrs and 2400 hrs when it is in deficit to maintain its maximum capacity. The energy drawn by ESU from EVs and grid is shown in Fig. 4(d) and 4(e), respectively.

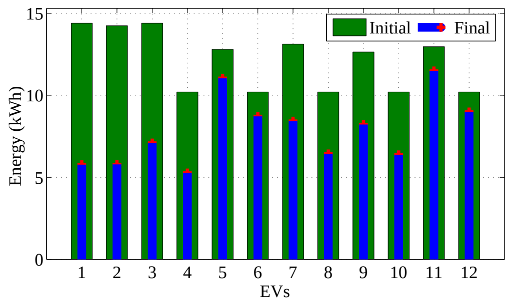
The EVs join the reward point scheme to participate in the energy management scheme for sustainability of DC using RES. The participating EVs supply the available energy to ESU whenever required. The ESU return the energy drawn from EVs when they leave the DC. The excess energy supplied to EVs above the energy drawn from it, reflects revenue. The price of excess energy supplied to EVs is computed using energy trading scheme based on Stakelberg game. Fig. 4(f) shows the revenue generated by DC using energy trading scheme. The proposed scheme supplies excess energy to EVs and gains revenue in addition to its objective of sustainability. It is evident from results that the proposed energy management scheme successfully sustains the energy consumption of DC using RES. However, to manage the intermittency of RES, the proposed scheme utilize the charging and discharging capability of EVs. In this regard, grid is also used as a partner to cope with the intermittency of RES.

7.3. Analysis of role of EVs particpating in reward point scheme

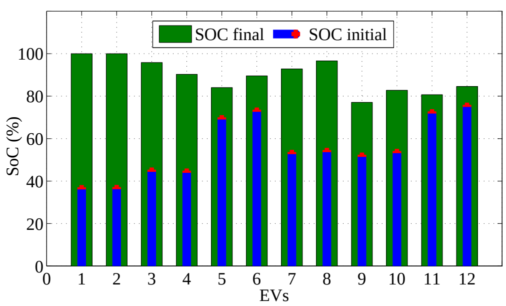
The above discussed results depicts that EVs play a vital role in managing the intermittency of RES in order to sustain the energy consumption of DC using RES. The EVs participate in energy management scheme join the reward point mechanism to tackle the intermittency of RES. The charging and discharging capability of EVs is utilized to manage the intermittency of RES to sustain energy consumption of DC. The EVs discharge the energy available with it to ESU when the energy generation by RES is in deficit. Fig. 5(a) shows the initial SoC and final SoC of participating EVs. The initial SoC is high and reaches at a low level once it discharge the required energy to ESU. Fig. 5(b) shows the initial and final energy level of participating EVs. After the discharging process, the EVs are supplied the energy



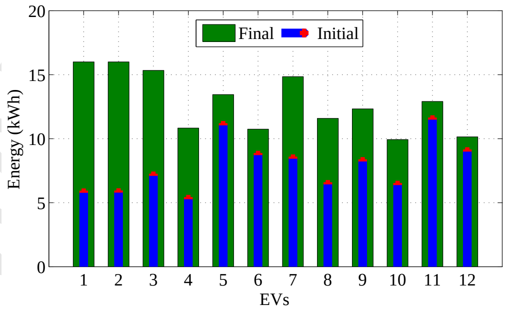
(a) SoC level during EV charging



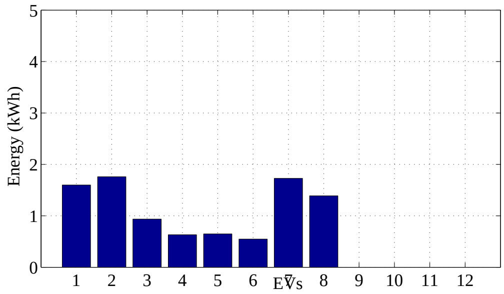
(b) Energy level during EV charging



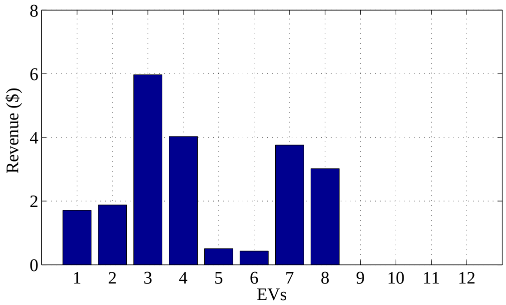
(c) SoC level during EV discharging



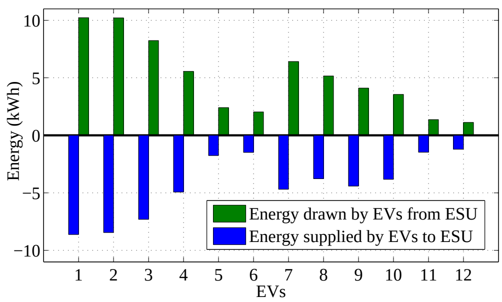
(d) Energy level during EV discharging



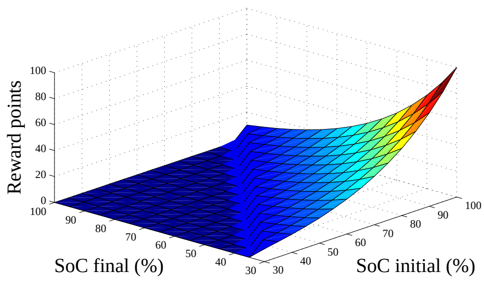
(e) Excess energy supplied to EVs



(f) Revenue generated



(g) Energy drawn and supplied by EVs



(h) Variation of reward points

Figure 5: Results for analysis of impact of EVs charging and discharging

whenever they require. The minimum energy to be supplied to EVs must meet the threshold level. Generally, the energy drawn from EVs is limited to the threshold SoC. However, in the evaluation results, the energy drawn from EVs is even lower than threshold limit at some time slots.

The initial SoC of EVs when they charge back the supplied energy is shown in Fig. 5(c). The final SoC attained after energy is supplied to participating EVs is shown in Fig. 5(c). Now, the energy supplied to EVs is more than the energy supplied by them to support the proposed energy management scheme. Fig. 5(d) shows the initial and final level of energy of EVs in the charging process. The excess energy supplied to EVs is charged with price computed using energy trading scheme. The participating EVs that are supplied excess energy above the initial level when they joined the charging process are shown in Fig. 5(e). The revenue generated by supplying excess energy to EVs is shown in Fig. 5(f). The energy supplied and drawn from various participating EVs is shown in Fig. 5(g). Hence, after supporting the intermittency of RES, the proposed scheme supports the DC with additional generation of revenue. The EVs that participate in the reward point scheme are given reward points in regard to the energy drawn from them. The reward points are computed on the basis of initial and final SoC of the EVs with respect to SoC threshold. The SoC threshold for the proposed scheme is fixed at 40% for evaluation. The variation of reward points gained by EVs with respect to initial and final SoC is shown in Fig. 5(h).

7.4. Analysis of energy trading scheme for EVs

The proposed single-leader multi-follower Stackelberg game for energy trading is designed to decide an optimal price for excess energy supplied to EVs. The initial and final SoC of the EVs that drew energy from ESU using the proposed energy trading scheme are shown in Fig. 6. The energy drawn by EVs from ESU is shown in Fig. 7(a). The price of energy is computed on the basis of peak and off-peak time. The peak and off-peak time is decided on the basis of energy available at ESU and energy required by EVs. Fig. 7(a) shows that the EV3 and EV4 charge energy from ESU when it is peak time. The price charged in peak time is more than the price charged in off-peak time. The revenue generated after supplying energy to EVs using the price computed by proposed Stackelberg game for energy trading is shown in Fig. 7(b). The high towers shown for EV3 and EV4 clearly depict the peak hours in the proposed scheme.

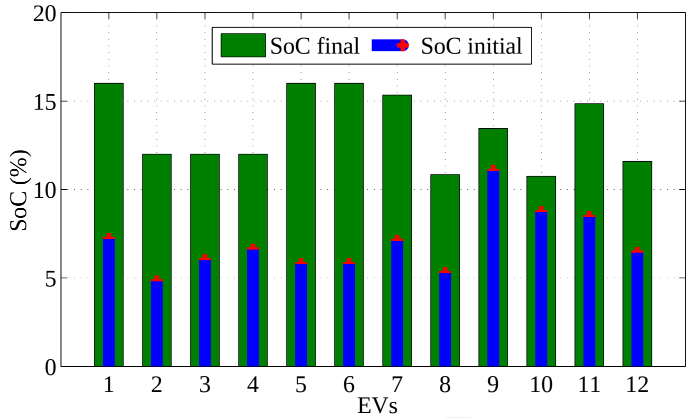
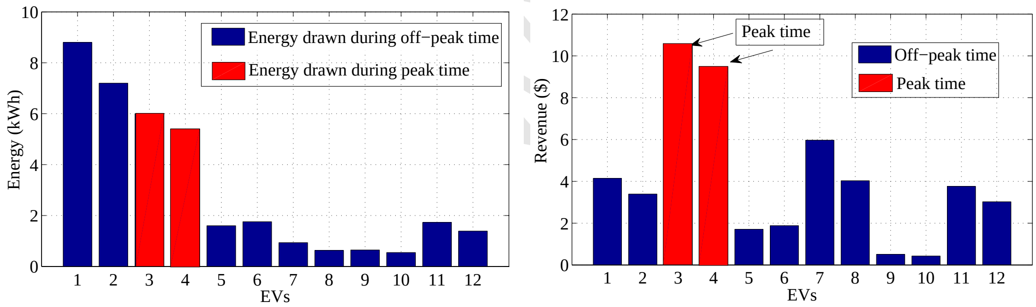


Figure 6: SoC level during energy trading



(a) Energy drawn by EVs (b) Revenue generated from EVs

Figure 7: Results for analysis of energy trading scheme

7.5. Existence of Nash equilibrium

The existence of Nash equilibrium is proved practically while deciding the optimal price of energy drawn from ESU by EVs using single-leader multi-follower Stackelberg game for energy trading. Table 6 shows the proof of existence of Nash equilibrium when 4 EVs request for energy from ESU. The single DC and multi followers reaches the equilibrium stage with respect to their utility functions. EV1 an CS shows the existence of Nash equilibrium and so EV1 is selected from the available EVs to charge the required energy from ESU.

Table 6: Existence of Nash equilibrium with respect to utility function

CS	**EV 1**	**EV 2**	**EV 3**	**EV 4**
EV 1	0.133/0.128	0.133/0.082	0.133/0.123	0.131/0.118
EV 2	0.067/0.128	0.067/0.082	0.067/0.123	0.067/0.118
EV 3	0.082/0.128	0.082/0.082	0.082/0.123	0.082/0.118
EV 4	0.034/0.128	0.034/0.082	0.034/0.123	0.034/0.118

8. Conclusion

In this paper, a SDN-based DC energy management scheme is proposed using RES along with penetration of EVs. The purpose of the proposed system is to sustain the energy consumption of DC using RES. However, due to intermittent nature of RES, it becomes a challenging task. For this purpose, EVs are used to support the energy consumption of DC. A reward point scheme is proposed to attract the participation of EVs. The SDN-based energy management algorithm effectively managed the integration of various components. SDN acts as a platform to tackle the uncertainty in energy generation, energy consumption, and number of incoming EVs. An energy-aware flow scheduling scheme is proposed for optimal management of route with SDN in DC networks. Finally, an energy trading scheme is designed for optimal pricing of energy supplied to EVs that are not participating in reward point scheme. The proposed scheme was validated using workload traces and various parameters. The results obtained clearly depict the effectiveness of the proposed scheme. The results show that EVs effectively support the energy consumption of DCs when the energy generation by RES was negligible. The results shows that apart from sustaining the energy consumption of DCs, the proposed scheme helps to generate revenue by selling the excess energy to EVs.

In this work, the energy consumed for performing routine computing tasks of DC is not minimized but the energy optimization for network infrastructure is considered. In future, energy-efficient techniques such as-VM consolidation, containers, etc would be explored to minimize the energy consumption associated to the computing tasks of DCs in order to manage the sustainability of DCs without the support of EVs.

Acknowledgment

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