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Rule-based AC Energy Exchange for Urban Prosumers to Enhance Local Energy Performance

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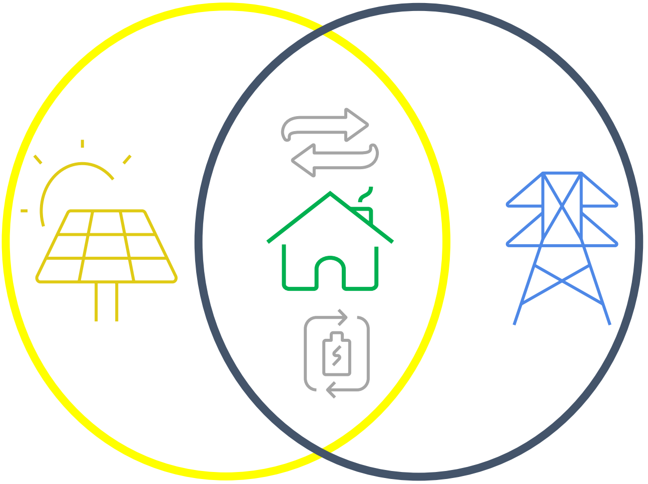
OUTLINE

INTRODUCTION

Urban Prosumer Challenges

Urban energy communities face a strong mismatch between PV generation and residential demand. Without practical exchange mechanisms, prosumers still rely on grid imports even when nearby surplus exists, reducing local efficiency and stressing urban feeders.

- **Midday PV peak vs. evening demand peak**
- **Unnecessary imports/exports despite nearby complementarity**
- **Bidirectional flows and voltage deviations stress**
- **Existing exchange/market solutions are complex**
- **No simple, real-time method to exchange energy**



Bridging the Urban Energy Mismatch

This work was supported by a grant from the Italian Ministry for NEST-Network for Energy Transition - Piano Nazionale di Ripresa e Resilienza (PNRR).

INTRODUCTION

Research Gap

Current energy-sharing solutions for prosumers remain difficult to apply in real networks. Key limitations include:

- Most methods depend on forecasting, optimization, or market negotiation.
- Very few studies validate exchange rules with full AC power-flow models.
- Lack of practical, real-time mechanisms for local exchange energy.

Research Aim

To develop AC-validate a minimal neighbor-first rule to match local complementarity Focus: Self-sufficiency (SS), Self-consumption (SC), Grid imports (GI), Feeder operation (voltage, losses), Electricity cost.

Contribution

- A rule-based neighbor-first AC exchange strategy for small prosumer communities
- Full validation on the modified IEEE 13-node feeder (Python + OpenDSS)
- Demonstrated SS and SC improvement and reduced grid imports
- No forecasting, optimization, or price signals required

RESEARCH METHODOLOGY

The study uses a modified IEEE 13-node radial feeder as the distribution testbed for evaluating the proposed neighbor-first exchange rule. Two residential prosumer buildings are modeled, each equipped with PV generation, a battery storage system, and realistic household load profiles.

Table illustrates Technical specifications of the two-prosumer test system on the modified IEEE 13-node feeder for the 24-hour simulation study.

Parameter	**Building 1 (Bus 645.2)**		**Building 2 (Bus 646.3)**		**Unit**
	Daily	**Peak**	**Daily**	**Peak**	
Load	23.221	1.67	27.708	1.68	kWh / kW
PV Generation	22.541	3.80	24.614	4.50	kWh / kW
Battery Capacity (C_i)	15.0		5.0		kWh
Rated Power (P^{max})	5.0		5.0		kW
Initial SoC (SoC_o)	7.5		2.5		kWh
Battery Efficiency (η_c , η_d)	0.95		0.95		–

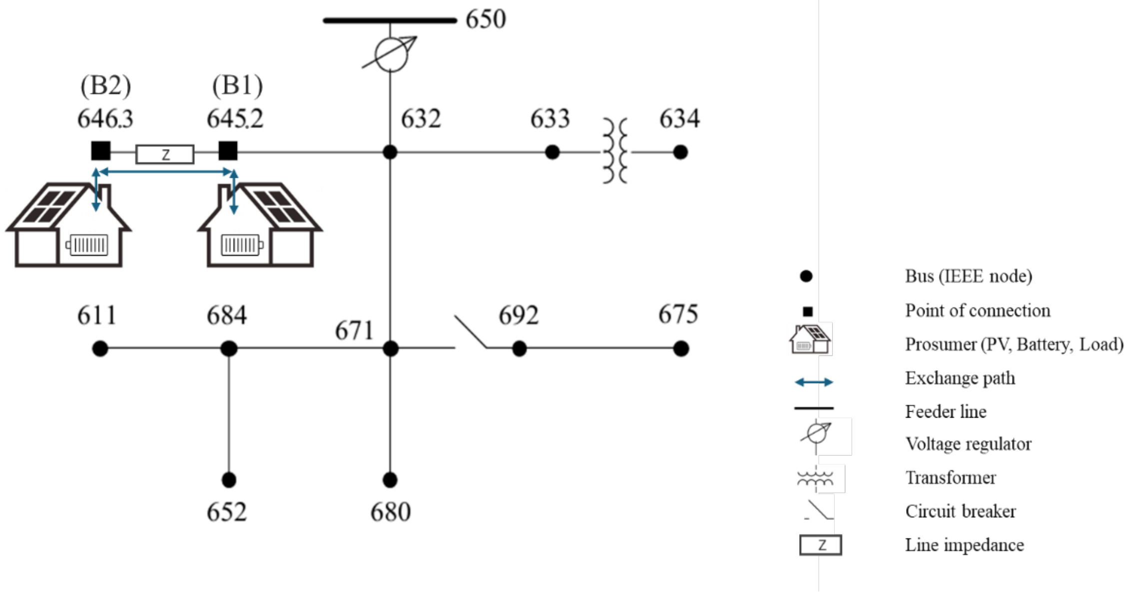


Figure shows Single-line diagram of the modified IEEE 13-node feeder showing buses, line impedances, transformer, and the locations of Building 1 (Bus 645.2) and Building 2 (Bus 646.3).

RESEARCH METHODOLOGY

Operation Strategy & Simulation Framework

Operation Strategy

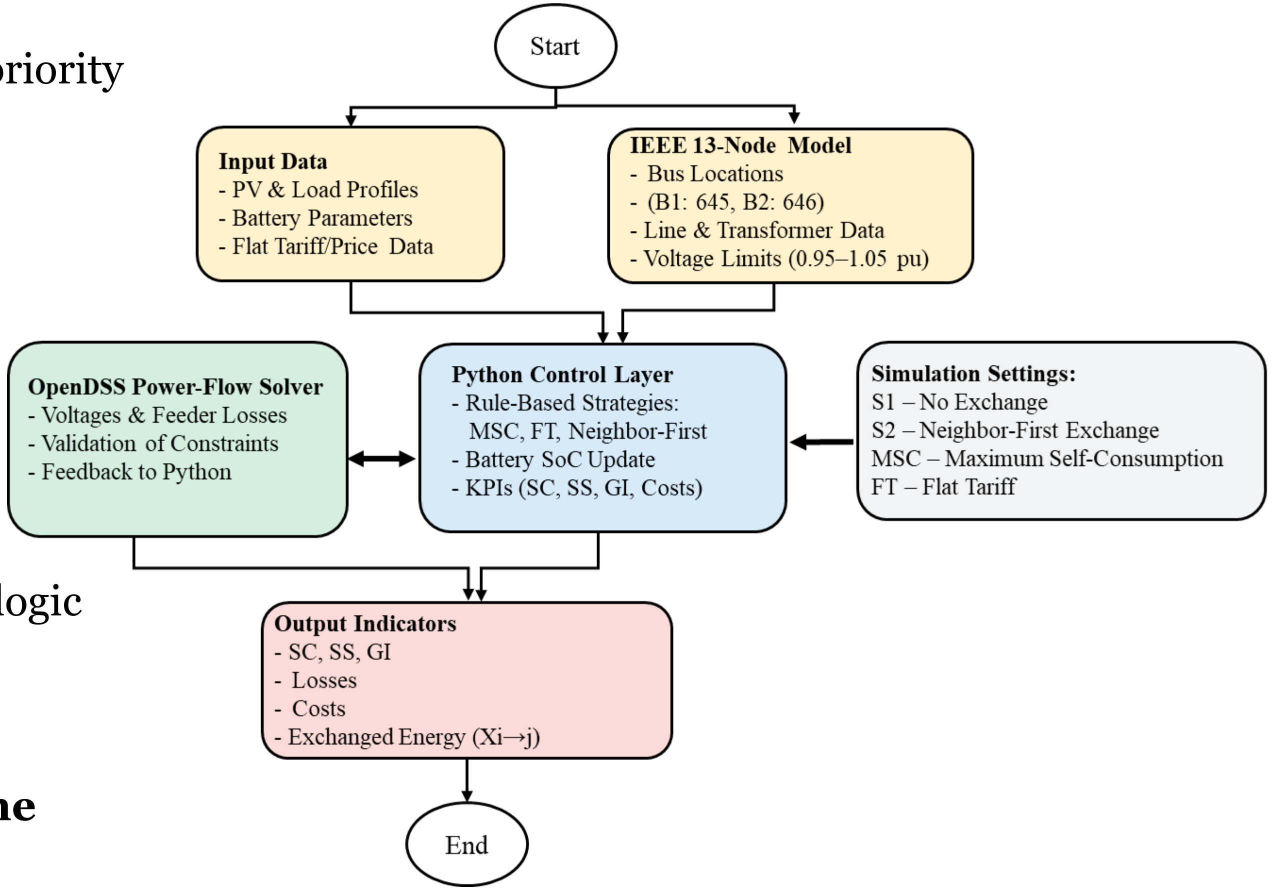
Each prosumer manages its energy locally using a simple priority rule designed to minimize grid usage:

1. **Serve local load with available PV**
2. **Store remaining surplus in the battery**
3. **Discharge the battery when PV is insufficient**
4. **Import from the grid only as the final option**

Simulation Framework

A co-simulation workflow integrates the rule-based control logic in Python with full AC power-flow validation in OpenDSS:

1. **Python computes (PV, load, battery, SoC)**
2. **Exchange rule decides possible transfers**
3. **OpenDSS validates power flows, voltages, and line constraints**
4. **Results are fed back to Python for the next time step**



Start

Input Data
- PV & Load Profiles
- Battery Parameters
- Flat Tariff/Price Data

IEEE 13-Node Model
- Bus Locations
- (B1: 645, B2: 646)
- Line & Transformer Data
- Voltage Limits (0.95–1.05 pu)

OpenDSS Power-Flow Solver
- Voltages & Feeder Losses
- Validation of Constraints
- Feedback to Python

Python Control Layer
- Rule-Based Strategies: MSC, FT, Neighbor-First
- Battery SoC Update
- KPIs (SC, SS, GI, Costs)

Simulation Settings:
S1 – No Exchange
S2 – Neighbor-First Exchange
MSC – Maximum Self-Consumption
FT – Flat Tariff

Output Indicators
- SC, SS, GI
- Losses
- Costs
- Exchanged Energy ($X_{i\rightarrow j}$)

End

Figure shows Simulation framework integrating Python-based control and OpenDSS power-flow validation for rule-based energy exchange analysis.

RESEARCH METHODOLOGY

Neighbor-First Exchange Rule

Control Principle

A prosumer with surplus PV supports its neighbor before importing from the grid, subject to inverter limits, battery SoC, and line-efficiency losses.

The rule is fully real-time and requires no forecasting or optimization.

Energy is transferred from Building *i* → Building j when:

- Building j has a residual deficit after using PV and storage.
- Building *i* has usable surplus (PV or battery).
- Power transfer is within inverter and line-loss limits.

Exchange Conditions

Net Power Balance (prosumer *i*= 1, 2)

$$\Delta_i(t) = G_i(t) - L_i(t)$$

Battery State of Charge

$$\mathrm{SoC}_i(t+1) = SoC_i(t) + \eta_c P_i^{ch}(t) - \frac{1}{\eta_d} P_i^{dis}(t)$$

Neighbor-First Exchange (B*i* → Bj)

$$X_{i \to j}(t) = \min(\Delta_j^-(t),\ P^{max},\ \eta_d\ SoC_i(t))\,\eta_x$$

RESEARCH METHODOLOGY

Performance Indicators

System performance is evaluated using energy-based KPIs to compare scenarios with and without energy exchange.

Performance Indicators

- **Self-Consumption (SC):**

$$SC = 1 - \frac{\sum_{t \in T} \sum_{i=1}^{2} Ei(t)}{\sum_{t \in T} \sum_{i=1}^{2} Gi(t)}$$

- **Self-Sufficiency (SS):**

$$SS = 1 - \frac{\sum_{t \in T} \sum_{i=1}^{2} Ii(t)}{\sum_{t \in T} \sum_{i=1}^{2} Li(t)}$$

- **Grid Import & Export:**

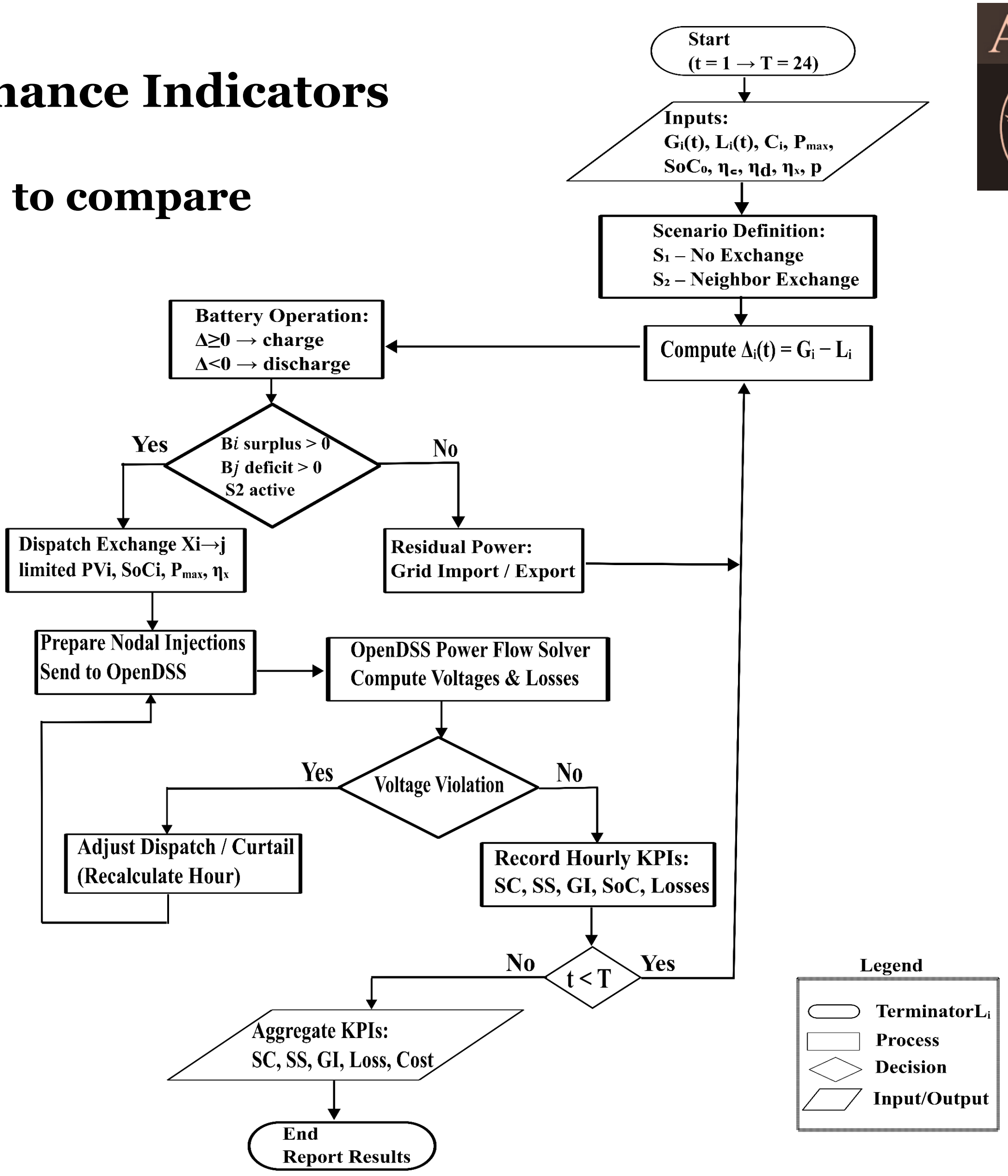
$$X_{tot} = \sum_{t \in T} [X_{1 \to 2}(t) + X_{2 \to 1}(t)]$$

- **System Losses:**

$$E_{loss} = \sum_{t \in T} [L_{batt}(t) + L_{ex}(t)]$$

- **Daily Electricity Cost:**

$$C_{sys} = p \sum_{t \in T} \sum_{i=1}^{2} Ii(t)$$



Start
($t = 1 \rightarrow T = 24$)

Inputs:
$G_i(t)$, $L_i(t)$, C_i, P_{max},
SoC_0, η_c, η_d, η_x, p

Scenario Definition:
S_1 – No Exchange
S_2 – Neighbor Exchange

Compute $\Delta_i(t) = G_i - L_i$

Battery Operation:
$\Delta \geq 0 \rightarrow$ charge
$\Delta < 0 \rightarrow$ discharge

B*i* surplus > 0
B*j* deficit > 0
S2 active

Yes

No

Dispatch Exchange $Xi \rightarrow j$
limited PVi, SoCi, P_{max}, η_x

Residual Power:
Grid Import / Export

Prepare Nodal Injections
Send to OpenDSS

OpenDSS Power Flow Solver
Compute Voltages & Losses

Voltage Violation

Yes

No

Adjust Dispatch / Curtail
(Recalculate Hour)

Record Hourly KPIs:
SC, SS, GI, SoC, Losses

t < T

No

Yes

Aggregate KPIs:
SC, SS, GI, Loss, Cost

End
Report Results

Legend

TerminatorL$_i$
Process
Decision
Input/Output

Figure shows Flowchart of the hourly simulation and control logic for rule-based AC energy exchange between two prosumers on the IEEE 13-node feeder.

RESULTS

Energy Exchange Behavior

The neighbor-first rule enables Building 1 to supply surplus PV to Building 2 whenever B2 experiences a deficit. Exchange occurs mainly during high-PV periods and directly reduces B2's grid dependence.

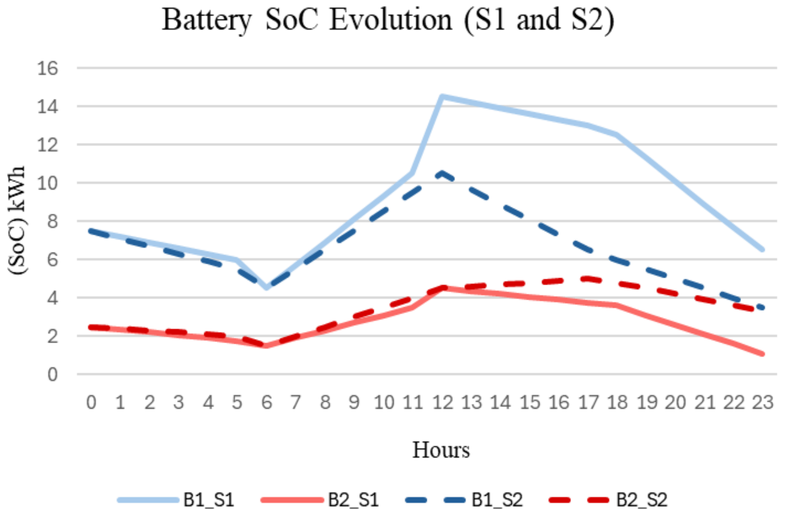


Figure demonstrates Battery state-of-charge (SoC) evolution of Building 1 and Building 2 under scenarios S1 and S2.

Total daily exchanged energy: 7.74 kWh (B1 → B2)

- Exchange concentrated between 10:00–11:00, and peaked around 16:00–21:00, align with residential peak demand.
- B2's load deficit is partially covered by B1 instead of grid imports.
- Exchange automatically stops when sender surplus or receiver deficit is exhausted.

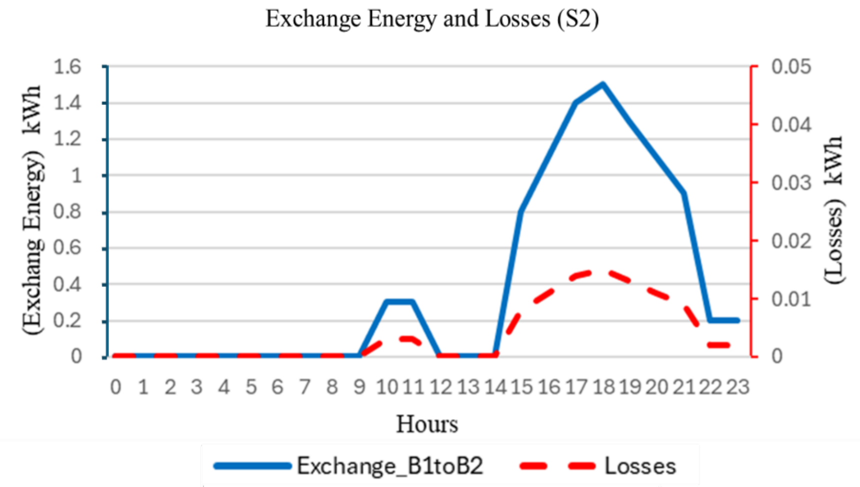


Figure shows Hourly profile of energy exchanged from B1 to B2 and associated losses under strategy S2.

Impact on Individual Buildings

- Building 1: Slight increase in grid imports due to exporting part of its surplus.
- Building 2: Large reduction in grid imports and better utilization of local PV resources.

RESULTS

System Performance Improvements

The neighbor-first rule improves local performance by using surplus PV more effectively and reducing grid imports.

Key Performance Changes (S1 → S2)

- **Self-Consumption (SC):** 74.3% → 78.5%
More PV used locally instead of exported.

- **Self-Sufficiency (SS):** 77.7% → 87.3%
More demand supplied by PV, battery, and exchange.

- **Grid Imports:**
Building 1: slight increase due to supplying B2.
Building 2: 11.36 kWh → 3.63 kWh (–68%).

- **Daily Energy Cost** (flat tariff 0.25 €/kWh):
Building 2: €2.84 → €0.91; System: €2.84 → €1.62

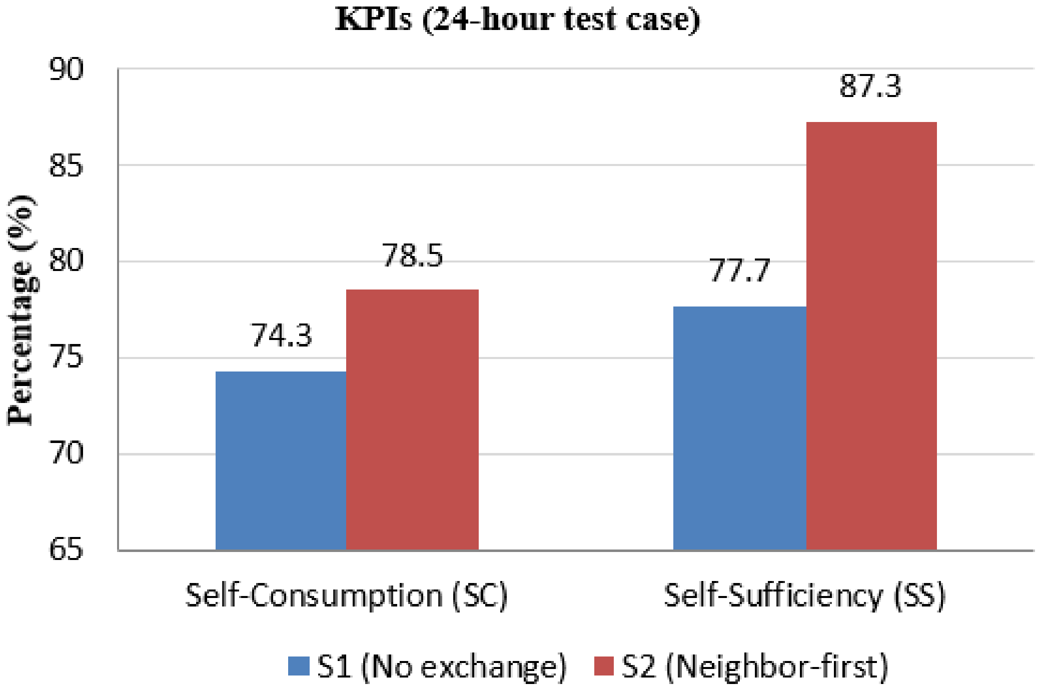


Figure demonstrates Comparison of key performance indicators for scenarios S1 (no exchange) and S2 (neighbor-first exchange), Self-consumption and self-sufficiency (%).

RESULTS

Technical Validation

Voltage Performance

- ❑ **All bus voltages remain within acceptable limits (0.95–1.05 pu).**
- ❑ **Exchange does not introduce voltage violations on the feeder.**
- ❑ **Minor voltage rise during peak PV remains compliant with standards.**

Line Loading and Losses

- ❑ **Line currents stay below thermal ratings under both S1 and S2.**
- ❑ **Total daily feeder losses: 2.58 kWh under S2.**
- ❑ **Slight increase in losses is expected due to additional power transfers.**

CONCLUSION

Technical Validation

A practical not complex real-time neighbor-first exchange rule was successfully validated on the modified IEEE 13-node feeder using Python + OpenDSS co-simulation. All voltages remained within limits; no line overloads or instability observed.

Key Outcomes

- Higher community self-sufficiency and self-consumption.
- Significant reduction in grid imports, especially for Building 2, also resulted in a substantial reduction in daily energy cost.
- Confirms that low-complexity energy exchange coordination can meaningfully enhance local energy performance.

Future Work

- Extension to multi-building and multi-feeder energy communities.
- Long simulations time frame with real-time demand and PV profiles.
- Integration with dynamic tariffs and P2P financial mechanisms.
- Inclusion of EV charging and flexible demand resources.

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Thank You!

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