Online Coordination of BESS and Thermostatically Control Loads for Shared Energy Optimization in Energy Communities

J.J. Moré[†], D. Deplano[⋆], A. Pilloni[⋆], A. Pisano[⋆], M. Franceschelli[⋆]

[†]Instituto LEICI, Faculty of Engineering, UNLP - CONICET, Argentina
[⋆]Department of Electrical and Electronic Engineering, University of Cagliari, Italy

IEEE 20th International Conference on Automation Science and Engineering (CASE), August 2024

Outline

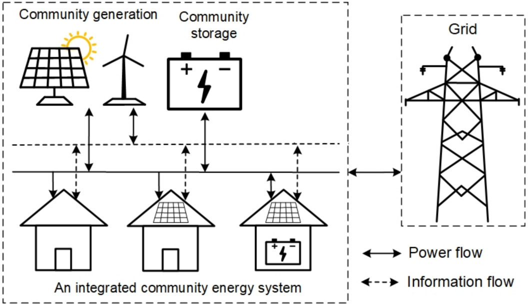
1. The problem of interest
2. Centralized MILP formulation
3. Results and discussion

Outline

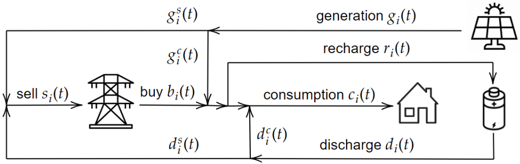
1. The problem of interest
2. Centralized MILP formulation
3. Results and discussion

Cooperative energy management in renewable energy communities (CER)

- **The set-up**: Each member in the community may:
  - Consume energy
  - Produce energy (e.g., solar panels)
  - Store energy (e.g., battery energy systems)
- **The objective**: minimize the costs by exploiting incentives on the energy shared within the community
- **The strategy**: control the charge/discharge behavior of the batteries and some controllable loads



Energy flow model of a member within the energy community



Model of the (dis)charging behavior of the battery:

$$e_i^{\mathrm{MAX}} \frac{d}{dt} \varepsilon_i(t) = \eta_i r_i(t) - d_i(t),$$

where:

- $e_i^{\mathrm{MAX}} \in \mathbb{R}_{\geq 0}$ is the maximum energy capacity.
- $\varepsilon_i(t) \in [0,1]$ is state of charge (SoC).
- $\eta_i \in [0,1]$ is the efficiency

Model of the Thermostatically Control Load:

$$C_i^{\mathrm{TCL}} \frac{d}{dt} \Theta_i(t) = \zeta_i \underbrace{P_i^{\mathrm{TCL}} \delta_i(t)}_{\leq c_i(t)} - R_i^{\mathrm{TCL}} \left(\Theta_i(t) - \Theta_i^{\mathrm{AMB}}\right),$$

where:

- Θ_i, Θ_i^{AMB}: TCL/ambient temperatures.
- C_i^{TCL}, R_i^{TCL}: thermal capacity/resistance.
- $\zeta_i \in [0,1]$: efficiency

The concept of shared energy (Italian regulation)

Given a continuous-time signal $x(t) \in \mathbb{R}$ with $t \in \mathbb{R}$ and a sampling time $\Delta \in \mathbb{N}_+$, we denote by $t_k = \Delta k$ with $k \in \mathbb{N}$ the discrete times at which the signal is sampled, yielding the discrete time signal $x(t_k) \in \mathbb{R}$. We also denote by $[x]_k^T$, where $k, T \in \mathbb{N}$ the vector collecting T samples of the continuous time signal starting from t_k and use the slender notation $\boldsymbol{x}$ when clear from the context:

$$\boldsymbol{x} = [x]_k^T = [x(t_k), \cdots, x(t_{k+T-1})]^\top. \tag{1}$$

Definition

The shared energy is the minimum between the energy fed into the network and the energy consumed by the community members in a given $W = \Upsilon\Delta$ with $\Upsilon \in \mathbb{N}$:

$$E_{sh}(\boldsymbol{b}, \boldsymbol{s}, \Upsilon) = \min\left\{\sum_{i \in \mathcal{V}} g(\boldsymbol{b}_i, \Upsilon), \sum_{i \in \mathcal{V}} g(\boldsymbol{s}_i, \Upsilon)\right\} \in \mathbb{R}^{\lceil k, \Upsilon \rceil},$$

where, given the horizon $H = h\Upsilon\Delta$ with $h \in \mathbb{N}$, the function g is defined as follows:

$$g(\boldsymbol{x}, \Upsilon) = \Delta \begin{bmatrix} \mathbf{1}^\top [x]_k^{\Upsilon - \mathrm{mod}(k, \Upsilon)} \\ I_{h-1} \otimes \mathbf{1}_\Upsilon^\top [x]_{\lceil (k+1)/\Upsilon \rceil \Upsilon}^{(h-1)\Upsilon} \\ \mathbf{1}^\top [x]_{(\lceil k/\Upsilon \rceil + h - 1)\Upsilon}^{\mathrm{mod}(k, \Upsilon)} \end{bmatrix}.$$

Problem of interest

In the scenario of an energy community operating under an incentive scheme based on the self-consumption realized by the whole community, **the objective is to** minimize the costs for the whole community by maximizing the shared energy over the horizon.

Outline

1. The problem of interest
2. Centralized MILP formulation
3. Results and discussion

Optimization problem formulation: objective function and constraints

The objective function we aim to minimize is

$$f(\boldsymbol{v}) = p_e^\top \sum_{i\in\mathcal{V}} g(\boldsymbol{b}_i, \Upsilon) - p_{sh}^\top E_{sh}(\boldsymbol{b}, \boldsymbol{s}, \Upsilon), \qquad \boldsymbol{v} = \left[\boldsymbol{v}_1^\top, \cdots, \boldsymbol{v}_n^\top\right]^\top. \quad \text{and} \quad \boldsymbol{v}_i = \left[\boldsymbol{r}_i^\top, \boldsymbol{d}_i^\top, \boldsymbol{d}_i^{c\top}, \boldsymbol{g}_i^{c\top}, \boldsymbol{\delta}_i\right]^\top.$$

The local constraints are:

$$\begin{array}{ccccc}
\mathbf{0} & \leq & \boldsymbol{r}_i & \leq & r_i^{\text{MAX}}\mathbf{1}, \\
\mathbf{0} & \leq & \boldsymbol{d}_i & \leq & d_i^{\text{MAX}}\mathbf{1}, \\
\mathbf{0} & \leq & \boldsymbol{r}_i & \leq & m_i^r \cdot (\varepsilon_i^{\text{MAX}}\mathbf{1} - \boldsymbol{\varepsilon}_i), \\
\mathbf{0} & \leq & \boldsymbol{d}_i & \leq & m_i^d \cdot (\varepsilon_i(k,T) - \varepsilon_i^{\text{MIN}}\mathbf{1}), \\
\mathbf{0} & \leq & \boldsymbol{d}_i^c & \leq & \boldsymbol{d}_i, \\
\mathbf{0} & \leq & \boldsymbol{g}_i^c & \leq & \boldsymbol{g}_i, \\
\mathbf{0} & \leq & \boldsymbol{b}_i & \leq & b_i^{\text{MAX}}\mathbf{1}, \\
\mathbf{0} & \leq & \boldsymbol{s}_i & \leq & s_i^{\text{MAX}}\mathbf{1}, \\
\Theta_i^{\text{MIN}}\mathbf{1} & \leq & \boldsymbol{\Theta}_i & \leq & \Theta_i^{\text{MAX}}\mathbf{1},
\end{array}$$

Optimization problem formulation: objective function and constraints

Together with those related to the (dis)charge dynamics of the battery:

$$\frac{e_i^{\mathrm{MAX}}}{\Delta}\left(\mathbf{D}_\varepsilon \varepsilon_i(k,T) - \mathbf{e_1}\varepsilon_i(t_{k-1})\right) = \eta_i r_i(k,T) - d_i(k,T), \quad \text{where} \quad \boldsymbol{e}_1 = \begin{bmatrix}1\\0\\\vdots\\0\end{bmatrix}, \mathbf{D}_\varepsilon = \begin{bmatrix}1 & 0 & \cdots & \cdots & 0\\ -1 & 1 & 0 & \cdots & 0\\ 0 & \ddots & \ddots & \ddots & \vdots\\ \vdots & \ddots & \ddots & \ddots & 0\\ 0 & \cdots & 0 & -1 & 1\end{bmatrix}.$$

and the TCL's dynamics:

$$\begin{aligned}&\mathbf{D_i^{\Theta}}\Theta_i(k,T) - \mathbf{e}_1 e^{-\alpha_i\Delta}\Theta_i(t_{k-1}) = \left(1 - e^{-\alpha_i\Delta}\right)\Theta_i^{\mathrm{AMB}}\\ &+ \left(1 - e^{-\alpha_i\Delta}\right)\zeta_i R_i^{\mathrm{TCL}} P_i^{\mathrm{TCL}} \delta_i(k,T)\end{aligned}, \quad \text{where} \quad \mathbf{D_i^{\Theta}} = \begin{bmatrix}1 & 0 & \cdots & \cdots & 0\\ -e^{-\alpha_i\Delta} & 1 & 0 & \cdots & 0\\ \vdots & \ddots & \ddots & \ddots & \vdots\\ 0 & 0 & \ddots & \ddots & 0\\ 0 & \cdots & 0 & -e^{-\alpha_i\Delta} & 1\end{bmatrix}.$$

Optimization problem formulation: MILP transformation

We compactly write the optimization problem as follows:

$$
\begin{aligned}
\min_{\boldsymbol{v},\boldsymbol{\theta}} \quad & p_e^\top \sum_{i\in\mathcal{V}} g(\boldsymbol{b}_i,\Upsilon) - p_{sh}^\top E_{sh}(\boldsymbol{b},\boldsymbol{s},\Upsilon),\\
\text{s.t.} \quad & \text{Local constraints} \quad \forall i\in\mathcal{V}.
\end{aligned}
$$

By using the standard trick $z=\min\{x,y\} \Rightarrow z\le x$ and $z\le y$, we obtain an LP formulation:

$$
\begin{aligned}
\min_{\boldsymbol{v},\boldsymbol{\theta}} \quad & p_e^\top \sum_{i\in\mathcal{V}} g(\boldsymbol{b}_i,\Upsilon) - p_{sh}^\top \boldsymbol{\theta},\\
\text{s.t.} \quad & \text{Local constraints} \quad \forall i\in\mathcal{V},\\
& \boldsymbol{\theta} - \textstyle\sum_{i\in\mathcal{V}} g(\boldsymbol{b}_i,\Upsilon) \le \mathbf{0},\\
& \boldsymbol{\theta} - \textstyle\sum_{i\in\mathcal{V}} g(\boldsymbol{s}_i,\Upsilon) \le \mathbf{0}.
\end{aligned}
$$

Outline

1. The problem of interest
2. Centralized MILP formulation
3. Results and discussion

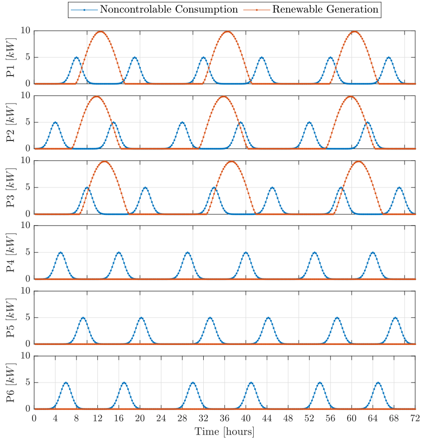
Numerical Simulations: members consumption and generation powers

Six agents community example

- Sampling time: $\Delta = 15$ minutes,
- Horizon time: $H = 12$ hours
- Simulation time: 3 days.

Param.	Value	Param.	Value
r_i^{MAX}	5kW	d_i^{MAX}	5kW
b_i^{MAX}	20kW	s_i^{MAX}	20kW
Θ_i^{MAX}	20°C	Θ_i^{MIN}	18°C
R_i^{TCL}	83.33°C/kW	C_i^{TCL}	300kWs/°C
P_i^{TCL}	0.2kW	ζ_i	0.8
$\varepsilon_i^{\mathrm{MAX}}$	0.9	$\varepsilon_i^{\mathrm{MIN}}$	0.1
m_i^r	50kW	m_i^d	50kW
e_i^{MAX}	20kWh	η_i	0.8

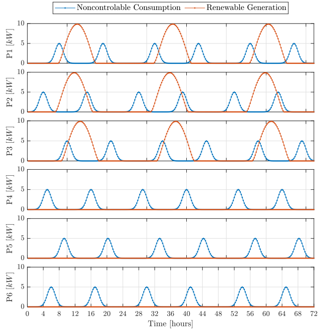
Table: Constants and parameters in simulation

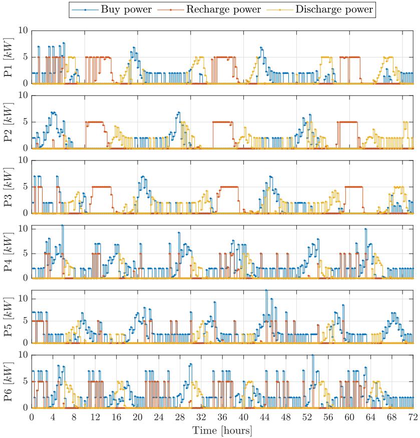


Numerical Simulations: members buy (b_i), recharge (r_i) and discharge (d_i) powers

Six agents community example

- Sampling time: $\Delta = 15$ minutes,
- Horizon time: $H = 12$ hours
- Simulation time: 3 days.

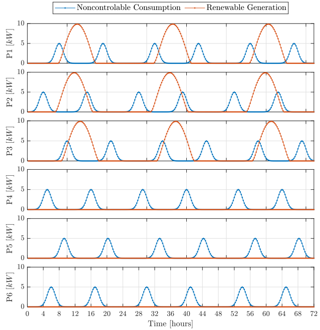


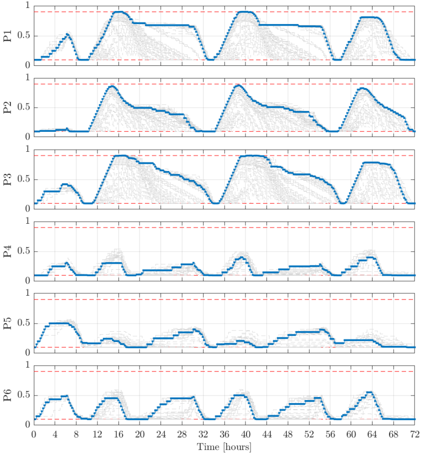


Numerical Simulations: members batteries SoC ($\varepsilon_i(k, T)$)

Six agents community example

- Sampling time: $\Delta = 15$ minutes,
- Horizon time: $H = 12$ hours
- Simulation time: 3 days.

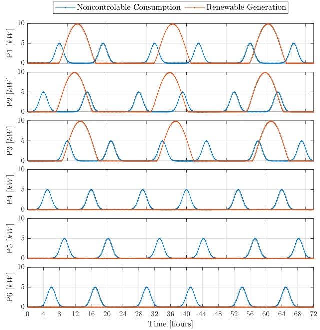


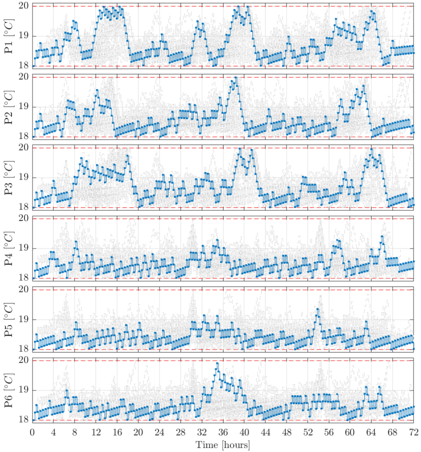


Numerical Simulations: members TCL temperatures ($\Theta_i(k,T)$)

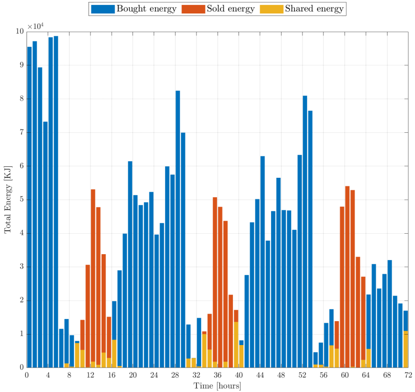
Six agents community example

- Sampling time: $\Delta = 15$ minutes,
- Horizon time: $H = 12$ hours
- Simulation time: 3 days.

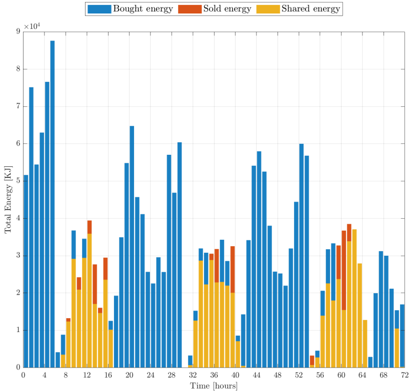




Numerical Simulations: 10% cost reduction via shared energy increase



No optimization



With optimization

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | UNIVERSITÀ DEGLI STUDI DI CAGLIARI | 2024 IEEE 20th INTERNATIONAL CONFERENCE ON AUTOMATION SCIENCE AND ENGINEERING CASE 2024

Online Coordination of BESS and Thermostatically Control Loads for Shared Energy Optimization in Energy Communities

Thank you for your attention!

Diego Deplano

Email: diego.deplano@unica.it
Webpage: https://diegodeplano.github.io/

SCAN ME