Optimal Regulation of Prosumers and Consumers in Smart Energy Communities

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Overview

Figure: Energy community. Image source https://revieval.org/objectives/

Introduction: Smart energy communities

- Community members group together to achieve a common goal.
- It utilizes the existing local energy infrastructures and enables community members' participation, cooperation, and coordination for the community's welfare.
- It also facilitates balancing community members' needs and preferences fairly and help keep monetary benefit within the community.
- One of the technological challenge is to develop mechanisms to handle the uncertainty in energy production and consumption patterns.

Why smart energy communities?

- Smart energy communities can help in becoming an energy community self-sustainable [1], [2], [3].
- Smart energy communities can help in achieving a cleaner and more affordable energy.
- Smart energy communities can facilitate social interaction and build relationships among the community members that are unavailable in the traditional energy systems.

Energy consumers and energy prosumers

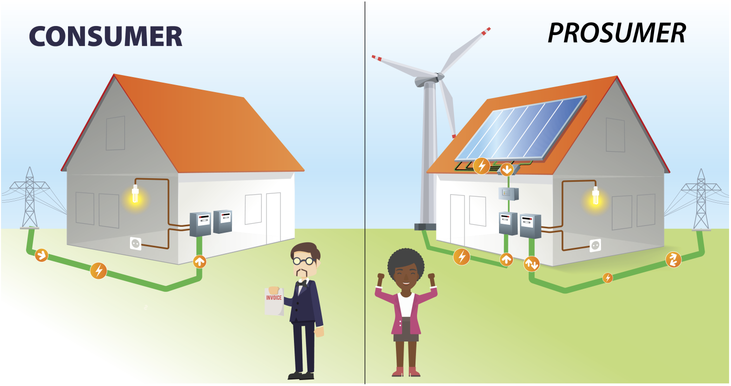


Figure: Energy consumer and energy prosumer. Image source, Sarah Harman, `https://www.energy.gov/eere/articles/consumer-vs-prosumer-whats-difference`

- Energy prosumers are the consumers that can also produce energy.

Scenario: Households with solar panels and wind turbines

- Each household in a smart energy community has either solar panels or wind turbines installed.
- They may sell the surplus produced energy to other community members for monetary benefits.
- The members can support specially-abled people or improve the local environment by using sustainable energy sources.
- These can have an impact on the prosperity of the society and can help in achieving net-zero emission targets, too [4].

System model

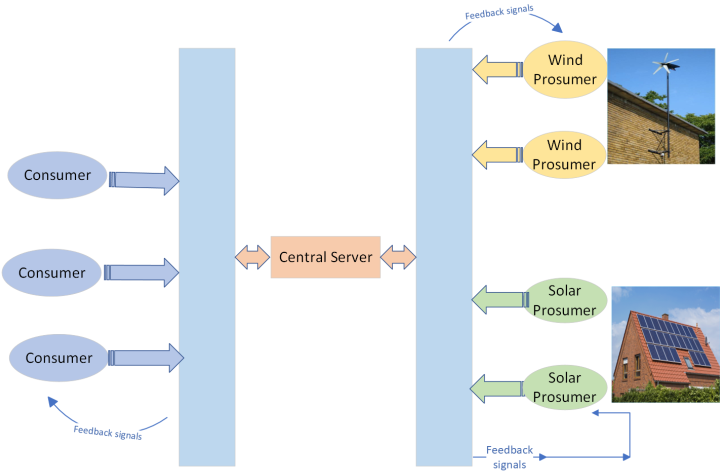


Figure: Basic system model with prosumers and consumers.

Notations

- N solar prosumers, M wind prosumers, and U energy consumers in the smart energy community. $k \in \mathbb{N}$ denotes time steps.
- $\xi_i(k) \in \{0,1\}$, when the solar prosumer i is active then $\xi_i(k) = 1$ is updated; otherwise, $\xi_i(k) = 0$.
- $\eta_j(k) \in \{0,1\}$ denotes whether wind prosumer j is active or not at k.
- $\zeta_u(k) \in \{0,1\}$ denotes whether consumer u is active or not at k.
- $x_i(k) \in [0,1]$ denotes the average of the number of times solar prosumer i was active until time step k:

$$x_i(k) \triangleq \frac{1}{k+1} \sum_{\ell=0}^{k} \xi_i(\ell), \quad i = 1, 2, \ldots, N. \tag{1}$$

- $y_j(k) \in [0,1]$ denotes the average of the number of times wind prosumer j was active until time step k, $j = 1, 2, \ldots, M$.
- $z_u(k) \in [0,1]$ denotes the average of the number of times consumer u was active until time step k, $u = 1, 2, \ldots, U$.

Notations

- $f_i : [0,1] \to \mathbb{R}_+$ is the cost function of prosumer i which is associated with a cost to the production of solar energy for prosumer i, for $i = 1, 2, \ldots, N$.
- $g_j : [0,1] \to \mathbb{R}_+$ is the cost function of the prosumer j which is associated with a cost to production of wind energy, for $j = 1, 2, \ldots, M$.
- $h_u : [0,1] \to \mathbb{R}_+$ is the cost function of consumer associated with a cost to consumption of energy, for $u = 1, 2, \ldots, U$.
- The cost functions f_i, g_j, and h_u are convex, continuously differentiable, and increasing.

Optimization problem

For $\mathbf{x} = (x_1, \ldots, x_N)$, $\mathbf{y} = (y_1, \ldots, y_M)$, and $\mathbf{z} = (z_1, \ldots, z_U)$; we model the problem as the following optimization problem:

Problem

$$\min_{\mathbf{x}\in[0,1]^N, \mathbf{y}\in[0,1]^M, \mathbf{z}\in[0,1]^U} \quad \sum_{i=1}^{N} f_i(x_i) + \sum_{j=1}^{M} g_j(y_j) + \sum_{u=1}^{U} h_u(z_u)$$

$$\textit{subject to} \quad \sum_{i=1}^{N} x_i = C_s; \sum_{j=1}^{M} y_j = C_w;$$

$$\sum_{u=1}^{U} z_u = \sum_{i=1}^{N} x_i + \sum_{j=1}^{M} y_j;$$

$$x_i \geq 0, \quad y_j \geq 0, \quad z_u \geq 0;$$

$$\textit{for } i = 1, \ldots, N; j = 1, \ldots, M; u = 1, \ldots, U.$$

Solutions

- We developed algorithms that regulate the number of prosumers and the number of consumers in a smart energy community with heterogeneous energy sources to minimize the overall cost to the community.
- The number of active solar prosumers reaches the optimal value as in

$$\lim_{k\to\infty} x_i(k) = x_i^*; x_i(k) \triangleq \frac{1}{k+1}\sum_{\ell=0}^{k}\xi_i(\ell), \text{ for } i = 1, 2, \ldots, N.$$

- Prosumers and consumers make decisions using a probabilistic rule.
- Prosumers and consumers do not require to share information with other users.

Solution contd.

The central server updates the feedback signal and broadcasts to solar energy prosumers in the community:

$$\Theta^s(k+1) = \Theta^s(k) - \frac{\tau^s}{k+1}\left(\sum_{i=1}^{N} \xi_i(k) - C_s\right).$$

After receiving the feedback signal, prosumer i responds with probability $\varphi_i^s(x_i(k))$ at the next time step as follows:

$$\varphi_i^s(x_i(k)) \triangleq \Theta^s(k)\frac{x_i(k)}{f_i'(x_i(k))}.$$

Analogously, feedback signals $\Theta^w(k+1)$ and probability $\varphi_j^w(y_j(k))$ are defined for wind prosumers.

Solution contd.

The central server updates the feedback signal and broadcasts to energy consumers in the community:

$$\Theta^c(k+1) = \Theta^c(k) - \frac{\tau^c}{k+1}\left(\sum_{u=1}^{U}\zeta_u(k) - \sum_{i=1}^{N}\xi_i(k) - \sum_{j=1}^{M}\eta_j(k)\right).$$

After receiving the feedback signal, consumer u responds with probability $\varphi_u^c(z_u(k))$ at the next time step.

Experimental setup

- We chose $N = 100$ prosumers with solar panels, $M = 80$ prosumers with wind turbines, and $U = 160$ consumers. We chose capacities $C_s = 50$ and $C_w = 60$.
- We chose the cost functions as in [9] (Moret and Pinson, 2019):
    - For solar energy prosumers:

$$f_i(x_i) = a_{1i}x_i + b_{1i}x_i^2, \quad \text{for } i = 1, 2, \ldots, N. \tag{2}$$

    - For wind energy prosumers:

$$g_j(y_j) = a_{2j}y_j + b_{2j}y_j^2, \quad \text{for } j = 1, 2, \ldots, M. \tag{3}$$

    - For energy consumers:

$$h_u(z_u) = a_{3u}z_u + b_{3u}z_u^2, \quad \text{for } u = 1, 2, \ldots, U. \tag{4}$$

Experimental Results

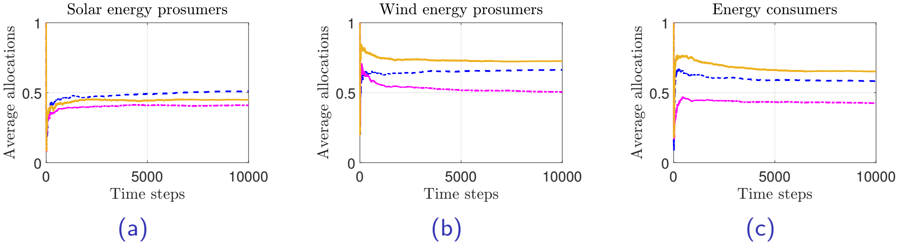


Figure: (a) The evolution of the average number of times prosumers with solar panels are active. (b) The evolution of the average number of times prosumers with wind turbines are active. (c) The evolution of the average number of times consumers are active.

Experimental results contd.

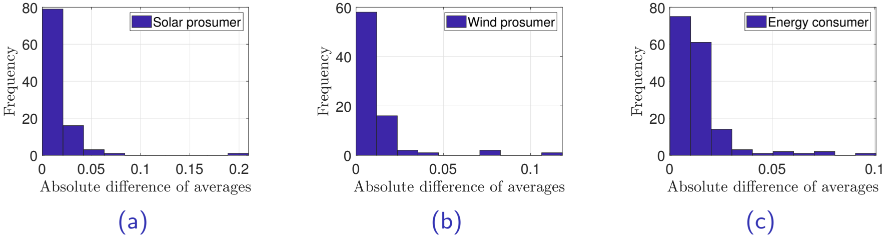
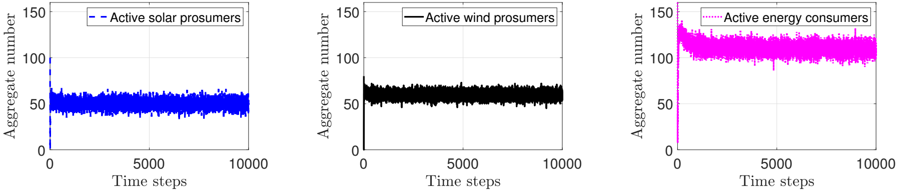


Figure: (a) The histogram of absolute difference of average number of active solar prosumers and the optimal value, $N = 100$. (b) The histogram of absolute difference of average number of active wind prosumers and the optimal value, $M = 80$. (c) The histogram of absolute difference of average number of active consumers and the optimal value, $U = 160$.

Experimental results contd.



(a) (b) (c)

Figure: (a) The evolution of the total number of active prosumers with solar panels, $C_s = 50$, (b) the evolution of the total number of active prosumers with wind turbines, $C_w = 60$, and (c) the evolution of the total number of active energy consumers.

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Conclusion

- We saw the solution to regulate the number of prosumers and consumers in a smart energy community.
- The solution incurs little communication overhead.
- We saw that the average number of times prosumers and consumers were active reaches optimal value over time.
- Proving convergence through multi-time scale stochastic approximation techniques will be interesting future work.

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A preprint is available at https://arxiv.org/pdf/2206.12679.pdf

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