Communication-efficient Distributed AI for Grid-edge Energy Management

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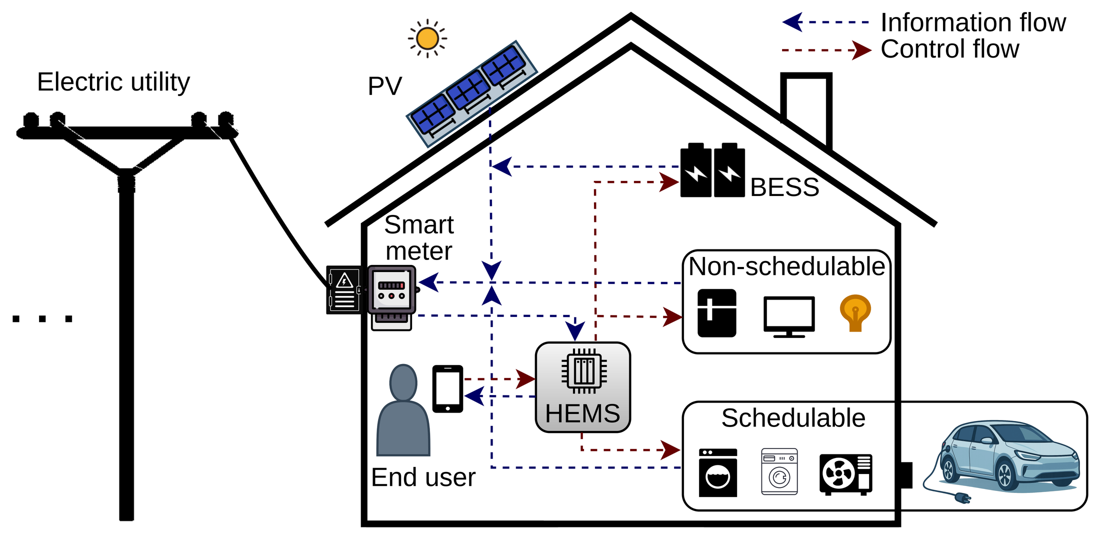
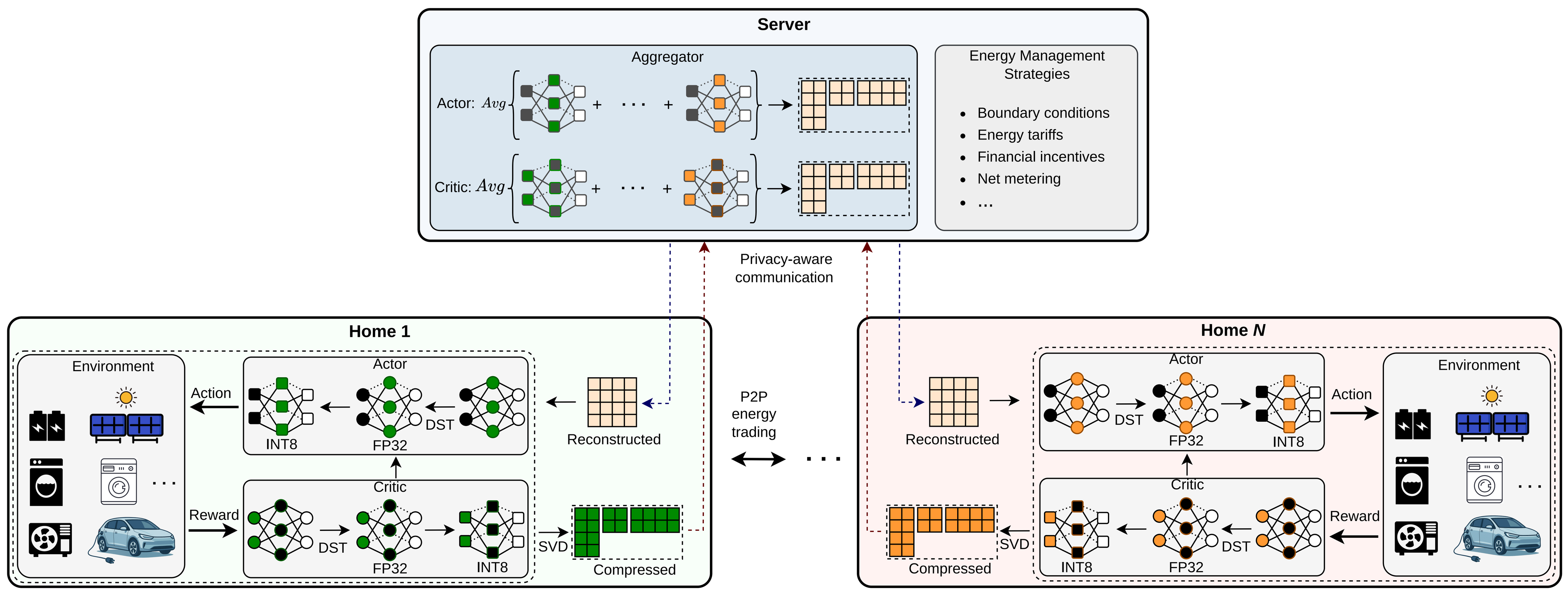
1. Introduction



Motivation:

- **Limited generalization** to multiple households
- **Missing grid-awareness** limiting performance in grid-influenced environments
- Need for **privacy-preserving coordination**

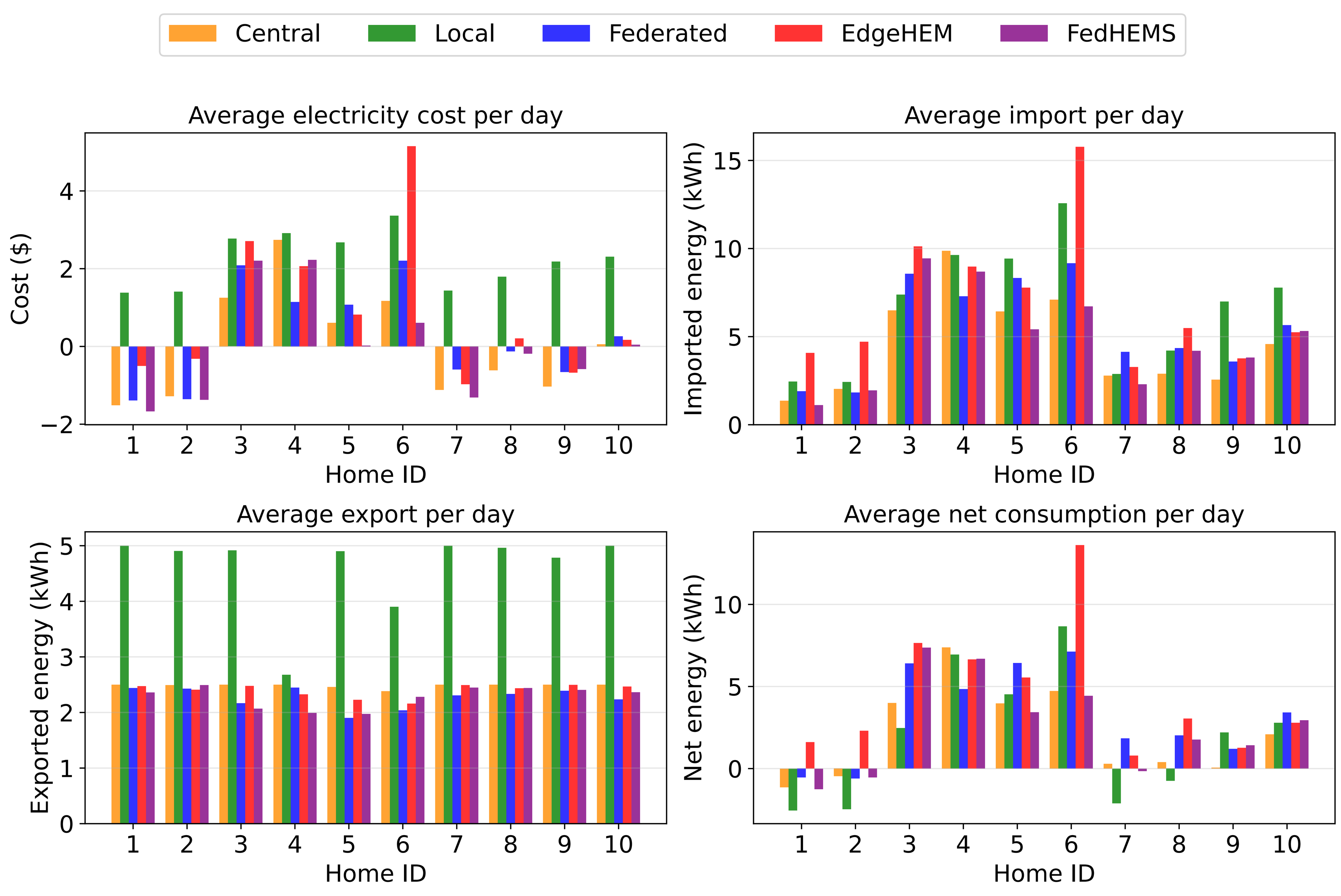
3. Methodology



Contribution:

- Federated HEMS algorithm that uses **FedAvg** for privacy-aware aggregation; **dynamic sparse learning, SVD, and quantization** for efficient communication; and periodically considers inputs from the grid (DSO).

4. Preliminary Results



Model	Electricity cost ↓	Communication cost ↓	Collaboration	Privacy
Central	low	none	✓	×
Local	high	none	×	✓
Federated	medium	high	✓	✓
EdgeHEM *(Li et al. 2025)*	medium	medium	✓	✓
FedHEMS (ours)	**low**	**low**	✓	✓

Acknowledgment

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2. Problem Formulation

Reward function:

$$r^t = w_{\text{elec}}\,\hat{r}^t_{\text{elec}} + w_{\text{comf}}\,\hat{r}^t_{\text{comf}}, \qquad w_{\text{elec}} + w_{\text{comf}} = 1. \tag{1}$$

Electricity cost:

$$\hat{r}^t_{\text{elec}} = \frac{r^t_{\text{elec}}}{\pi_{\max} P_{\max}\,\Delta t + \varepsilon}, \tag{2}$$

$$r^t_{\text{elec}} = \begin{cases} -P^t_{\text{net}}\,\pi^t\,\Delta t, & P^t_{\text{net}} > 0, \\ -P^t_{\text{net}}\,\pi_{\text{exp}}\,\Delta t, & P^t_{\text{net}} \le 0. \end{cases} \tag{3}$$

User comfort:

$$\hat{r}^t_{\text{comf}} = \tfrac{1}{4}\left(\hat{r}^t_{\text{WMt}} + \hat{r}^t_{\text{WMd}} + \hat{r}^t_{\text{temp}} + \hat{r}^t_{\text{EV}}\right). \tag{4}$$

- *WM Operation Time:*

$$\hat{r}^t_{\text{WMt}} = -\left(\frac{\delta^t_{\text{WMt}}}{\delta^{\max}_{\text{WMt}}}\right)^2, \qquad \delta^t_{\text{WMt}} = \begin{cases} t^{\text{WMt}}_{\text{start}} - t & t < t^{\text{WMt}}_{\text{start}}, \\ t - t^{\text{WMt}}_{\text{end}} & t > t^{\text{WMt}}_{\text{end}}, \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

- *WM Cycle Duration:*

$$\hat{r}^t_{\text{WMd}} = \begin{cases} -\left(\dfrac{\Delta t_{\max} - \Delta t_{\text{act}}}{\Delta t_{\max}}\right)^2, & \text{if } t = t_{\text{end}}, \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

- *Thermal Comfort:*

$$\hat{r}^t_{\text{temp}} = -\left(\frac{\delta^t_T}{\Delta T_{\max}}\right)^2, \qquad \delta^t_T = \begin{cases} T_{\min} - T^{t+1}_{\text{in}}, & T^{t+1}_{\text{in}} < T_{\min}, \\ T^{t+1}_{\text{in}} - T_{\max}, & T^{t+1}_{\text{in}} > T_{\max}, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

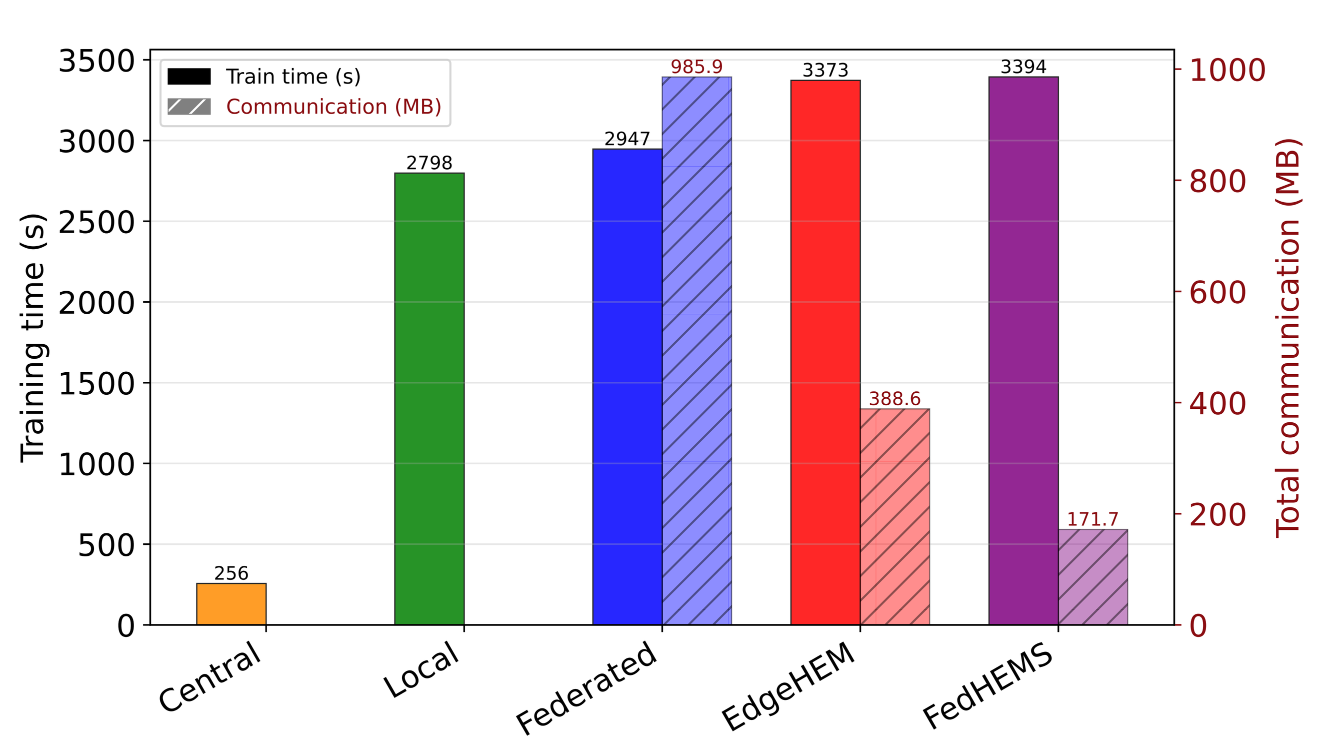
- *EV Readiness:*

$$\hat{r}^t_{\text{EV}} = \begin{cases} -\left(1 - \text{SoE}^t_{\text{EV}}\right), & \text{if } t = t^{\text{EV}}_{\text{end}}, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

Key variables:

$\pi^t,\ \pi_{\text{exp}},\ \pi_{\max}$	Import, export, and maximum tariff ($/kWh)
$\Delta t,\ P_{\max},\ \varepsilon$	Duration (h); peak capacity (kW); constant
$T^{t+1}_{\text{in}},\ [T_{\min}, T_{\max}]$	Indoor temperature; comfort band (°C)
$t^{\text{WM}}_{\text{start}},\ t^{\text{WM}}_{\text{end}}$	Start and end of preferred WM operating window
$\delta^{\max}_{\text{WM}}$	Worst-case WM timing deviation (for normalization)
$\Delta t_{\max},\ \Delta t_{\text{act}}$	Maximum and actual WM run duration (h)
SoE^t_{EV}	EV state of energy
$t^{\text{EV}}_{\text{end}}$	EV departure time

5. Communication Evaluation



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