Real-Time Price Based Optimal Energy Mix in Smart Distribution Network

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Abstract. With the increasing penetration of Distributed Energy Resources (DERs) in Smart Distribution Networks (SDNs), balancing energy mix is a crucial task for Distribution System Operators. The aggregate consumption, generation, and power exchanged from the upstream network are essential for the Energy Management System. Appropriate allocation and scheduling of DERs and Energy Storage can minimize the total power drawn from the upstream network. This paper analyzes the Real-Time Price (RTP) based approach for optimizing the scheduling of DERs and power transfer from the upstream network. The Mixed Integer Linear Programming (MILP) based optimization approach is used to maximize the total profit made by maintaining optimal energy mix in SDNs by using the Energy from DER and Energy Storage. When upstream network's tariff is higher, the energy balance is maintained by DERs and ESSs as far as possible. It is also observed that with the reduction in the energy pricefrom DERs, power export from the SDN to the upstream network is increased.

Keywords: Day ahead pricing, DERs, Energy Management System, Renewable Energy Sources, Optimal Energy Mix

1 Introduction

Global awareness about environmental concerns, economic challenges and increased energy demand have encouraged power system operators to incorporate more renewable energy[1] in the power system. The transmission system operators (TSOs) focus more on reduced inertia[2] due to the large volume of DERs interfaced through a static conversion system. However, the distribution system operators (DSOs) have problems like terminal voltage rise, reverse power flow, thermal over the limit of cables, [3] and obtaining an optimal energy balance in the network. The technical impacts due to the increased integration of distributed energy resources (DERs) at distribution network can be addressed by the transition of conventional operational and management approaches to the smart distribution network (SDN) paradigm [4].

During recent years substantial explorations have been accompanied on the topics of optimal operation of SDN, and diverse techniques have been demonstrated in the literature. Most of the previous studies in SDN cover identifying optimal allocation and optimal sizing of DERs [9–12].In [9], the authors presents a robust approach using Jaya Algorithm for optimal placement of DERs in radial distribution networks to minimize the load demand. The optimum penetration level of

augmented Distributed Generations is studied in [10]. In [11] allocation of fixed and portable energy storage devices (ESDs) is proposed to mitigate the uncertainties of critical DERs for alleviating voltage unbalance in the system. In [12] the uncertainty of multiple RESs are handled in SDN by considering total energy procurement cost as an objective function.
Most of the research in smart distribution networks covers congestion management [13, 14] loss payment minimization [15]. In [13] scheduling flexible energy resources of prosumers for reducing network congestion is done considering iterative distribution locational marginal price. Author [14] demonstrates implementation of the market-based approach in handling the congestion in the distribution network. Authors in [15] propose an appropriate way for reducing the losses payment considering a day-ahead energy market price in a distribution system with energy storage systems and demand response.

In [16] the author presents economic environmental energy-saving day-ahead scheduling problem of power systems considering wind generation (WG) and demand response (DR) using multi-objective dynamic optimal power flow (MDOPF) to minimize fuel cost, carbon emission, and active power losses. An attempt to reduce the operating cost based on the local transactive market is analyzed for a radial distribution system in [17].

In this paper, an optimal energy mix is obtained based on the day ahead RTP by formulating a Mixed Integer Linear Programe to compute the optimization problem.The main contribution made by authors in this article are:

1. Develop a MILP to compute the optimization problem for a system with distributed generations (PVs and Wind), Energy Storage and Microhydro Plants (MHPs).
2. Obtain the optimal scheduling of charging and discharging of ESSs and generation schedule of MHPs based on Real Time Pricing.
3. The efficacy of the proposed method is validated by achieving the energy balance by proper scheduling and reducing the power exchange from the upstream network.

Section II describes the problem formulation approaches especially mathematical modeling of system components, objective functions, and operating constraints. Simulation Requirements, system data, cases, obtained results after simulation, and discussion is described in section III. finally, the last section concludes the main contribution of the work done in this analysis.

2 Problem Formulation

In this paper, an approach for optimal energy mix among PVs, WTs, ESS, MHP, and power exchanged from the upstream network are explored. In this section modeling of the system components especially ESS and MHP, the main objective function to be fulfilled and corresponding operating constraints are discussed.

2.1 Modeling of System Components

In this subsection, mathematical modeling of the system under consideration is described. Mainly, the mathematical modeling of controllable sources Energy Storage System and MHP is highlighted. PV and Wind are considered as unregulated renewable energy sources for this analysis and hence a detailed description of them is left behind.

Modeling of ESS : ESS is modeled based on the linearized power output [15] between ± P^{ESS}_{rated}. where, P^{ESS}_{rated} is the rated power output of ESS. The power output from the ESS for i number of setpoint is given by

$$P^{ESS}_{out}(i) = \frac{P^{ESS}_{rated} - (-P^{ESS}_{rated})}{N^{ESS}_{setpoint} - 1} * (i-1) - P^{ESS}_{rated},\ for\, i = 1, 2, ..., N^{ESS}_{setpoint} \tag{1}$$

where, $P^{ESS}_{out}(i)$ is the output power from ESS at i^{th} setpoint. P^{ESS}_{rated} is the rated power of ESS. $N^{ESS}_{setpoint}$ is the number of setpoint level of ESS. The ESS can operate at one setpoint at a time. This define a constraint for ESS setpoint.

Relative change of ESS state of charge (SOC) level due to ESS operation at a time is defined as the ratio of power output at that time to rated Energy of the ESS E^{ESS}_{rated}. The relative change in SOC is given by Equation (2).

$$\Delta SOC^{ESS}_{t} = \pm \frac{t}{E^{ESS}_{rated}} * P^{ESS}_{out}(t),\ \ t\varepsilon T \tag{2}$$

The SOC of ESS at a particular time is the sum of relative change in SOC and the SOC of ESS at an instant prior to that particular instant. Equation (3)

$$SOC^{ESS}_{t} = SOC^{ESS}_{t-1} + \Delta SOC^{ESS}_{t} \tag{3}$$

the state of charge of ESS is limited to a minimum and maximum values defined before the optimization process. This will define a constraint for the operation of ESS.

$$SOC^{ESS}_{minimum} \leq SOC^{ESS}_{t} \leq SOC^{ESS}_{maximum} \tag{4}$$

The charging and discharging power can be obtained by considering the output power from the ESS. If the power output is less than zero then charging action is performed in ESS while if the power output is higher than one then discharging action is performed. Equations (5) and (6) are the conditions for the ESS to be in charging or discharging mode based on the SOC and power output from ESS.

$$P^{ESS}_{Charging} = P^{ESS}_{out},\ if\ P^{ESS}_{out} < 0 \tag{5}$$

$$P^{ESS}_{discharging} = P^{ESS}_{out},\ if\ P^{ESS}_{out} > 0 \tag{6}$$

Table 1lists out the technical and operational limits of ESS considered in this analysis.

Modeling of MHP : Microhydro power plants (MHPs) are small hydropower plants [18] specially designed to fulfill the local power demand in a small community. Normally the micro-hydro are only operated when they are to fulfill the minimum amount of load demand to make the operation economical. In this analysis, MHP is designed as linearized power output between the minimum and maximum power output for a specific level of operational setpoints. Equation (7) gives the linearized output of the power output from MHP.

Table 1. Technical characteristics and operational limit of ESS [15]

Parameter	Value	Unit
P_{rated}^{ESS}	0.6	MW
E_{rated}^{ESS}	1	MWh
$SOC_{initial}^{ESS}$	0.2	-
$SOC_{minimum}^{ESS}$	0.1	-
$SOC_{maximum}^{ESS}$	0.9	-
$N_{setpoint}^{ESS}$	4	-

$$P^{MHP}(i) = \frac{P_{max}^{MHP} - P_{min}^{MHP}}{N_{setpoint}^{MHP} - 1} * (i-1) + P_{min}^{MHP},\ \ i = 1, 2, ..., N_{setpoint}^{MHP} \tag{7}$$

To optimize the power output from MHP, a new binary optimization variable is y introduced. y check the suitable power output from MHP for the economic operation of MHP. The power output of MHP is given by Equation (8).

$$P_{out}^{MHP} = \sum y * P^{MHP} \tag{8}$$

However, this power output P_{out}^{MHP} is desired to be operated at a range of minimum and maximum set values. This defines two operational constraints Equations (9) and (10).

$$P_{out}^{MHP} \geq P_{minimum}^{MHP} \tag{9}$$

$$P_{out}^{MHP} \leq P_{maximum}^{MHP} \tag{10}$$

MHP is designed to operate at a limited operational cost due to the limitation of operating manpower in remote isolated areas and to minimize the losses incurred during the operation. Equation (11) gives the expression for operation cost at a particular setpoint of operation. Fixed cost in the expression is a factor that is required just to operate the MHPs.

$$Operational\ Cost_{setpoint}^{MHP} = Fixed\,Cost * P_{out}^{MHP}(i),\ i = 1, 2, ..., N_{setpoint}^{MHP} \tag{11}$$

The total operational cost given by Equation (12) is defined as the cost of operation for a particular level of operation of MHP

$$Total\ Operational\ cost = \sum y. * Operational\ Cost_{setpoint}^{MHP} \tag{12}$$

where y is the binary optimization variable to check the level of the setpoint of operation of MHP. The total operational cost is limited by a constraint to manage the economics of the MHP operation. Equation (13) gives the constraint to limit the operational cost of MHP.

$$Total\ Operational\ cost \leq Operational\ Cost_{limit}^{MHP} \tag{13}$$

Table 2lists out the technical and operational limits of MHP considered in this analysis.

Table 2. Technical characteristics and operational limit of MHP [18]

Parameter	Value	Unit
$P^{MHP}_{maximum}$	0.8	MW
$P^{MHP}_{minimum}$	0.2	MW
$Fixed\, cost$	0.0315	Eur/MW
$Operational\, Cost^{MHP}_{limit}$	0.5	Eur/day
$N^{MHP}_{setpoint}$	4	-

Modeling of Power balance : In order to balance the supply and demand of energy in the SDN, following power flow constraints and operational limits [15] should be satisfied. The fundamental concept behind this is to fulfill the power demand by power production from available different sources. Equations (14) and (15) give the power balance equation for the study.

$$PT_t + P^{wind}_t + P^{PV}_t - PD_t + P^{ESS}_t + P^{MHP}_t = 0 \tag{14}$$

$$QT_t + Q^{wind}_t + Q^{PV}_t - QD_t + Q^{MHP}_t = 0 \tag{15}$$

where,

PT_t and QT_t are the net active and reactive power transfered from upstream network. P^{PV}_t, P^{wind}_t, PD_t, P^{ch}_t, P^{dch}_t, P^{MHP}_t, Q^{wind}_t, QD_t and Q^{MHP}_t are the active and reactive power generation and demand from PV, wind, battery, load and MHP respectively. However in this analysis, only active power balance is considered as a part of optimization approach.

To use the DERs as a first priority source of a generation when the power import and export from the upstream network is limited to some power import and power export limit. The power will be exported from the SDN if their excess power generation from DERs and will be imported from the upstream network if there is local generation may not fulfill the load demand. These imports and exports are defined as the power exchange.

$$PT_t = P^{wind}_t + P^{PV}_t - PD_t + P^{ESS}_t + P^{MHP}_t \tag{16}$$

The power transferred can be defined as import or export depending on the following cases

$$PT = \begin{cases} P_{import} & if PT < 0 \\ P_{export} & if PT > 0 \end{cases} \tag{17}$$

The import and export limits are given by Equations (18) and (19)

$$P_{export} \leq PT_{limit} \tag{18}$$

$$P_{import} \geq -PT_{limit} \tag{19}$$

Table 3. Power import and export limit of SDN

Parameter	Value	Unit
P_{import}	0.8	MW
P_{export}	0.8	MW

2.2 Objective Function

The main objective of the proposed method is to provide the optimal energy mix for DERs especially ESS and controllable MHP in order to maximize the profit from optimal energy sharing from different energy sources. Following optimization problem is solved.

$$Profit = \sum_{t \epsilon \Omega_T} EC_t \tag{20}$$

$$EC_t = \sum_{i \epsilon n} \left[P_i^{ESS} - P_i^{D} \right] * poolprice_i + \sum_{i \epsilon n} \left[P_i^{MHP} + P_i^{wind} + P_i^{PV} \right] * average(poolprice) \tag{21}$$

where Profit is the total profit obtained while balancing the energy supply and demand and EC_t is the hourly cost of energy at time t. The hourly energy price for wind, PV, and power from the micro hydropower plant are considered the average of the pool price. Proper allocation of energy from ESS controllable MHP will increase the profit from the total cost paid for the energy balance.

2.3 Operating Constraints

Some of the operating constraints that have to be fulfilled are described below. Constraints are Equations (4), (9),(10), (13), (18), and (19).

3 Simulation Results and Discussion

3.1 Overall Methodology

The Block diagram shown in Figure(1) describes the overall methodology of obtaining optimal energy mix in SDN. Initially, the load data and the generated data from DERs (PV and Wind) are measured/predicted for a period of 24 hours and stored in a database. Mathematical models of ESS and MHP are developed with their operational conditionals and constraints. Then the processed data and the models are fed to an optimization block. The optimization block performs optimization based on the objective function described in Equation (21). The optimization process is executed until the optimal solution fulfilling all the requirements described in the subsection2.3. Finally, an appropriate Energy Management System is achieved for optimal energy mix in SDN by scheduling the operation of ESS and MHPs in an optimal fashion.

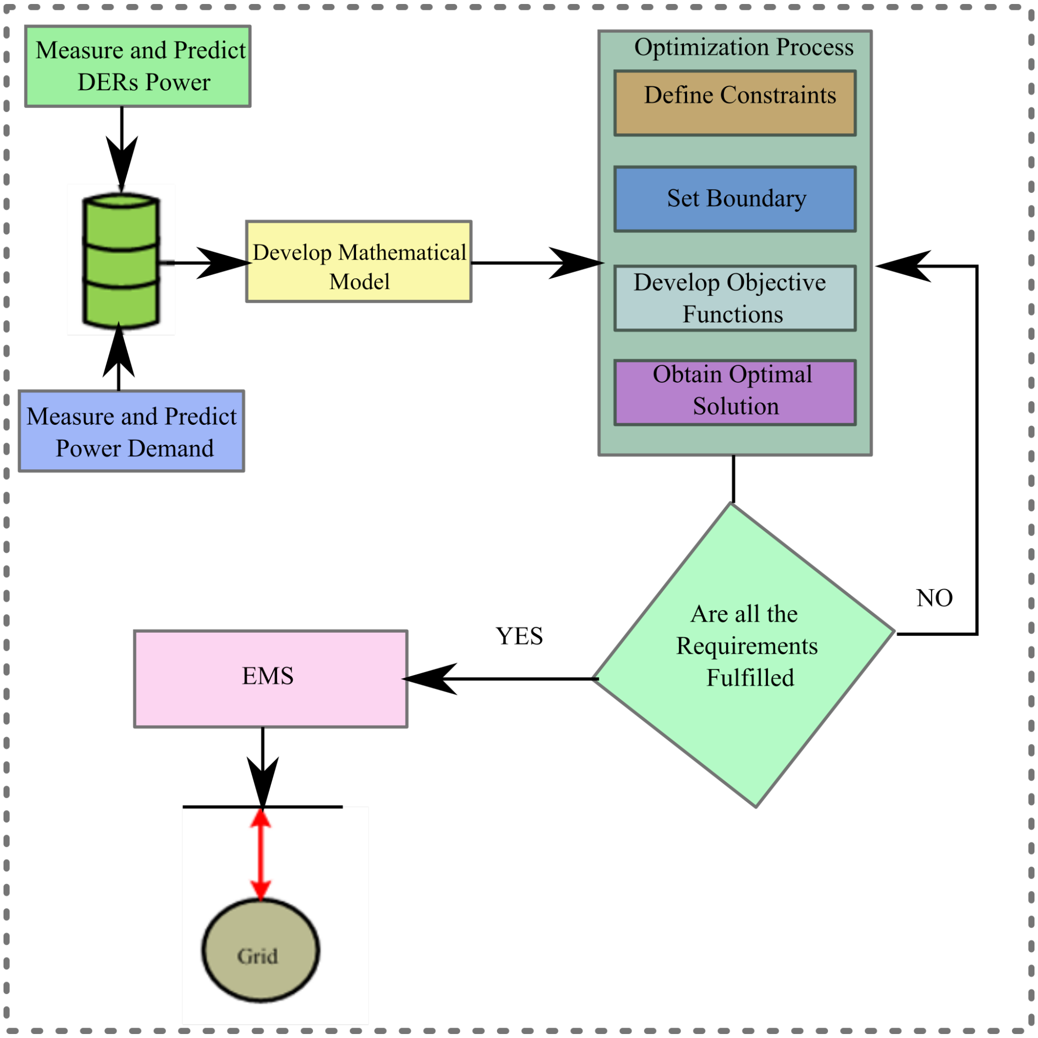


Fig. 1. The overall process of obtaining Optimal Energy Mix

3.2 System Data

Figure (2) shows the layout of the considered system. The distribution network considers is a network with 30 numbers of households. For now, the network configuration and network parameters are not considered in this analysis. The load data in the network are measured and accumulated on an hourly basis and fed into the optimization model as a single load profile. The table 4 shows the data [12] for load demand, forecasted PV, and Wind generation. The electricity price of the network is taken from [22] and is as shown together with hourly load and generation profile of PV and Wind in Figure (3). The energy pricefrom the DERs (PV and Wind) are taken as the average of the pool price to maintain constancy in the price paid to the prosumers.

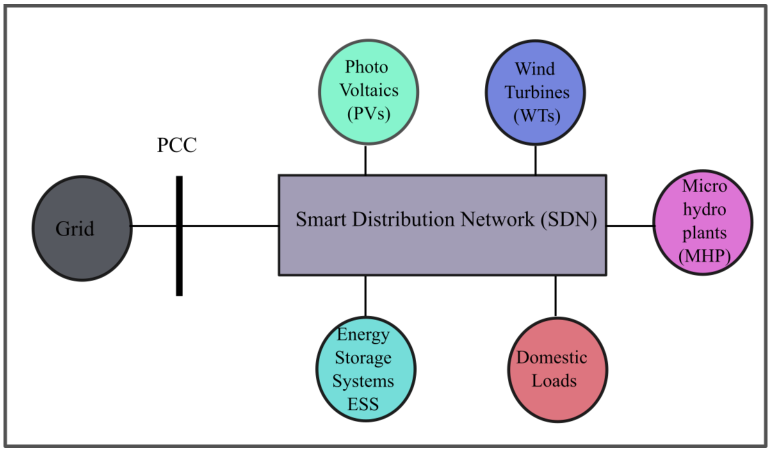


Fig. 2. System Layout of SDN Distribution Network.

3.3 Simulation Studies

The proposed optimization algorithm is implemented in a Matlab environment running on Intel (R) Core (TM) i5-8265U CPU@1.60 GHz 8GB ram and 64-bit operating system. An optimization is performed for the given system data described in the previous section. Figure (4) shows the state of charge and charging and discharging profile of ESS. ESS is charged when the energy price from the upstream network is lower and discharged to supply the energy at a higher price.

Similarly, Figure (5) shows the power exchange profile between the SDN and the upstream network. Positive values of power exchange indicate that power is exported to the upstream network. In contrast, the negative value indicates that the power is imported to the SDN to balance the energy demand. If we analyze the power profile, The SDN tries to export the power when energy price from the upstream network is higher than the energy price from the available DERs, ESS, and MHPs.

Figure (6) shows the power production schedule from the MHP. MHP operates first to fulfill the local demands first. Two case studies figures are present here to show how the generation profile changes with the change in the price of the power production from the MHPs. When the price is lower for MHPs, it will operate more time than when the price is higher.

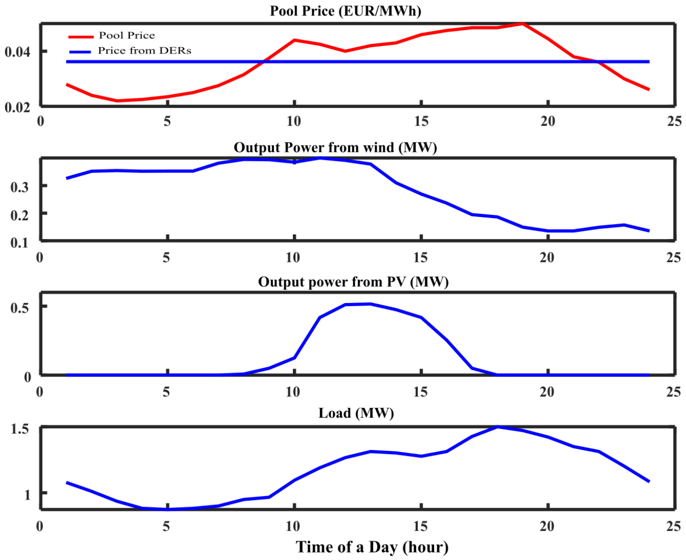


Fig. 3. Day-ahead tariff from Nord Pool [22],output power from wind, PV and variation in load

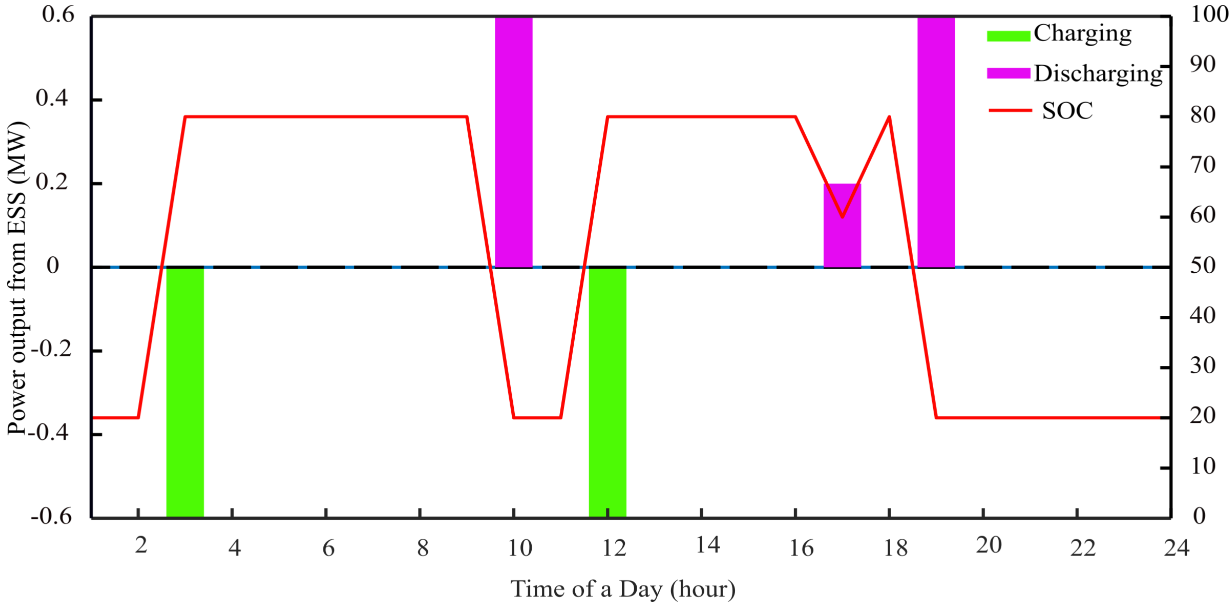


Fig. 4. State of Charge of ESS.

Table 4. Forecasted hourly demand, the output power of Wind Turbine and PV

Hour of Day	Total Load Demand[15]	P_t^{Wind}[19]	P_t^{PV}[20]
1	1.0785	0.3260	0
2	1.0110	0.3520	0
3	0.9360	0.3544	0
4	0.8820	0.3520	0
5	0.8730	0.3524	0
6	0.8820	0.3524	0
7	0.9000	0.3812	0
8	0.9495	0.3948	0.008
9	0.9660	0.3940	0.050
10	1.0950	0.3848	0.125
11	1.1895	0.4000	0.418
12	1.2660	0.3916	0.511
13	1.3125	0.3780	0.516
14	1.3020	0.3104	0.475
15	1.2765	0.2692	0.418
16	1.3125	0.2364	0.254
17	1.4265	0.1948	0.050
18	1.5000	0.1864	0
19	1.4715	0.1492	0
20	1.4229	0.1356	0
21	1.3500	0.1356	0
22	1.3125	0.1488	0
23	1.2015	0.1572	0
24	1.0830	0.1356	0

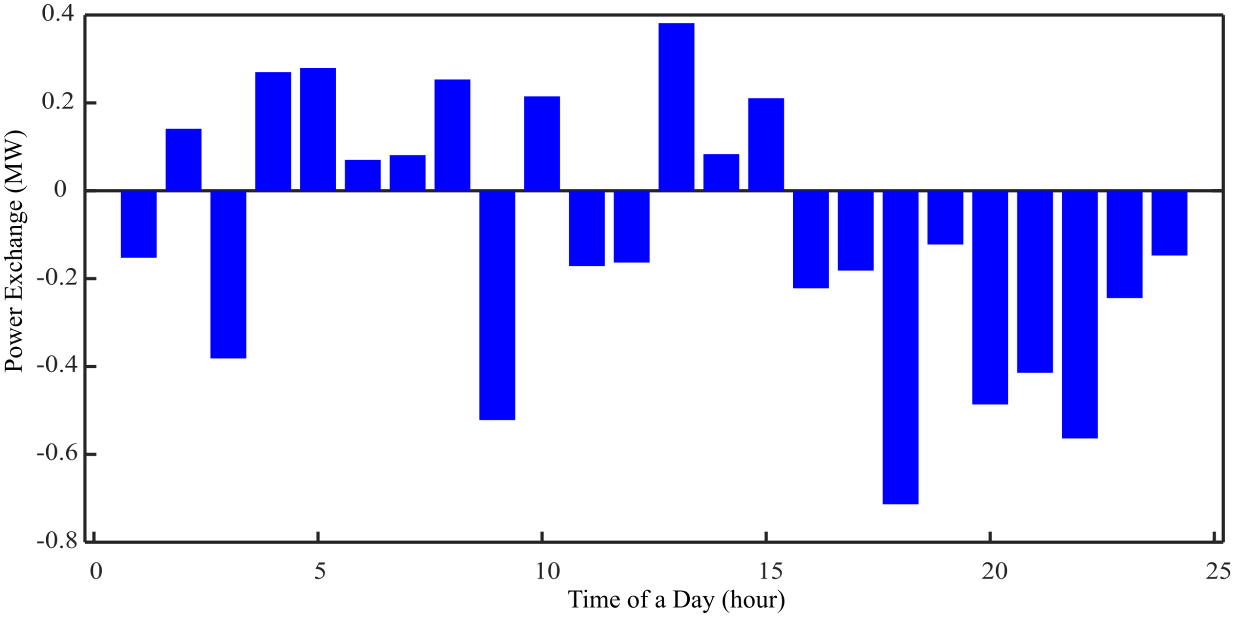


Fig. 5. Power Exchange Profile

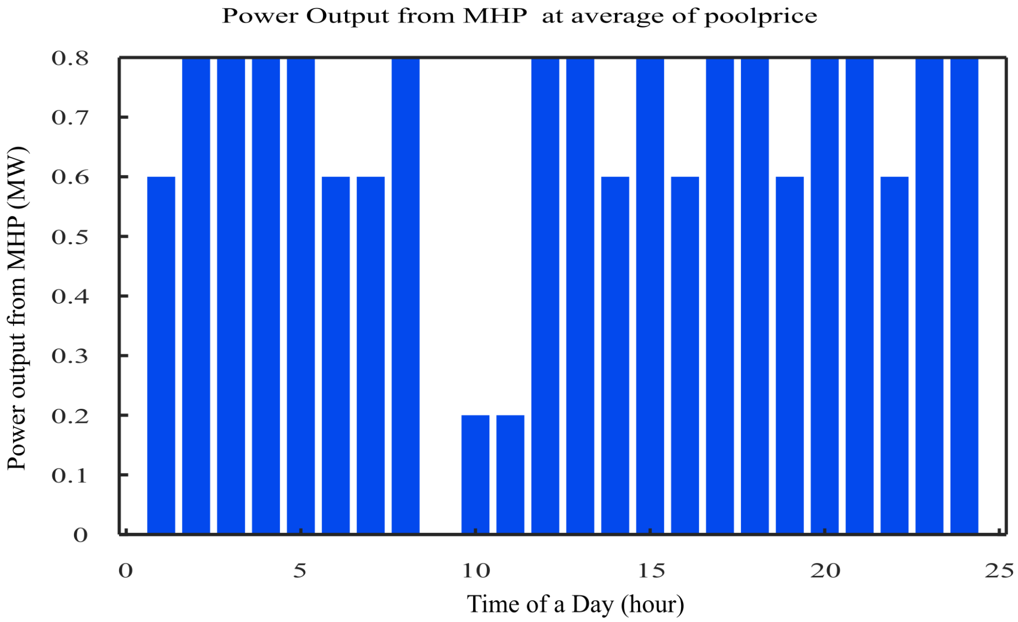
To check the effectiveness of the proposed energy mix methodologies following two cases are studied. In the first analysis, the energy price from DERs is considered the average of the energy price from the upstream network. The total power export from SDN to the upstream network is evaluated in this condition. A similar analysis with reduced energy price from DERs (20 % below the average energy price in this case) is performed, and the total power export from SDN is obtained. The table 5 shows the comparison of power export from the SDN to the upstream network in these two scenarios. When the energy price from the available DERs is lower, DERs will first fulfill the energy demand for loads and then start producing more power to export energy to the upstream network. From the table 5, it is also observed that energy export at a reduced price is more.

Table 5. Energy Export from SDN

energy price from DERs	Energy Export	Unit
at average of pool price	1.9857	MWh
at 20% *below of average of pool price*	2.1857	MWh

3.4 Discussion

From the analysis, we observed that the load demand is fulfilled first from DERs as the energy price from DERs is lower than that of the upstream network. With the increase in generation from DERs,


Power Output from MHP at average of poolprice

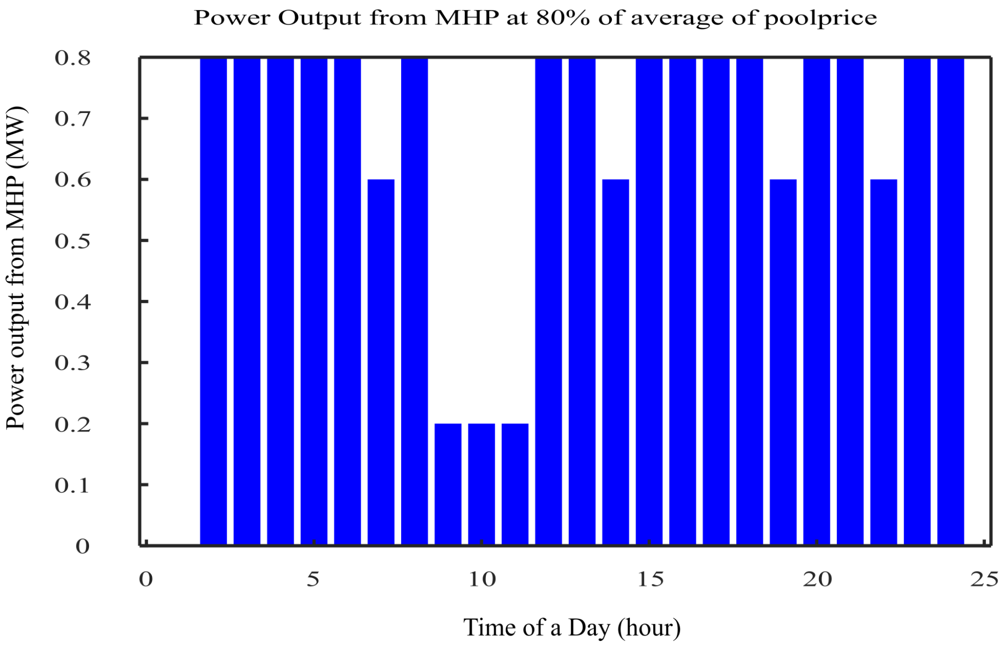

Power Output from MHP at 80% of average of poolprice

Fig. 6. Power Output from MHP

the power exchanged is reduced. The charging of the ESS is performed when the energy price from the upstream stream is lower and is discharged to fulfill the load demand (not covered by DERs) when the pool price is higher. Similarly, MHPs operate at those instances when the energy price is lower than the energy price from upstream network. The MHPs are only operated either to produce power at/above minimum setpoint value or to stop production for making the operation economical. Depending on the energy requirement, the MHPs are operated at different setpoints. However, MHPs also produce more energy when their operation makes the energy cheaper than buying from the upstream network.

4 Conclusion

This paper presents the optimal energy mix in a smart distribution network considering the day ahead real-time energy price of the network. Optimal scheduling of charging and discharging of the ESS and local generation MHP to maximize the profit by optimal scheduling of ESS and MHP in the distribution network is observed. This method can achieve the energy balance by utilizing energy sources that can produce energy at a lower price. Also, we will achieve cost-effective management of energy resources in a smart Distribution Network. The distribution system operator can plan for scheduling generation from DERs and order the deficit amount of energy from the upstream network in an optimal way using this approach. Future research in this orientation can be the implementation of regulated DERs considering network configuration and parameters of the SDN.

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