Community Energy Sharing in a Microgrid Architecture with Energy Storage and Renewable Energy Support

R. Karthikeyan¹, A.K. Parvathy², S. Priyadarshini²

¹Department of Electrical and Electronics Engineering, Velammal Institute of Technology, TamilNadu, India
²Department of Electrical and Electronics Engineering, Hindustan Institute of Technology and Science, TamilNadu, India
Karthikeyan.eee@velammalitech.edu.in

Abstract. The increase in the number of installed renewable energy in a residential network needs an efficient energy management system (EMS) to store or sell the surplus energy back to the grid during the surplus generation. Selling of power back to the grid can affect the reliability of the traditional grid system, to avoid this energy sharing is proposed to share the surplus energy with close neighbours to avoid the transmission loss and increase the utilization rate of renewable energy. In this paper, we use the cyber-physical system (CPS) to coordinate the neighbours and to collect data from all the homes using the smart meters. The system's objective is to reduce the grid cost and to benefit each home which shares the energy. This system reduces the need for a huge energy storage system (ESS) which is a major capital cost during the installation. We adopt a scheduling algorithm to manage the loads during the shortage of supply and flexibility in scheduling the loads helps to improve energy management without disturbing the user comfort. The whole model is validated with an experimental setup in the university as a part of the MNRE Funded Project.

1. Introduction
The increase in energy demand and depletion of fossil fuels, the climate changes due to the emission of CO2 has forced the country to move towards cleaner energy generation and modernization of existing power grids. Currently, India is the Third Largest producer of electrical energy of about 356.10 GW as per the Central Electrical Authority (CEA) where 21.80 % of total energy is produced RES (Renewable Energy Sources). To increase the RES penetration into existing modern communication technology for data transfer between the generation and load is needed. The Microgrid (MG) is defined as building blocks of the smart grid [1] or as the energy balance cell in the existing power distribution grids. The existing traditional grid cannot withstand the variable generation and sudden changes in the distribution due to its vertical one-way communication between the generation and load. Interconnected MG [2] can operate in grid-connected or island mode. All MG can exchange power among themselves through the power exchange lines. EMS is essential for each prosumer to maintaining the energy balance and optimize energy utilization in the home [3,4]. However, the RES which depends on weather conditions and island mode operation needs a huge ESS to compensate for the loss of renewable energy. We use CPS for safe intercommunication between the prosumers and to operate the smart meters during the sharing conditions. CPS helps in achieving the interoperability, flexibility, and reconfiguration of the system with more efficiency in system and energy consumption.
The performance of prosumers is compared under various conditions in the community connected and grid-connected.

MG integration has various objectives [5] such as cost, transmission loss, renewable energy penetration, reduction in carbon footprint, and mainly customer satisfaction. The cost of maintenance and operation of the system can be reduced by selling surplus energy to the grid and buying the energy during the demand [6,7] thus reducing the usage of diesel generators [8,9] and increasing the penetration of renewable energy [10,11,12]. The penetration of renewable energy can be increased by sharing surplus energy to the neighbours during demand [13]. The transmission loss is the important factor since a country like India has more than 20% as transmission loss during the energy trading back to the grid since most of MG system is in low voltage system when compared to the grid which causes huge loss [7] during the power selling back to the grid. The transmission loss can be reduced by sharing energy between neighbours since most of the neighbours in MG are located close. Stability and greenhouse gas [14] benefit in the system can be improved by integration of MGs to the grid and by increasing the penetration of renewable energy the system can avoid blackouts by using the energy storage system. The scheduling of appliances [15] at home to satisfy the energy demand may affect customer satisfaction therefore the user interaction is necessary to make the load as critical and non-critical based on the usage of individual user comfort. To optimize the usage of renewable energy in the MGs time of use [16] is considered for controlling the individual appliances in residential homes. Real-time pricing with the scheduling of appliance options and demand control algorithm [17], reduces the peak demand and cost. Various optimization algorithm such as GA [18], are used to reduce the peak demand and improve the utilization of RES. To reduce the CO2 emission and energy cost a model is developed to optimize the energy utilization in MG and EMS is proposed to operate in multi RES to reduce the operation cost. For multi-resource allocation least of data exchange [19] between the system is essential to reduce the operating time and to reduce the data size for speedier response. For cost optimization [20], in the residential network, MG is interconnected with heat, generators, and RES. To enhance the intercommunication between the prosumer in the MG a CPS is used for faster data processing and controlling the system. In this paper, we use MILP based mathematical formulation for an energy sharing in MG which is renewable energy connected to the grid system with an ESS. The objective of the system is to minimize energy consumption cost.

2. System Overview

A sustainable MG architecture is described in this section where the prosumers and consumers are connected and interactions between the prosumers are discussed. Each prosumer is equipped with renewable energy (Solar PV, Wind Etc) where the excess energy is stored for future use. A common power line is designed for sharing of power between the prosumers and a communication line is established between the systems for sharing the data from the load centre to the CPS controller. The smart meter is installed in all the homes to measure the generation and consumption by the load and a relay is used to control the energy sharing between the prosumers. Excess energy is sold to other prosumers when the energy storage in the system reaches the maximum capacity and when there is demand in the community. Each home is equipped with smart meters to account for the usage of power from renewable energy, power grid, and sharing. ESS is essential for the energy balance in the system and increases reliability. The lifetime of the battery depends on the charging cycle and decreases due to the deep discharge and overcharging. It is essential to operate the storage battery under the safe operating limits normally between 20 to 90% [21] to enhance the lifetime of the storage system. Maintaining the battery is essential since the installation, maintenance, and replacement cost of the battery are overhead charges for each system. The proposed Smart CPS is designed for making the current appliances into smart appliances by scheduling them to use RES more without disturbing the user comfort. The SCPS compares the generation and demand of loads and decides the solution based on the comfort setting by the user. Due to the controller, the appliances are scheduled automatically based on the user preferences, slab rates in grid operator availability of energy from neighbours. The system aims to maximize renewable energy utilization with optimal scheduling. The
The challenge of the system is to predict the availability of RES. The SMEU aims in minimizing the utilization of power from the grid operator during the non-availability of RES.

![Proposed MG Architecture in the University Campus](image)

**Figure 1.** Proposed MG Architecture in the University Campus

### 3. System Design

The primary objective of the system is to minimize the cost and increase the utilization of RES. By using smart plugs, the conventional home appliances can be converted into smart appliances [22]. A MG consists of smart homes h, and objective function is derived with cost for time T.

where $C_{grid}$, $C_{solar}$, $C_{wind}$, $C_{ess}$ refers to the cost of grid, maintenance and operation cost of solar, wind, battery respectively and $C_{sharing}$ is the cost of energy sharing between the prosumers.

\[
\begin{align*}
\text{min } f(\text{cost}) &= \sum_{h=1}^{H} \sum_{t=1}^{T} \{ C_{grid} + C_{solar} + C_{wind} + C_{ess} - C_{sharing} \} \\
P_g(t, h) + P_{pv}(t, h) + P_{mw}(t, h) + P_{Bdis}(t, h) + P_{sh}(t, h) &= P_L + P_{Bch}(t) + P_{sell}(t, h)
\end{align*}
\]

The whole design is made for $t=24$ hrs and h refers to number of homes, $P_g$ is the power consumed by each home in the grid and $P_{pv}, P_{mw}$ is the power generated by the solar and wind by homes, $P_{Bdis}$ is the battery discharge and $P_{sh}$ is energy shared by the homes. $P_L$ is the total load of the system, and $P_{sell}$ is the power sold to the grid. The equation (2) refers to the grid balance equation. In a system if sum of renewable energy and battery discharge is greater than the load the Home is referred surplus state and when it is lesser then the demand it is referred as Demand State.

\[
\begin{align*}
P_{pv}(t) + P_{mw}(t) + P_{Bdis}(t) &> P_{D}(t) \\
P_{pv}(t) + P_{mw}(t) + P_{Bdis}(t) &< P_{D}(t)
\end{align*}
\]

### 3.1. Constrains

\[
\begin{align*}
0 &\leq P_g(t) \leq P_{gmax}(t) \\
0 &\leq P_{pv}(t) \leq P_{pvmax}(t) \\
0 &\leq P_{mw}(t) \leq P_{mwmax}(t) \\
SOC_{Bmax} &\leq SOC_{B}(t) \leq 1 \\
C_{grid} &= (P_g(t) \times dt) \times C_g(t)
\end{align*}
\]

The cost of the grid is calculated by using equation 9 where $C_g(t)$ is the cost of grid at time interval $t$.

#### 3.1.1. Photovoltaic Power

\[
P_{pv}(t) = A_{pv} \times \rho \times SI(t)
\]
The power produced from the PV system must be always less than $P_{pv}^{max}(t)$ condition and equation (10) represents the output generated with respect to the $A_{pv}$ Area of the PV panels and solar irradiation in time (t). The cost of solar power is calculated by using equation 11.

$$C_{solar} = \left( (P_{pv}(t) \times dt) \times C_{pv} \right) \quad (11)$$

### 3.1.2. Micro Wind Turbine

A permanent magnet wind Turbine [23] is used in the system since it has advantages such as high reliable operation, low maintenance expenses and light weight with simple structure.

$$P_{mw}(t) = 0, \text{if } V < V_c \text{ or } V_f > V_0 \quad (12)$$

$$P_{mw}(t) = P_{rated}, \text{if } V_r \leq V_f \leq V_co \quad (13)$$

$$P_{mw}(t) = P_{rated} \times \frac{V_f-V_{ci}}{V_r-V_{ci}} \text{ if } V_f \leq V_r \quad (14)$$

$$C_{wind} = \left( (P_{mw}(t) \times dt) \times C_{mw} \right) \quad (15)$$

The equation (12), describes the maximum energy which is generated in the micro wind turbine, the generation of power from Windmill depends on the wind speed, $V_f$, $V_r$, $V_{ci}$ and $V_{co}$ represents the Forecast wind speed, rated wind speed, cut in wind speed and cut out wind speed respectively.

### 3.1.3. Energy Storage System

A lead acid battery is used in the system and State of charge is used to determine the remaining energy in the battery.

$$P_{Bch}(t) \leq P_{B}^{cmax} \times C(t) \quad (16)$$

$$P_{Bdis}(t) \leq P_{B}^{dmax} \times D(t) \quad (17)$$

$$C(t) + D(t) \leq 1 \quad (18)$$

The equation (16) and (17) represent the maximum charging and discharging allowed limit to the system. $C(t)$ and $D(t)$ is the charging and discharging coefficient. The operation cost of the ESS is calculated by using equation (19)

$$C_{ESS} = \left( (P_{Bdis} \times dt) \times C_{Bdis} \right) \quad (19)$$

### 4. Input Parameters

The input parameters are taken from references for validation of the results. We choose the load system in which the average demand for the day 3.2 KW, peak demand 8 KW, and low demand of the day. The cost of grid power is calculated from TNEB tariff chart based on the last month consumption the tariff is generated since we use block rate tariff method. The maintenance cost for battery, solar and wind are considered as 20 paisa per KW. We propose two sharing algorithm with sharing ratio where the system sorts the buyers sorts the supplier according to the satisfaction ratio.

**Step 1:** The system expects the supplier to sort atleast 30% of the demand when the supplier is less than 30% the byer is allowed to buy from the grid to avoid the transmission loss and multiple sharing in the system.

**Step 2:** Once the supplier is sorted the byuer sends the request to the supplier for energy sharing.

**Step 3:** If the energy requested by the consumer is less than the Surplus energy it grants the available energy and remaining energy from the grid. If Surplus energy is more than the requested energy the energy is sold to the grid.

**Step 4:** once the request it accepted the Cyber physical Controller allows the energy sharing and until the sharing is completed the supplier is not allowed to share energy with other neighbours.

A case study is done with 3 smart homes with solar and wind energy as renewable sources and with different demand profiles. We use two algorithms here where Algorithm 1 allows only one user to share the energy at a time where multiple sharing is not allowed when one user cannot satisfy the load.
the user is allowed to get power from grid, where algorithm 2 allows user to get power from multiple user at the same time to satisfy the load. The system output is compared between the two algorithms and we found that algorithm 2 improves the SOC of the battery and also reduces the dependency on the grid since the multiple energy sharing is allowed. The total Grid consumption cost of the 3 smart homes in the MG is reduced by algorithm-2 where the sharing of energy between the prosumer increases in algorithm 2 which enables multiple sharing and charging of surplus power to the battery. Where the cost of Home 3 in the algorithm is increased due to the storage of surplus energy in the battery.

![Figure 2. Case 1 Load curves and Load Sharing of homes in a microgrid.](image)

### Table 1. Energy Consumption by using proposed Methods for Case Study.

|                | Algorithm-1 | Algorithm-2 |
|----------------|-------------|-------------|
| H1 $P_{\text{grid}}$ (KW) | 23.32       | 23.32       |
| H2 $P_{\text{grid}}$ (KW) | 13.30       | 13.30       |
| H3 $P_{\text{grid}}$ (KW) | 17.08       | 12.54       |
| H1-H3 (KW)     | 0           | 4.71        |
| H1-H3 (KW)     | 9.40        | 9.40        |
| H3 Total Shared(KW) | 9.40       | 14.11       |
| H1 Cost (Rs)   | 46.64       | 41.93       |
| H2 Cost (Rs)   | 17.2        | 17.20       |
| H3 Cost (Rs)   | 34.16       | 39.19       |

5. Experimental Setup
The real-time prototype is developed in the university campus. The System is installed in such a way that there are four prosusers each having a capacity of 2KW,2KW, 1KW of solar PV each, and one of the prosusers has 1KW of PMSG wind generator. Each system is connected with MPPT, Charge Controller and ESS. Each home is designed in such a way that the energy can be shared among the
homes. The system further uses MIPS dsPIC30F at each Prosumer Node as a Slave unit along with the Lumisense IoT board to upload all the data such as Power consumed, Battery status, battery temperature, voltage, current and status of sharing to the master controller through cellular communication. Each slave board is equipped with a GPRS modem to activate internet connection also equipped with a controller to process all input UART data to GPRS based online data. The data is collected from the Energy meter connected to each Prosumer Node. The System Uses Indigenous Made ICD Meters for Both AC and DC measuring applications. Which Enables us to get real-time data for monitoring purposes. ICD makes DC ENERGY METER (DEM 9004F) is used for measuring the solar panel output to the battery sours with the operating range of 0 – 800V DC and the current range of 0 – 999.9 A. The meter has PC Interface Optically isolated RS485 communication provided by the MODBUS – RTU which enables us to directly port the data into the system. Further, Each Prosumer is connected with ICD SEM 9510 (Single Phase Energy Meter) meter with a wide operating range. The Data Collection is done through Optical Port / IrDA with IEC 62056-21 protocol (standard) and Isolated RS232 / RS485 with MODBUS RTU protocol [24] is used for Data Collection through Optical Port with DLMS (Optional). Both AC and DC Meter connected in the system are directly capable of porting data to the system and all the data are processed and uploaded to the cloud each minute to get the Realtime scheduling of the system.

**Figure 3.** Real time Solar PV and Micro Wind Turbine Setup

The system is controlled by the cyber-physical master controller and all the decisions for scheduling is done based on the energy available in the storage system and based on the availability of the RES. The system improves the utilization of renewable energy to reduce the electricity bills and for quick recovery of the solar return.

**Figure 4.** Hardware setup of Master and Slave Control

As we are dealing with solar PV systems and the loads being classroom loads of the University, the generation curve and load curve are more or less matching. Considering the scenario that 1kW source is not working, 2 kW is in working condition: 1 kW consumer load is shed (or in this case connected to the utility grid), while load could be shared from 2 KW generation, (Since 2kW consumer have no load demand). This sharing phenomenon saves 2.9 kWhr which amounts to Rs 23.2/half day.
Figure 5. Battery Storage, MPPT setup and Smart Energy Meter arrangement.
The same phenomenon could be carried out for other generation sources as well. The experimental setup for this project can facilitate sharing among all four generation sources and connected load. The algorithm improves the RES utilization and reduces the payback period.

Figure 6. Controlling and Monitoring Website Snapshot and Battery Soc Display in the System

Figure 7. Load curve and SMS Message to Prosumer during Sharing

6. Conclusion
The proposed CPS based EMS improves the performance of the household prosumers and reduces the payback period of the RES. The sharing algorithm reduces the load dependency on the grid and CPS manages the sharing between the homes. The system is designed in such a way that the number of RES and Homes can be increased. The user comfort is not affected like other algorithms since the scheduling of load is not done in this system. The proposed system is validated by a real-time system in university and future work of the system is to add diesel generator and to implement load scheduling without affecting user comfort.

References
[1] Hatzigiorgiou, N. “MGs: Architectures and Control” Wiley-IEEE Press, 2014
[2] H. Zou, S. Mao, Y. Wang, F. Zhang, X. Chen and L. Cheng, "A Survey of Energy Management in Interconnected Multi-MGs," in IEEE Access, vol. 7, pp. 72158-72169, 2019
[3] Y. s. Son, T. Pulkkinen, K. d. Moon, and C. Kim, “Home energy management system based on power line communication,” IEEE Trans.on Consumer Electronics, vol. 56, pp. 1380–1386, Aug 2010.
[4] A. C. Luna, N. L. Diaz, M. Graells, J. C. Vasquez and J. M. Guerrero, "Cooperative energy management for a cluster of households prosumers," in IEEE Transactions on Consumer Electronics, vol. 62, no. 3, pp. 235-242, August 2016
[5] H. Zou, S. Mao, Y. Wang, F. Zhang, X. Chen and L. Cheng, "A Survey of Energy Management in Interconnected Multi-MGs," in IEEE Access, vol. 7, pp. 72158-72169, 2019
[6] A. Ouammi, H. Dagdougui, L. Dessaint, and R. Sacile, “Coordinated model predictive-based power flows control in a cooperative network of smart MGs,” IEEE Trans. Smart Grid, vol. 6, no. 5, pp. 2233–2244, Sept. 2015.

[7] D. An, Q. Yang, W. Yu, X. Yang, X. Fu, and W. Zhao, “Sto2Auc: A stochastic optimal bidding strategy for MGs,” IEEE Internet of Things J., vol. 4, no. 6, pp. 2260–2274, Dec. 2017.

[8] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, “Optimal interconnection planning of community MGs with renewable energy sources,” IEEE Trans. Smart Grid, vol. 8, no. 3, pp. 1054–1063, Nov. 2017.

[9] A. Parisio, C. Wiezorek, T. Kyntäjä, J. Elo, K. Strunz, and K. Johansson, “Cooperative MPC-based energy management for networked MGs,” IEEE Trans. Smart Grid, vol. 8, no. 6, pp. 3066–3074, 2017.

[10] S. R. Cominesi, M. Farina, L. Giulioni, B. Picasso, and R. Scattolini, “A two-layer stochastic model predictive control scheme for MGs,” IEEE Trans. Control Syst. Technol., vol. 26, no. 1, pp. 1–13, Jan. 2018.

[11] H. Wang, and J. Huang, “Incentivizing energy trading for interconnected MGs,” IEEE Trans. Smart Grid, vol. 7, no. 6, pp. 2647–2657, July 2018.

[12] Y. Zhang, T. Zhang, R. Wang, Y. Liu, and B. Guo, “Dynamic dispatch of isolated neighboring multi-MGs based on model predictive control,” Proc. IEEE ICSGCE 2017, Chengdu, China, Oct. 2016, pp. 50–55.

[13] H. Liang and W. Zhuang, “Stochastic modeling and optimization in a MG: A survey,” Energies, vol. 7, no. 4, pp. 2027–2050, Mar. 2017.

[14] G. Li, D. Wu, J. Hu, Y. Li, M. S. Hossain, and A. Ghoneim, “HELOS: Heterogeneous load scheduling for electric vehicle-integrated MGs,” IEEE Trans. Veh. Technol., vol. 66, no. 7, pp. 5785–5796, July 2017.

[15] Y. Huang, S. Mao, and R.M. Nelms, “Adaptive electricity scheduling in MGs,” IEEE Transactions on Smart Grid, vol. 5, no. 1, pp. 270–281, Jan. 2014.

[16] F. Bizzozero, G. Gruosso and N. Vezzini, “A time-of-use-based residential electricity demand model for smart grid applications,” 16th IEEE Int. Conf. on Environment and Electrical Engineering, pp. 1-6, 2016.

[17] L. Gelazanskas and K. Gamage, “Demand side management in smart grid: A review and proposals for future direction,” Sustainable Cities and Society, vol. 11, pp. 22-30, 2014.

[18] Z. Zhao, W. C. Lee, Y. Shin, and K-B Song, “An Optimal Power Scheduling Method for Demand Response in Home Energy Management System,” IEEE Trans. Smart Grid, vol. 4, no. 3, pp. 1391-1400, 2013.

[19] P. Dimitrov, L. Piroddi, M. Prandini, “Distributed allocation of a shared storage system in a MG”, American Control Conference (ACC), pp. 3551-3556, 2016.

[20] R. Wang, P. Wang, G. Xiao, “A robust optimization approach for energy generation scheduling in MGs”, Energy Conversion and Management, vol. 106, pp. 597-607, 2015.

[21] “IEEE Guide for Optimizing the Performance and Life of Lead-Acid Batteries in Remote Hybrid Power Systems,” IEEE Std 1561-2007, pp. C1–25, May 2008.

[22] Mohamed El-Hendawi, Hossam A.Gabbar, Gaber El-Saady & El-Nobi A. Ibrahim (2018) Optimal operation and battery management in a grid-connected MG, Journal of International Council on Electrical Engineering, 8:1, 195-206

[23] Y. liyong, Y. peiye, C. Zhenguo, C. Zhigang, L.Zhengxi, “ A Novel Control Strategy of Power Converter used to Direct Driven Permanent Magnet Wind Power Generation System” IEEE Power electronics and intelligent transportation system (PEITS), 2nd International Conference vol. 1, pp. 456-459, Dec 2009.

[24] http://www.icdipl.net/product/single-phase-staticmeter/