An inventive method for eco-efficient operation of home energy management system

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***Abstract*—Home energy management systems (HEMSs) based on demand response (DR) synergized with renewable energy sources (RESs) and energy storage systems (ESSs) optimal dispatch (DRSREOD) are used to implement demand-side management in homes. Such HEMSs benefit the consumer and the utility by reducing energy bills, reducing peak demands, achieving overall energy savings and enabling the sale of surplus energy. Further, a drastically rising demand of electricity has forced a number of utilities in developing countries to impose large-scale load sheddings (LSDs). A HEMS based on DRSREOD integrated with an LSD-compensating dispatchable generator (LDG) (DRSREODLDG) ensures an uninterrupted supply of power for the consumers subjected to LSD. The LDG operation to compensate the interrupted supply of power during the LSD hours; however, accompanies the release of GHGs emissions as well that need to be minimized to conserve the environment. A 3-step simulation based posteriori method is proposed to develop a scheme for eco-efficient operation of DRSREODLDG-based HEMS. The method provides the tradeoffs between the net cost of energy ($CEnet$) to be paid by the consumer, the time-based discomfort (TBD) due to shifting of home appliances (HAs) to participate in the HEMS operation and minimal emissions ($TEMiss$) from the local LDG. The search has been driven through multi-objective genetic algorithm and Pareto based optimization. The surface fit is developed using polynomial models for regression based on the least sum of squared errors and selected solutions are classified for critical tradeoff analysis to enable the consumer by choosing the best option and consulting a diverse set of eco-efficient tradeoffs between $CEnet$, TBD and $TEMiss$.**

***Index Terms*—Eco-efficient home energy management, dispatch of renewables and energy storage systems, load-shedding-compensating dispatchable generators, optimization using surface fitting techniques, multi-objective genetic algorithm, pareto optimization**

I. Introduction

Over the past few decades, demand for electrical energy has increased at a drastic pace while energy generation capabilities have not been upgraded at a sufficient rate to cope with the rising demand. The balance between demand and generation is a vital requirement for stable power system operation. The problem to maintain this balance has conventionally been addressed in the past; utilities have upgraded their centrally located generation and transmission capacities using an approach known as supply-side management. However, during the last decade, demand-side management (DSM) has emerged as an alternative method to manage the increasing demand of energy focusing on the consumer side. A home energy management system (HEMS) is used to implement DSM in a home. Major approaches for HEMS operation include price-based DR, and DR synergized with renewable energy sources (RESs) and energy storage systems (ESSs) optimal dispatch (DRSREOD) [1]. The demand response-based (DR-based) HEMS operation schedules the consumer's loads by shifting them towards the off-peak periods. Such scheduling benefits the consumer with a minimized CE based on the acceptable value of TBD [2], [3]. The DRSREOD-based HEMS operation schedules the load in coordination with the optimal dispatch of the power grid, renewable energy sources (RESs) and energy storage systems (ESSs). The operation of such HEMS introduces additional benefits by reducing energy bills, reducing peak and permanent demands, increasing overall energy savings and enabling the sale of surplus energy to the utility [4]-[8]. The aforementioned HEMSs are modeled to optimize the objectives comprising the net cost of energy, consumer discomfort/ inconvenience, and peak and permanent demands.

Further, utilities in a large number of developing countries with energy-deficient power supply networks are subjecting consumers to load shedding (LSD) for maintaining a balance between the demand and generation of energy [9]. The consumers in such systems are thus helpless to use a power supply with compromised power quality. While a number of consumers in developing countries are already participating in DSM making use of the DRSREOD-based HEMSs; the scenario has incentivized the consumers in homes to integrate load shedding-compensating dispatchable generators (LDGs) into the already installed HEMSs in order to ensure an uninterrupted supply of power [10]. DRSREOD integrated with LDG (DRSREODLDG) based HEMS adds a vital benefit of an uninterrupted supply of power to its set of advantages inherited from DRSREOD-based HEMS. The Kyoto protocol of United Nations Framework Convention on climate change has signed by 192 countries all over the world which proposes a reduction in GHG emissions through selling of emission commodities [11]. The research on HEMS now seems to focus on reducing the GHG emissions along with the other well-known objectives for energy cost(CE), time based discomfort(TBD), etc. In [12], a scheme for DR-based HEMS is presented and it is validated that implementation of the DR program effectively reduces the cost of generation on the supply-side; however, the emission on this side is reduced only when peak demand is met by high emission fuels based peaking plants. In [13], authors present a scheme for optimal scheduling of shiftable home appliances (SHAs) integrated with the optimal dispatch of RES and SB. The objectives include reductions in $CEnet$, temperature based discomfort, peak load, and the GHG emissions.

Further, in [14], an operational scheme is developed for a stand-alone HEMS operation using particle swarm optimization (PSO). In [15], an optimal dispatch scheme for a PV unit, a WTB, an ESS, a DG, and the power grid to supply a fixed load profile in a MGD is computed using GA. An algorithm for optimal sizing of LDG for DRSREODLDG-based HEMS was proposed in our recent research [10]. To implement an eco-efficient operation of DRSREODLDG-based HEMS, optimal tradeoffs between net cost of energy ($CEnet$), TBD and minimal GHG emissions ($TEMiss$) need to be computed. This research introduces a method to harness a diversified set of solutions to decision vector Tst and the related tradeoffs for $CEnet$, TBD and minimal $TEMiss$ for an eco-efficient HEMS operation.

The proposed method for an eco-efficient operation of DRSREODLDG-based HEMS is based on a three-step approach. This research evaluates the tradeoff parameters for $CEnet$ to include the cost of energy purchased from the grid, cost of energy sold to the grid and the cost of energy supplied by the LDG; $TEMiss$ to include the energy supplied by the LDG during LSD hours, EFT based on the calorific value of the fuel, the consumption efficiency of the LDG and the related emission factors for GHGs; and TBD to include the delay in the starting times of delay scheduling (DS) type and advanced completion of the job of advanced scheduling (AS) type for HAs. The trend for $TEMiss$ is exploited to screen out/ exclude a set of tradeoffs with larger values of $TEMiss$ using a constraint filtration mechanism.

The remainder of the paper is organized as follows. Related work relevant to the present research performed in recent years is presented in Section II. The system model is described in Section III. The techniques used to solve this problem are presented in Section IV. In Section V, simulations are presented to demonstrate the validity to generate schemes for DRSREODLDG-based HEMS operation in terms of Tst and the primary tradeoffs between $CEnet$, TBD and $TEMiss$. The harnessed eco-efficient tradeoff solutions are classified and a critical tradeoff analysis for the consumer is carried out in Section VII. Conclusions and future work are discussed in Section VIII.

II. Related Work

With the installation of smart grid technologies enabling DSM, a widespread deployment of DR- and DRSREOD-based HEMSs has been carried out throughout the world in the past few years [16], [17]. In recent years, authors have presented various models and methods for the optimal operation of such systems [2]-[8]. The objectives for optimal HEMS operation include minimizing CE, TBD, PAR, peak/ permanent demands and daily cost of generation. Further, utilities owning energy deficient power networks in developing countries are subjecting their consumers to LSD to balance demand and generation. In such power networks, consumers deploy a LSD-compensating DG in DRSREOD-based HEMS to ensure an uninterrupted supply of power [10]. The aforementioned objectives for optimal HEMS operation have been achieved using optimization techniques like linear programming (LP), MILP, advanced heuristics, etc.

Additionally, the issue regarding serious environmental concerns over the use of fossil fuels has been raised at international forums consistently in the past few decades. Recently, worldwide consensus has been reached to reduce the GHG emissions by selling them as commodities [11]. Such trading sets quantitative limitations on the emissions made by polluters that may include utilities, independent MGD operators and the prosumers having local fossil fuel based generations. The present scenario based on polluter pays principle has incentivized utilities to reduce not only the generation cost; however, the supply-side emissions as well while making use of the RESs installed for DRSREOD-based HEMSs [13],[18], [19]. Further, MGD operators having RESs, ESSs and DGs also include $TEMiss$ as an objective in the optimal dispatch scheme for their systems [14], [15], [20]. Furthermore, in energy-deficient power networks, DRSREODLDG-based HEMSs having LSD-compensating DGs are used to ensure an uninterrupted supply of power during LSD hours [10]. The operation of LDG in such HEMSs; however, does accompany the release of emissions, that needs to be minimized.

The related work includes the recent research on models and methods to achieve important objectives for DR and DRSREOD-based HEMSs including reductions in $TEMiss$ (supply-side), $CEnet$, and TBD; for MGDs including reductions in $TEMiss$ and $CEnet$; and for DRSREODLDG-based HEMS including reductions in $TEMiss$ (local), $CEnet$ and TBD. In [13], authors present a scheme for optimal scheduling of SHAs integrated with the optimal dispatch of RES, SB, and the power grid. The objectives include reductions in $CEnet$, temperature based discomfort, peak load, and the supply-side emissions. In [14], a solution for DRSREOD-based HEMS operations for a stand-alone home including WTB, DG, and SB is computed using PSO. The local fossil fueled DG is operated at rated power for an improved efficiency and reduced emissions. A separate objective function for emissions; however, is not included. An optimal dispatch for an MGD is computed in [15] using GA. The model does not include load shifting while computing the dispatch for power sources. A method to compute an optimal dispatch of RESs and DGs for a MGD is presented in [20].

In developing countries with energy-deficient power supply networks, utilities are subjecting consumers to LSD in order to maintain the balance between demand and generation of energy [9], [10]. An algorithm for optimal sizing of an LDG for DRSREOD-based HEMS was presented in our recent research [10]; however, such a DG does introduce emissions when operated during LSD hours. Based on the recent scenario for quantitative restrictions on carbon emissions, research on the optimized operation of DRSREODLDG-based HEMS focusing reduction in $TEMiss$ looks pertinent. A simulation-based posteriori method for an eco-efficient operation of DRSREODLDG-based HEMS takes into account the tradeoffs between $CEnet$, TBD, and minimal $TEMmiss$ is proposed.

III. System model

The major components of such HEMSs include home appliances, renewable energy sources, an energy storage system, an LSD-compensating DG, a HEMS controller, a local communication network, and a smart meter for communication between the consumer and the utility. The proposed optimal operation for such HEMS are based on DR synergized with the optimal dispatch scheme for RESs, ESSs and an LDG. The operating scheme takes into account the MS of SHAs, the shared parallel operation of the PV unit, the SB and the power grid, and the energy sold to the grid based on the parametric values of power vector from PV(P_{pv}), vectors of the state of charge (SoC), the maximum charge/discharge rates, and the tariff scheme. The PV unit is the preferred source that supply the scheduled loads. Any excess PV energy in a time slot is stored in the SB that is used to supply the load during peak hours or is sold to the grid for a monetary benefit. However, during LSD hours, the excess energy from the PV unit, if available after supplying the load and charging the SB, is dissipated in a dummy load. The LDG supplies the scheduled load during load shedding hours in parallel with the PV unit and the SB to avoid power interruptions. The operation of the LDG in such systems ensures an uninterrupted supply of power; however, such operation of the LDG accompanies the release of GHGs emissions as well. The problem for DRSREODLDG-based HEMS operation has been formulated as multi-objective-optimization (MOO) to minimize $CEnet$, TBD, and $TEMiss$.

A three-step simulation based posteriori method is proposed to provide tradeoff solutions for an eco-efficient operation of DRSREODLDG-based HEMS. The method evluates the harness eco-efficient schemes for HEMS operation in terms of Tst and the related tradeoffs for $CEnet$, TBD, and minimal $TEMiss$. At step-1, primary tradeoffs solutions for $CEnet$, TBD, and $TEMiss$ are generated using MOGA/ PO based heuristic proposed in this work. At steps-2, the primary tradeoff solutions are passed through an AVCF to filter out the tradeoffs with extremely high and above average values of $TEMiss$. The filtrate is then passed through an ASCF to screen out the tradeoffs with even the marginally higher values of $TEMiss$ at step-3. The simulations to validate the method for harnessing the desired tradeoffs for eco-efficient operation of DRSREODLDG-based HEMS are presented in section V. Major components of the proposed model for DRSREODLDG-based HEMS are presented below.

A. Parameters for scheduling

A scheduling resolution of 10 minutes/ slot has been adopted. To formulate the HEMS operations, a time horizon of 24 hours is sub-divided into 144 slots. While scheduling, each SHA is to be operated once within the proposed horizon for a specified number of slots. The proposed model for HEMS operation is based on a dynamic electricity tariff, an IBR scheme, a PV system, an SB, LDG and SHAs. The specifications of these parameters are taken from [10].

B. Step-1 to generate operating schemes and the primary tradeoffs for DRSREODLDG-based HEMS

This step computes a set of primary tradeoff solutions for optimized HEMS operation based on MS of SHAs synergized with the optimal dispatch of the PV system, the SB, the grid, and an LDG. The LDG supplies the load only during LSD hours in coordination with the PV unit and the SB. Tradeoffs for $CEnet$, TBD, and $TEMiss$ are based on the underlying scheme for HEMS operation. At the start, vector Tst for SHAs is generated that is followed by the production of $Pschd$ vector. The PV system is regarded as the preferred source to directly supply scheduled load ($Pschd$). The dispatch planning is mainly based on the excess PV energy in each slot denoted by $Pres$ which is the arithmetic difference between Ppv and $Pschd$. Two main cases arise with regard to the relative values of these two quantities and in each case, state of charge (SoC), the maximum charge/discharge rates, the grid status and the power from the LDG play major roles in the dispatch. In the first case, where excess PV energy is available, the energy is stored in the SB if SoC is less than its maximum value; otherwise, it is sold to the grid. However, during LSD hours, the excess energy that would be sold to the grid is instead supplied to a dummy load. Hence, any excess energy left after charging the SB is sold to the grid. However, during LSD hours, the excess energy that would have been sold to the grid is instead supplied to a dummy load. In the second case, in which Ppv is less than or equal to $Pschd$, the PV energy is insufficient to completely supply the load. The residual energy in this case will be supplied from the grid if SoC is less than or equal to its minimum limit or from the SB otherwise. Moreover, the SB will still also not be discharged if cheap energy is available from the grid. However, during LSD hours, the LDG will supply the load in place of the grid. SB shall supply the load only during peak hours when the cost of energy is greater than a maximum price limit. If the minimum computed value is equal to the maximum discharge rate or to the residual capacity of the SB before discharging to the minimum SoC, then one of these constraints is restricting the ability to supply the full load from the SB, and the remaining load must be supplied from the grid. However, during LSD hour, the LDG will supply the remaining load in place of the grid. For each slot in the scheduling horizon, one of the above two cases will hold, the vectors Ppv, Pgd, Pds, and Pgn will be computed for dispatch accordingly. Similarly, the loads for each slot are computed for $Pschd, Pch, Pdl$, and $Psold$. $TEMiss$ is computed (applying EFT) for the net generation from LDG. $CEnet$ is computed by arithmetically adding CE

(applying PE/IBR), cost of generation from LDG (applying PEg) and cost of energy sold to the grid (applying PEf). The values for the mentioned objective functions are computed for each MOGA iteration.

C. Step-2 and Step-3 for filtration mechanism to harness eco-efficient tradeoffs for DRSREODLDG-based HEMS

The filtration process is computed in two steps as stated below:

Step-2: An AVCF based on the average value of $TEMiss$ is developed taking into account all of the primary tradeoffs. The residuals for $TEMiss$ ($TEMiss\_Resid\_avg$) for each solution are then computed. A tradeoff solution with the value of $TEMiss\_Resid\_avg$ less than 0 indicates an above average value for $TEMiss$ and all such tradeoffs are filtered out. The tradeoff solutions with average (or less than average) $TEMiss$ values are collected and forwarded to step-3 for further processing.

Step-3: An ASCF based on the average surface fit (using polynomial-based regression) is developed making use of the tradeoff solutions forwarded from step-2. The residuals for $TEMiss$ ($TEMiss\_Resid\_avgs$) for each solution are then computed by taking the difference between the $TEMiss$ and the average surface fit of $TEMiss$ computed in terms of $CEnet$ and TBD. A tradeoff solution with the value of $TEMiss\_Resid\_avgs$ less than 0 indicates the $TEMiss$ value greater than the respective value on the average surface fit, and all such tradeoffs are filtered out. The remaining trade-off solutions with the $TEMiss$ values equal to (or less than) the respective values on the average surface fit are selected and declared final eco-efficient tradeoffs for DRSREODLDG-based HEMS operation.

IV. Simulations for DRSREODLDG-based HEMS operation and the filtration mechanism to harness eco-efficient tradeoffs solutions

Simulations were conducted using MATLAB 2015. The simulations reported in subsection A are based on step-1. They demonstrate the validity of MOGA/ PO based heuristic for DRSREODLDG-based HEMS to compute operational schemes for SHAs in terms of vector Tst and the primary tradeoffs for $CEnet$, TBD and $TEMiss$. The results of simulations enable analyzing the trends exhibited by the trade-off parameters taking into consideration vital factors affecting these parameters. The critical analysis of the primary tradeoffs enabled designing a filtration mechanism to extract desired set of eco-efficient tradeoff solutions with minimal $TEMiss$. The simulations reported in subsection B are based on step-2. They demonstrated the validity of the filtration mechanism to harness eco-efficient tradeoffs. Regression based polynomial formulations and the procedure to finalize the model fits for the proposed mechanism are also elaborated in subsection B. Simulations have been conducted for the following:

-DRSREODLDG-based HEMS operation to compute primary tradeoffs for HEMS (based on algorithm 1/ step-1).

-Application of filtration mechanism to harness eco-efficient tradeoffs for HEMS (based on algorithm 2/ step-2 and step-3).

A. Simulations for DRSREODLDG-based HEMS operation to compute primary tradeoffs using step-1

Simulations were performed to validate the DRSREODLDG-based HEMS operation using step-1. Operating schemes for SHAs in terms of Tst and the primary tradeoffs were computed. The trends exhibited by the tradeoff parameters were analyzed. Critical analysis for validating the relation between the tradeoff parameter: $TEMiss$ and the tradeoffs for $CEnet$, TBD, enabled designing a filtration mechanism required to harness the desired eco-efficient tradeoff solutions with minimal $TEMiss$ from a large set of primary tradeoffs.

For the simulations, a 2-stage ToU tariff scheme with an IBR value of 1.4 was considered. This consists of a rate of 15 Cents/kWh during the peak hours from 19:00 to 23:00 (slot numbers 115-138) hours and a rate of 9 Cents/kWh during the rest of the day are taken from [10]. For the application of the IBR factor, a threshold power demand of 2.4 kW was considered. A feed-in tariff, PEf, valued at 0.7 times of PE was considered for the PV energy sold to the grid. The detailed specifications and the control parameters for the NSHAs, SHAs, PV system, SB, inverter and the LDG to implement the simulations for DRSREODLDG-based HEMS operation are taken from [10].

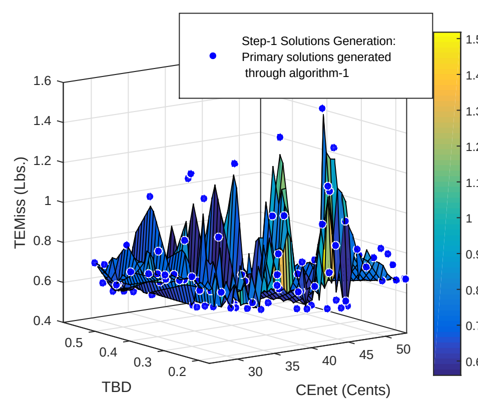

Fig. 1. Primary tradeoff solutions with un-even surface for $TEMiss$ generated through step-1.

The primary tradeoffs are graphically shown in Fig. 1. The trends exhibited by the tradeoff parameters and the relationship between them has been analyzed to approach a filtration mechanism that enables harnessing tradeoffs with diversified options for $CEnet$, TBD, and minimal value of $TEMiss$.

The tradeoff parameter $CEnet$ is based on the dispatch from various sources to supply the scheduled load and the energy sold to the utility. The rates for energies including PE, PEf and PEg in different slots play vital role in the computation of $CEnet$. The loss of the harnessed PV energy due to the unavailability of the grid, given by Pdl, is another important factor affecting the value of $CEnet$. The parameter $TEMiss$ primarily depends on the energy supplied by the LDG, Pgn, during LSD hours. The EFT for the LDG is also important while evaluating $TEMiss$. The TBD is based on the time shift of SHAs from their preferred times of operation. The relationships between the tradeoff parameters for the primary tradeoff solutions are graphically presented in Fig. 2.

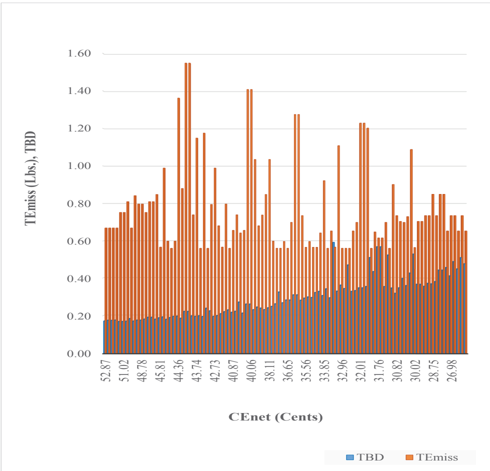

Fig. 2. Relations among primary tradeoffs for CEnet, TBD and TEMiss using step-1

The trends exhibited by the tradeoff parameters comprising $CEnet$, TBD and $TEMiss$ are analyzed in subsection 1 to 3 below. The primary tradeoffs with extreme values of the parameters have especially been investigated.

1) Trends for $CEnet$: The objective to minimize the $CEnet$ is mainly based on the following factors: 1) Maximized usage of the PV energy to supply the load directly: This avoids the loss of energy in the SB due to storage/re-use of the PV energy while supplying the load (a net loss of 20% has been assumed for the SB). The energy thus saved enables to reduce the demand from the grid and the LDG which ultimately results in a reduced value of $CEnet$. 2) Maximized usage of the stored PV energy to supply the load during the peak hours: This reduces the energy to be supplied from the grid during the peak hours as well as from the LDG during the peak LSD hours that results in a reduced value of $CEnet$. 3) Selling of the extra PV energy to the utility: A direct usage of the energy from the PV unit is better than selling it to the utility as PEf is generally lesser than the PE (PEf is assumed as 70% of the PE). However, it is beneficial to sell the PV energy to the utility, if surplus of it is available after supplying $Pschd$ and the charging load. The above-mentioned factors enable in reducing the $CEnet$ parameter through an optimal use of the PV energy based on the PE, PEf, PEg and the SB efficiency. Other factors to reduce $CEnet$ parameter include the followings: 1) Load shifting towards the off-peak hours: The load left after being supplied from the PV and the SB unit should have been shifted towards off-peak hours. This shifting minimizes the $CEnet$ based on the tariff PE. 2) Load to be supplied by the LDG during LSD hours: The algorithm enables supply of the energy from the LDG during LSD hours. If more load is shifted towards LSD hours, LDG is required to supply that load in coordination with the PV/SB at a higher cost of energy (PEg) that results in an increased value of $CEnet$. 3) Loss of the harnessed PV energy: During the LSD hours, the excess energy from the PV unit, if available, after supplying the scheduled load and charging the SB is ought to be dissipated in a dummy load. The mentioned energy, designated as Pdl, represents a loss of the PV energy that could not be sold due to the unavailability of the grid. The Pdl has been identified as a factor of vital importance for reducing $CEnet$. Fig. 3 reveals a direct relationship between the $CEnet$ and the Pdl. The Pdl needs to be minimized to achieve an optimal value of $CEnet$. A larger Pdl indicates a loss of the PV energy due to lesser shifting of the load (including charging of the SB) towards the LSD hours having the harnessed PV that results in a larger $CEnet$.

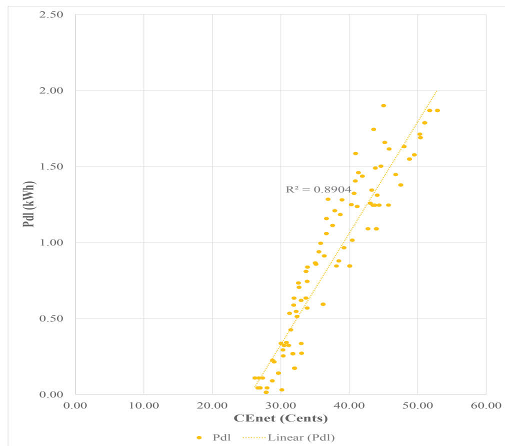

Fig. 3. Relation between $CEnet$ and Pdl for DRSREODLDG-based HEMS

To investigate the variations in $CEnet$ parameter based on the above mentioned 6 number of factors, solution-1 and solution-100 with the maximum and the minimum values of $CEnet$ are analyzed as case studies. The analysis is based on the related HEMS operation including the power profiles for the loads and the dispatch scheme for the power sources and the SB.

Solution-1 shows a $CEnet$ value of 52.87 Cents, the largest of all solutions. This largest value of $CEnet$ may be analyzed based on the above-mentioned factors by focusing on the power profiles for this solution shown in Fig. 4.

First, a very small portion of the load ($Pschd$) has been supplied directly from the PV energy that is available from time slot no. 37. Some of the available PV energy has been used to charge the SB while most of the PV energy is sold to the utility at cheap rates (PEf equals 70% of PE). A part of the load, instead of being supplied directly from the PV unit, is shifted towards the off-peak slots and supplied from the grid at the off-peak time rate. This load thus has been supplied at a net 30% increased cost of the energy as compared to the cost of energy sold to the grid. Second, a load larger than the capacity of the SB is shifted towards the peak-time slots. An average load of 0.21 kWh is thus

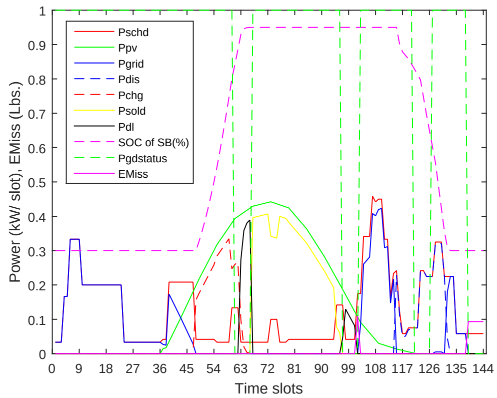

Fig. 4. Power and emission profiles for DRSREODLDG-based HEMS operation for solution-1

supplied from the grid during peak time slot nos. 132-134. The $CEnet$ could be reduced if the load exceeding the capacity of the SB was shifted towards off-peak time. Third, a net load of 0.348 kWh has been supplied from the LDG during LSD based slot nos. 139-144 at a rate of PEg (viz higher than PE). This load is based on NSHAs only and it can not be shifted. However, the LDG also supplies a load of 0.068 kWh during slot no. 102 that may be shifted towards the grid/ PV to reduce the $CEnet$. Fourth, the least of the load has been shifted within the PV harnessed LSD hours starting from slot nos. 61 and 97. Under this scenario, 1.87 kWh of the PV energy has been lost/ dumped during slot nos. 63-66 and slot nos. 97-101. More load could be shifted towards the mentioned slots to minimize the loss of the harnessed energy from the PV and thus to reduce the $CEnet$. In brief, a load shifting resulted in a non-optimal use of the PV energy, a very large value of the Pdl and other aforementioned factors resulted in the largest value of $CEnet$ for this solution. Solution-100, on the other hand exhibits the lowest $CEnet$ value of 26.22 Cents that is again based on the aforementioned factors. The lowest value of $CEnet$ may again be analyzed by focusing on the corresponding power profiles for the solution as shown in Fig. 5.

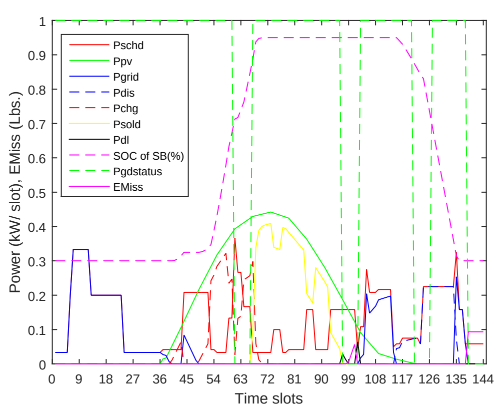

Fig. 5. Power and emission profiles for DRSREODLDG-based HEMS operation for solution-100

First, a larger portion of the load ($Pschd$), as compared to solution-1, has been supplied directly from the PV that is available from time slot no. 37. The harnessed PV energy has been used to charge the SB as well as to supply the maximum of the load, while a smaller value of the PV energy is sold to the utility at cheap rates. Second, the remaining load viz smaller as compared to solution-1 has been shifted towards the peak time slots so that the SB is able to supply most of the said load. Accordingly, an average load of 0.189 kWh is left to be supplied by the grid during the peak time slot nos. 135-137 that is smaller as compared to the same load in solution-1. Third, the LDG supplies a total energy of 0.054 kWh during slot nos. 100-101, that is smaller as compared to the same parameter in solution-1. Fourth, most of the load has been shifted towards the PV harnessed LSD hours and hence Pdl exhibits a minimal value 0.11 kWh. In brief, a load shifting enabling an optimal use of the PV energy, minimized value of Pdl and other aforementioned factors resulted in the lowest $CEnet$ for this solution. Similarly, the solutions with intermediate value of $CEnet$ may also be validated by focusing the same above mentioned factors affecting $CEnet$.

2) Trends for TBD: The value of TBD is based on the total time shifts of the SHAs from the preferred times ($STslot$ or $ENslot$ based on type of scheduling) provided by the consumers. It depends on the decision vector Tst through step-1. The simulations reveal an exponential relation between the $CEnet$ and TBD as shown in Fig. 6. The TBD increases exponentially while reducing the $CEnet$. The relationship between the $CEnet$ and TBD is very important in the context of the consumer's welfare. The optimal solutions provide diverse choices to the consumer for tradeoffs between $CEnet$ and TBD. However, it has been observed that $CEnet$ cannot be reduced beyond a specific value after the TBD reaches a knee-point value. A knee-point value of 0.48 for TBD may be realized from Fig. 6.

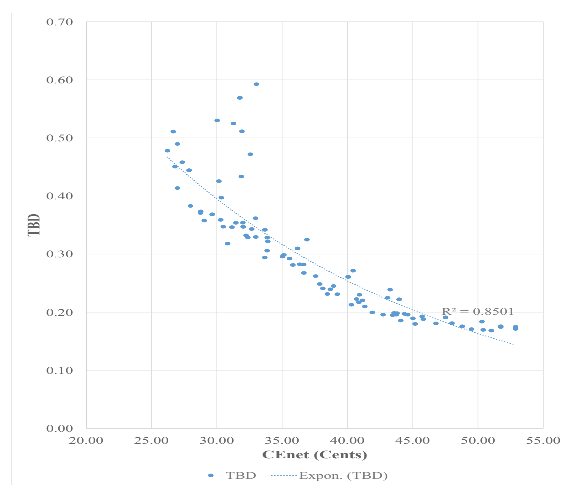

Fig. 6. Relation between $CEnet$ and TBD for a DRSREODLDG-based HEMS

On the other hand, the relation between the TBD and $TEMiss$ for DRSREODLDG-based HEMS is highly un-even as shown in Fig. 7. Such relations are not possible to be defined using standard techniques.

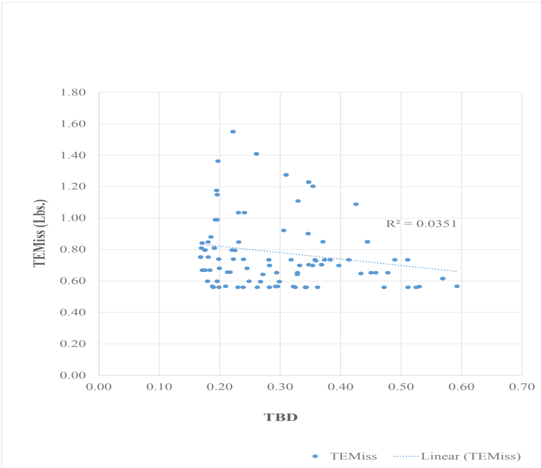

Fig. 7. Relation between TBD and $TEMiss$ for a DRSREODLDG-based HEMS

3) Trends for $TEMiss$: The variation in $TEMiss$ is analyzed based on the primary tradeoffs presented in the Fig. 2. Fig. 2 exhibits an extremely uneven variations in $TEMiss$ as related to $CEnet$ (and TBD), especially around the center of the data. The solution-23 with the largest and solution-27 with the smallest values of $TEMiss$ are analyzed as case studies.

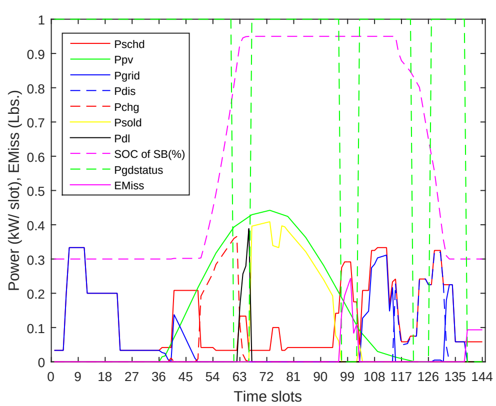

Fig. 8. Power and emission profiles for DRSREODLDG-based HEMS operation for solution-23

Solution-23 exhibits a $TEMiss$ value of 1.55 Lbs., the largest of all solutions. The value of $TEMiss$ parameter depends on profile for Pgn parameter. The profile for this solution is analyzed by focusing on the power/ emission profiles as shown in Fig. 8. The value of $TEMiss$ mainly depends on the operation of the LDG during four number of LSD hours discussed as follows. The loads shifted in the first LSD hour (starting at slot no. 61) and in the third LSD hours (the peak time hour starting at slot no. 121) are completely supplied by the PV and the SB respectively. So, in actual, the LDG has to operate only during the second LSD hour (starting at slot no. 97) and during the fourth LSD hour (starting at slot no. 139) to supply the shifted load as neither the grid nor the SB is available to supply within these hours. During the fourth LSD hour, a fixed load made up of NSHAs is supplied by the LDG completely. As no other source is available to supply during this hour, the fixed load has been supplied by the LDG in all scenarios. Focusing the second LSD hour, PV is available to supply the shifted load; however, the demand exceeding the energy harnessed from the PV (named excess demand) is only supplied through the LDG. This excess demand to be supplied by the LDG during the second LSD hour combined with the fixed demand in the fourth LSD hour, in fact, determines the net value of $TEMiss$. A maximum shifting of the excess demand out of the second LSD hour results in the minimization of the $TEMiss$. For solution-23, a maximum excess demand supplied through the LDG during the second LSD hour resulted in a maximum $TEMiss$ value of 1.55Lb. for this solution. The $CEnet$ parameter in this scenario assumes a near average value of 43.96 Cents that is based on the combined effect of the related parameters' values including: a PV energy loss of 1.09 kW; a supply of an average load of 0.2 kWh through the grid during peak time slot nos. 132-134; and a maximum supply of 0.98 kWh of energy from the LDG at a higher cost of value (PE_g).

Solution-27 exhibits a $TEMiss$ value of 0.56 Lbs, the lowest in all solutions and the power profiles shown in Fig. 9. The minimum value of $TEMiss$ in this scenario is because of zero loading of LDG during the second LSD hour. On the other hand, the $CEnet$ parameter shows a near average value of 43.57 Cents that is nearly similar to the $CEnet$ value in solution-23. The value is again based on the combined effect of the related parameters' values including: a PV energy loss of 1.75 kW; supply of an average load of 0.23 kW by the grid during the peak time slot nos. 132-134; and a minimum supply of 0.35 kWh of energy from the LDG at a higher cost, PEg.

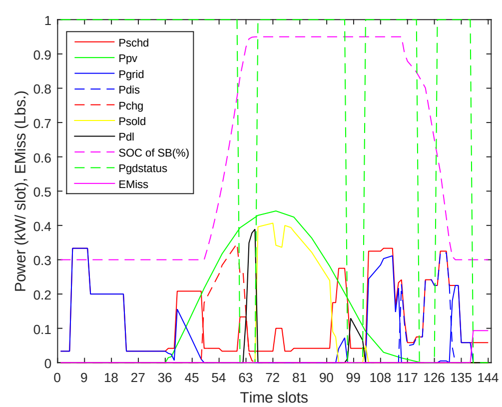

Fig. 9. Power and emission profiles for DRSREODLDG-based HEMS operation for solution-27

B. Simulations for filtration mechanism to harness eco-efficient tradeoffs using ASCF in step-2 and step-3

The simulation for filtration mechanism is based on step-2. The mechanism completes its task in two steps as follows:

- Application of an AVCF to the primary tradeoffs to filter out the the tradeoffs with extremely high and above average values of $TEMiss$ (step-2)
- Application of an ASCF to the filtrate of step-2 to filter out the tradeoffs with marginally higher values of $TEMiss$ (step-3)

1) Simulation for filtration using AVCF (step-2): This step includes the formulation and application of a constraint filter based on the average value of $TEMiss$ for the primary tradeoff solutions. Following are the software and hardware tools used to demonstrate the solution space, to formulate and apply the filter to validate the AVCF based filtration:

Machine: Core i7-4790 CPU @3.6 GHz with 16 GB of RAM
Platform: MATLAB 2015a
Regression model = Linear interpolation
Interpolation surface model = linearinterp
Method = Linear least square
Normalize = off
Robust = off
AVCF formulation and application:
$TEMiss\_Resid\_avg = average(TEMiss) - TEMiss$
Exclude = $TEMiss\_Resid\_avg < 0$

Where $TEMiss\_Resid\_avg$ is the decision element for the filter. The exclude option provided with the surface fitting function can be used to screen out the tradeoffs based on the formulation of the decision element. As per the formulation for $TEMiss\_Resid\_avg$, a tradeoff solution with a negative value of the decision element $TEMiss\_Resid\_avg$ indicates the above average value for $TEMiss$. The application of AVCF thus screens out the tradeoffs with extremely high as well as above the average values of $TEMiss$. The function of the AVCF to screen out the un-desired tradeoffs with larger values of $TEMiss$ are graphically shown in Fig. 10.

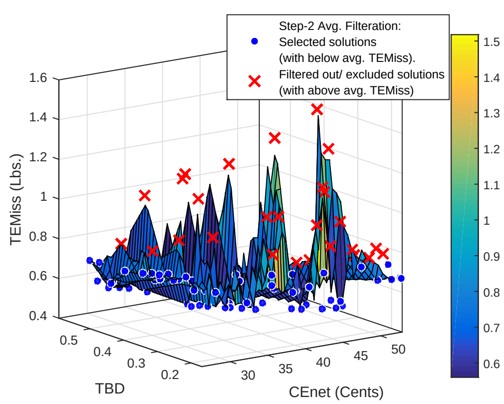

Fig. 10. Application of AVCF to screen out the tradeoffs with larger $TEMiss$ values

2) Simulation for filtration using ASCF (step-3): This step includes the formulation and application of a constraint filter based on the average surface fit for $TEMiss$. The average surface fit for $TEMiss$ in terms of $CEnet$ and TBD is generated using polynomial based regression for the tradeoffs achieved after the application of AVCF. The software and hardware tools used to develop the surface fit and to formulate and apply the filter to validate the AVCF based filtration are similar to previous step-1 except some, which are described as under:
Regression model = Polynomial
Polynomial surface model = Poly41
Method = Linear least square
$average\_surface\_fit$ = sfit($CEnet$, TBD)
$TEMiss\_Resid\_avgs = average\_surface\_fit - TEMiss$

Where $average\_surface\_fit$ is the value of emission obtained through the average surface fit based polynomial for the respective $CEnet$ and TBD tradeoff. And $TEMiss\_Resid\_avgs$ is the decision element for the filter. The exclude option provided with the surface fit function has been used to screen out the tradeoffs based on the formulation of the decision element. As per the formulation for $TEMiss\_Resid\_avgs$ in this research, a tradeoff solution with a negative value of the decision element $TEMiss\_Resid\_avg$ indicates the average surface fit for $TEMiss$. The application of ASCF thus screened out the tradeoffs with higher values of $TEMiss$ lying above the average surface fit for $TEMiss$.

Various polynomial model fit options were coupled with the ASCF. The best model fit for the polynomials was achieved after comparison of the actual tradeoffs for DRSREODLDG-based HEMS problem exhibited by various polynomial models ranging from Poly11 to Poly55. The tradeoff solutions harnessed through each polynomial based ASCF were analyzed for the average value of $TEMiss$ and the number of diverse tradeoffs harnessed for $CEnet$ and TBD. Poly11 based ASCF achieved the minimum average $TEMiss$ value of 0.58 Lbs.; however, the filter harnessed the least number of tradeoff solutions that did not include the desired solutions like ones with $CEnet$ value below 30 Cents. Poly12 based ASCF, on the other hand, included the tradeoffs with minimal $CEnet$ value less than 30 Cents; however, on the other hand, it lacked the diversification due to lesser number of tradeoff solutions. The options with the average $TEMiss$ value equal or less than 0.59 were focused and poly41 was selected based on the lesser average values for $TEMiss$ and TBD (0.59 Lbs. and 0.3 Cents) and more number of diverse solutions for tradeoffs between $CEnet/TBD$ (33 Nos.). In this way, the model fit is based on an optimal set of the performance tradeoffs for DRSREODLDG-based HEMS problem [26]. The eco-efficient solutions harnessed after the application of Poly41 surface filter are graphically shown in Fig. 11.

V. Conclusions and Future Work

A simulation-based posteriori method for eco-efficient operations of a DRSREODLDG-based HEMS is proposed. The method computes an optimal set of diversified tradeoffs for $CEnet$ and TBD against minimal $TEMiss$. Based on

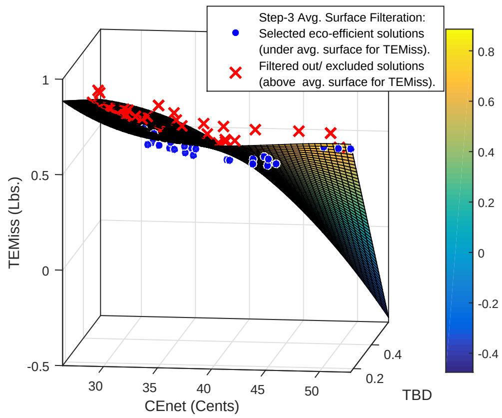

Fig. 11. Eco-efficient solutions selected using average surface filtration based on Step-3

simulations, the method completed its function in three-steps. A constraint filter based on the proposed surface fit has applied to screen out the tradeoffs with marginally higher values of $TEMiss$. The method delivered an eco-efficient set of 33 tradeoffs between $CEnet$ and TBD against a minimal $TEMiss$. The tradeoffs are classified to enable the consumer choosing the best eco-efficient option. The best eco-efficient solution for a consumer comprised maximized reduction of 60.78% in $CEnet$ against a 45% value of TBD and a 51.72% reduction in $TEMiss$. An overall reductions achieved for $CEnet$ ranges from 22.61% to 61.63% against the TBD of 17 to 53% while reductions in $TEMiss$ has kept within 50.53 to 58.58%. Relationship between the tradeoff parameters and various factors affecting their trends are analyzed as follows: $CEnet$ reduces exponentially with an increasing TBD; $CEnet$ increases linearly with an increasing loss of the PV energy (Pdl); the relationship between $TEMiss$ and the related tradeoffs for $CEnet$ and TBD remained undefined when analyzed for the primary tradeoffs data; however, $TEMiss$ exhibits a double-tailed polynomial relation with $CEnet$ when the parameters have analyzed for the final eco-efficient tradeoffs; an uneven/ irregular trend for $TEMiss$ as related to the tradeoffs between $CENet$ and TBD have exploited to design the proposed filtration mechanism for $TEMiss$. In future, this work will be extended using the other meta-heuristic and hybrid methods to generate the primary tradeoffs.

REFERENCES

[1] The Smart Grid: Enabling Energy Efficiency and Demand Response Clark W. Gellings, P.E., CRC Press, Taylor and Francis Group, 2009

[2] Danish M., N. Javaid , N. Alrajeh, Z. A. Khan, Umar Qasim,Realistic Scheduling Mechanism for Smart Homes, Energies pp 1-28, 2016, 9, 202

[3] M. Rastegar and M. F. Firuzabad,Outage Management in Residential Demand Response Programs, IEEE transactions on smart grid, vol. 6, NO. 3, MAY 2015, 1453-1462

[4] Adika CO, Wang Lingfeng., Autonomous appliance scheduling for household energy management, IEEE Trans. on Smart Grid 2014; 5(March (2)):67382

[5] S. Rahim, N. Javaid, A. Ahmad, S. Ahmed Khan, Z. Ali Khan, N. Alrajeh,Exploiting heuristic algorithms to efficiently utilize energy management controllers with renewable energy sources, Energy and Buildings 129 (2016), Pages 452-470

[6] Rajalingam S., Malathi V.,HEMS algorithm based smart controller for home power management system, Energy and Buildings, Volume 131, 1 November 2016, Pages 184-192

[7] O. Erdinc, N. G. Paterakis, Tiago D. P. Mendes,Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR, in IEEE transactions on Smart Grid, vol. 6, no. 3, pp. 1281-1291, May 2015

[8] M. Liu, F. L. Quilumba and W. J. Lee,A Collaborative Design of Aggregated Residential Appliances and Renewable Energy for Demand Response Participation, IEEE Transactions on Industry Applications, vol. 51, no. 5, pp. 3561-3569, Sept.-Oct. 2015

[9] Latest/Current Load Management schedule, official website Islamabad Electric Supply Company, Pakistan, available at http://www.iesco.com.pk/index.php/customer-services/load-shedding-schedule [Accessed on 22-3-17]

[10] B. Hussain, Q. Hasan, N. Javaid, M. Guizani, A. Almogren, A. Alamri, An Innovative Heuristic Algorithm for IoT-enabled Smart Homes for Developing Countries, IEEE ACCESS, vol. 6, no. 1, Pages 15550-15575, Feb. 2018

[11] Kyoto Protocol by United Nations Framework Convention on Climate Change (UNFCCC), Kyoto, and 11 December 1997 (Enter into force: 16 February 2005)

[12] G. Tsagarakis, R. C. Thomson, A. J. Collin, G. P. Harrison, "Assessment of the Cost and Environmental Impact of Residential Demand-Side Management," IEEE Transactions on Industry Applications, Vol. 52, No. 3, Pages 2486-2495, May-June 2016.

[13] H. Wu, A. Pratt and S. Chakraborty, "Stochastic optimal scheduling of residential appliances with renewable energy sources," 2015 IEEE Power and Energy Society General Meeting, Denver, Pages 1-5, 2015

[14] S. A. P. Kani, H. Nehrir, C. Colson and C. Wang,"Real-time energy management of a stand-alone hybrid wind-microturbine energy system using particle swarm optimization", IEEE Power and Energy Society General Meeting, San Diego, Page 1-1, 2011

[15] M. Elsied, A. Oukaour, H. Gualous, R. Hassan and A. Amin,"An advanced energy management of microgrid system based on genetic algorithm", IEEE 23rd International Symposium on Industrial Electronics (ISIE), Istanbul, Pages 2541-2547, 2014

[16] UN Climate Change Agreement, Paris, April 2016

[17] Global Status report by Renewable Energy Policy Network for 21st Century, Renewable, 2016

[18] M. C. Bozchalui, S. A. Hashmi, H. Hassen, C. A. Canizares and K. Bhattacharya,"Optimal Operation of Residential Energy Hubs in Smart Grids", IEEE Transactions on Smart Grid, Vol. 3, No. 4, Pages 1755-1766, Dec. 2012

[19] T. C. Chiu, Y. Y. Shih, A. C. Pang and C. W. Pai, "Optimized Day-Ahead Pricing With Renewable Energy Demand-Side Management for Smart Grids," in IEEE Internet of Things Journal, Vol. 4, No. 2, Pages 374-383, April 2017

[20] G. C. Liao, "The optimal economic dispatch of smart Microgrid including Distributed Generation," 2013 International Symposium on Next-Generation Electronics, Kaohsiung, Pages 473-477, 2013

[21] Diesel Generator Fuel Consumption Chart in Litres, ABLE Sales, Melbourne, Australia, https://www.ablesales.com.au/source/Diesel Generator Fuel Consumption Chart in Litres.pdf (accessed on February 19, 2018)

[22] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry and Other Land Use, Intergovernmental Panel on Climate Change, https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed on February 19, 2018)

[23] An Overview of Electricity Sector in Pakistan, Islamabad Chamber of Commerce and Industry, Pakistan, 2012, [Available Online] $http://icci.com.pk/data/downloads/63/1293619048_1.pdf$ (accessed on February 19, 2018)

[24] Curve and surface fittings in Matlab-2015a, https://www.mathworks.com/help/curvefit/fit.html (accessed on Feb. 19, 2018)

[25] Econometrics by examples, second edition, Damodar Gujarati, Palgrave Macmillan, St. Martins Press LLC, NY, 2015

[26] Applied univariate, bivariate, and multivariate statistics, Daniel J. Denis, John Wiley and sons, 2016.