SOLAR-ENABLED COMMUNITY ENERGY SYSTEMS: A MODULAR NEIGHBORHOOD APPROACH TO NET-POSITIVE NEIGHBORHOODS

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Abstract

This study investigates the integration of solar-based Community Energy Systems (CES) within a modular neighborhood framework, evaluating how urban form influences energy system performance. CES are defined as distributed, locally managed infrastructures that generate, store, and share energy at the neighborhood level to enhance self-sufficiency, resilience, and decarbonization.

Eleven representative neighborhood typologies, ranging from low-density detached housing to high-density mixed-use forms, were modeled in EnergyPlus to simulate annual thermal and electrical demands and assess local renewable generation potential. Rooftop, façade, and landscape-integrated photovoltaic (LPV) systems were evaluated in combination with district heating strategies (PV/T and geothermal), waste-to-energy systems, and bidirectional electric vehicle (V2G) integration. A total of 99 CES scenarios were tested across all typologies, quantifying performance using metrics such as Ratio of Performance (ROP), Self-Sufficiency Index (SSI), and net energy balance.

Results indicate that typology plays a defining role in CES performance. Medium-density residential neighborhoods (e.g., 56AH) achieved up to 2.2 ROP (Ratio of Performance) with LPV integration, representing an 83% increase over baseline scenarios. In high-density mixed-use areas (e.g., MU1), LPV reduced annual net deficits by over 610,000 kWh, while geothermal scenarios delivered the highest ROP improvements, increasing performance by 25–35% compared to all-electric configurations.

A dual-ranking framework, EPN (Energy-Positive Neighborhood) and NZE (Net-Zero Energy) scores, was developed to guide CES selection based on policy priorities. The EPN score favors energy surplus and grid export, while the NZE score targets balanced, self-sufficient designs with SSI ≥ 0.85. This approach allows planners to identify optimal CES setups per typology and enables strategic clustering of high-surplus and energy deficit neighborhoods for resilience and flexibility.

Keywords: Type your keywords here, separated by commas, in italic. Insert 5-7 keywords

1. Introduction

In response to intensifying climate change and rising greenhouse gas (GHG) emissions, national and regional energy strategies have increasingly shifted toward decarbonization through the deployment of renewable energy technologies. As of October 1, 2021, 51 countries and the European Union had formally adopted net-zero emissions targets through legislation, proposed laws, or national policy frameworks, collectively covering approximately 65% of global CO_2 emissions. In addition, 4,500 non-state actors had committed to similar goals via the UN-backed “Race to Zero” campaign (Jeudy-Hugo et al, 2021). Central to this energy transition are technologies such as solar photovoltaics (PV), low-temperature district heating (LTDH), thermal energy storage (TES), and vehicle-to-grid (V2G) infrastructure (Chen, S., Zhang, C., & Lu, X. (2023).). However, their intermittent nature poses challenges for grid stability, particularly in dense urban contexts (Impram, S., Nese, S. V., & Oral, B. 2020; Medina, C., Ana, C. R. M., & González, G. 2022).). Simultaneously, energy resilience has become a critical consideration, encompassing the system’s capacity to withstand climate-related disruptions and operational uncertainties (Khan, M. I., & Al-Ghamdi, S. G. 2023; Kasimalla, et al, 2024).

Community Energy Systems (CES), defined as neighborhood-scale infrastructures integrating local renewable generation, storage, district heating, and demand-side flexibility (Ahmed, S., Ali, A., & D’angola, A. 2024), are increasingly recognized as pivotal tools for achieving urban energy resilience and decarbonization (Ullah

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et al., 2024; Masrur et al., 2024). CESs often rely on cooperative or municipally governed models and aim to reconfigure the traditional centralized paradigm into more efficient, distributed energy systems (Perez-DeLaMora et al., 2021; Nouicer et al., 2020). These systems vary in composition, combining distributed renewable energy (e.g., PV, wind, biomass) with energy storage, smart controls, and sometimes combined heat and power (CHP) plants or low-carbon thermal resources (Jendoubi et al., 2020; Booth et al., 2020).

Advanced digital tools and predictive energy management systems are enabling more effective implementation of CESs, yet their technical and performance outcomes remain highly dependent on spatial conditions and neighborhood form. Research shows that built form, land use intensity, and surface availability significantly shape CES feasibility and energy self-sufficiency. For instance, Mussawar et al. (2023) demonstrate that compact high-rise neighborhoods generally underperform due to limited solar deployment potential, while Hachem et al (2011 and 2019) highlights that street grid orientation and urban layout directly affect energy performance and generation performance. Hachem-Vermette and Singh highlight the role of urban morphology on solar performance and show how spatial design, and typological characteristics influence energy sharing, vulnerability reduction, and the feasibility of hybrid energy systems such as PV coupled with borehole storage (Hachem-Vermette & Singh, 2022a, 2022b, 2023).

Although prior literature provides important insights into CES operations and community governance, systematic comparative analyses of CES performance across different neighborhood typologies are rare. Most studies either examine technological performance in isolation (e.g. Inayat & Raza, 2019; Al-Nini, et al, 2023) or focus on behavioral and policy aspects without accounting for spatial form (e.g. Von Wirth et al., 2018; Hearn & Castaño-Rosa, 2021). This study contributes to filling this gap by introducing a structured evaluation of CES scenarios across a typology spectrum. It evaluates the performance of eleven neighborhood typologies under 9 CES configurations, integrating rooftop PV, landscape PV (LPV), TES, geothermal and PV/T-based district heating, and V2G-enabled EV infrastructure. Key performance metrics employed in this study are Ratio of Performance (ROP), Self-Sufficiency Index (SSI), and Net Energy Balance. This framework enables a comparative understanding of CES effectiveness across diverse built forms.

Rather than focusing solely on technology optimization, the methodology assesses how urban form interacts with CES configuration. By doing so, the research identifies which neighborhood types are inherently more compatible with self-sufficient or energy-positive CES operations and which require external support or technological compensation. The findings offer critical insights for early-stage planning, spatial energy mapping, and policy development targeting net-zero and resilient urban energy systems.

2. Methodology

This study introduces a scenario-based framework to assess energy performance across diverse urban typologies by integrating key Community Energy System (CES) components—microgrids, low-exergy district heating (PV/T and geothermal), vehicle-to-grid (V2G) infrastructure, and landscape-integrated photovoltaics (LPV). The analysis draws on simplified performance models calibrated using real-world data and validated references. EnergyPlus simulations were used to calculate annual thermal and electrical demand, while energy generation potentials were based on geometric and adequate surface availability for PV installation, of each neighborhood unit (NU).

2.1. Neighborhood Typologies

Eleven representative Neighborhood Units (NUs) were designed to reflect typical urban development patterns in Canadian cities. These are organized into two main categories, **Residential** and **Mixed-Use**, and modeled employing a fixed surfaced area of 5 acres. The designs follow a **fused grid urban layout** (Masoud, 2019; Sun & Lovegrove, 2013) and incorporate walkability, mixed land uses, and green space. Table 1 presents key physical and spatial characteristics of these. neighborhoods.

Table 1: Neighborhood Typology Summary (Residential and Mixed-Use)

Typology	Type	Density (ppl)	Floor Area Ratio (FAR)	Key Features
24DH	Residential	96	0.26	24 detached houses
48DH	Residential	192	0.52	48 detached houses (higher density)
56AH	Residential	224	0.50	56 attached houses (row/townhomes)
8A-4F	Residential	1024	1.24	8 mid-rise apartment blocks (4 floors)
12A-4F	Residential	1536	1.86	12 mid-rise apartments (high-density)
CR	Mixed-Use	100	0.46	Housing + small retail and restaurants
CR/I-V1	Mixed-Use	215	0.73	Primary school + retail + attached housing
CR/I-V2	Mixed-Use	400	1.55	Mid-rise apartments + secondary school
MU-S	Mixed-Use	400	1.59	Hotel + retail + apartments
MU1	Mixed-Use	1200	3.97	Hospital + 15-story residential towers
MU2	Mixed-Use	1600	5.96	High-rise 20-story towers + offices + retail

2.2. Energy Demand Modeling

Energy simulations were conducted using EnergyPlus, supported by custom MATLAB scripting to model and evaluate 11 Neighborhood Units (NUs). Each NU was composed of multiple building types, ranging from single-family homes to 20-story towers. The original models are based on adapted DOE reference models and optimized for northern Canadian climates. Electric loads included lighting, appliances, HVAC, and ventilation systems, while thermal loads covered space heating and domestic hot water (DHW). All buildings incorporated high-performance envelopes, with wall insulation rated at 7 $m^2 \cdot K/W$, roof insulation at 14 $m^2 \cdot K/W$, and low-U glazing ($\leq$ 1.068 $W/m^2 \cdot K$). Heat pumps with a COP of 3 were assumed for thermal supply, and heating/cooling setpoints were set at 20°C and 25°C respectively. Simulations assumed an occupancy rate of 2.5 persons per residential unit.

On-site renewable generation included rooftop and façade-integrated photovoltaics (PV), vertical-axis wind turbines (VAWTs) placed along main streets (cluster-staggered, 10D spacing), and waste-to-energy (WtE) conversion based on solid waste yields (estimated at 650 kWh/tonne). Theoretical maximums for each energy source were modeled. Key performance indicators included: Ratio of Performance (ROP), Self-Sufficiency Index (SSI), and Net Energy Balance. This framework enabled systematic comparison of CES feasibility and energy performance across typologies and system configurations.

2.3. CES Scenario Configuration

This study employs a conceptual microgrid framework to support the comparative analysis of Community Energy Systems (CES) across eleven neighborhood typologies. While microgrids were not dynamically simulated, their operational assumptions, such as bidirectional power flow, local balancing, and load aggregation are based on established findings in the literature (Eklund et al., 2023). The microgrid acts as an enabling layer for integrating local generation (PV, LPV), district thermal systems, and EV infrastructure, while allowing for the evaluation of net energy balance and CES performance at the neighborhood scale.

Three core CES configurations were evaluated, each building on different thermal energy strategies: S1- All-electric microgrid with heat pumps (COP = 4.0), S2- PV/T hybrid thermal collectors supported by heat pumps, and S3- District heating network with 30% geothermal energy contribution.

These base configurations were extended to include V2G-enabled electric vehicles (1.5 EVs per household, 15 kWh/day per EV, 90% charging efficiency), and landscape-integrated photovoltaics (LPV), yielding a total of nine CES scenarios (see Table 2). LPV systems were assumed to occupy 20% of available green/setback space with 50% usable layout, producing approximately 608 MWh/year per 5-acre unit, based on standard PV module efficiencies (15–18%). EV discharge contributions and round-trip losses were incorporated based on values from Dalla Chiara et al. (2019) and Ray et al. (2023).

Each scenario was applied to all eleven neighborhood units, producing 99 simulation cases.

Table 2: CES Scenarios

Scenario	Configuration
S1	Microgrid with all-electric heating; heat pump COP = 4
S2	PV/T hybrid collectors for thermal energy and heat pumps
S3	District heating with 30% geothermal contribution
S1-EV(V2G)	S1 + electric vehicles (1.5 EV/household) with V2G
S2-EV(V2G)	S2 + EV + V2G
S3-EV(V2G)	S3 + EV + V2G
S1-EV(V2G)-LPV	S1-EV(V2G) + landscape-integrated PV (LPV)
S2-EV(V2G)-LPV	S2-EV(V2G) + LPV
S3-EV(V2G)-LPV	S3-EV(V2G) + LPV

3. Results

3.1 CES Performance Variation Across Neighbourhood Typologies

Performance outcomes exhibit strong correlations with urban morphology and land-use intensity. Neighborhoods characterized by low- to medium-density configurations, such as CR/I, 48DH, CR, and other detached or attached housing types (e.g., 24DH and A56H) demonstrates consistently superior CES performance relative to high-density, mixed-use forms such as MU1, MU2, and 12A-4F.

Low-density residential typologies, particularly under configurations excluding vehicle-to-grid (V2G) integration, achieve Ratio of Performance (ROP) values exceeding 2 and Self-Sufficiency Index (SSI) of 1, indicating full on-site energy self-sufficiency with considerable net energy surplus. When V2G is introduced, ROP values decrease due to increased electric load demand; however, these typologies still maintained surplus generation under most scenarios. In contrast, high-density mixed-use typologies exhibit significantly lower energy autonomy. ROP values rarely exceeded 0.7, and SSI consistently remained below 0.6, reflecting substantial reliance on external energy supply or the need for inter-neighborhood energy compensation mechanisms. For instance, MU2 under scenario S2-EV(V2G)-LPV achieves an ROP of only 0.50, with a remaining annual energy deficit of approximately 4.6 GWh. These results underscore the limitations imposed by high-density urban form, including reduced PV deployment capacity and elevated per-area demand intensity. These performance discrepancies are primarily driven by the availability of surface area for photovoltaic (PV) system deployment and the proportional relationship between thermal and electrical demand intensities within each typology.

A detailed summary of neighborhood-level results across the various CES scenarios is provided in Figure 1. These outputs offer insights into the influence of density, land use, and CES.

Figure 1: Total Demand (kWh), On-Site energy use kWh), On-Site Generation (kWh), ROP, SSI, Net Energy Balance (kWh), for each scenario associated with each neighborhood unit

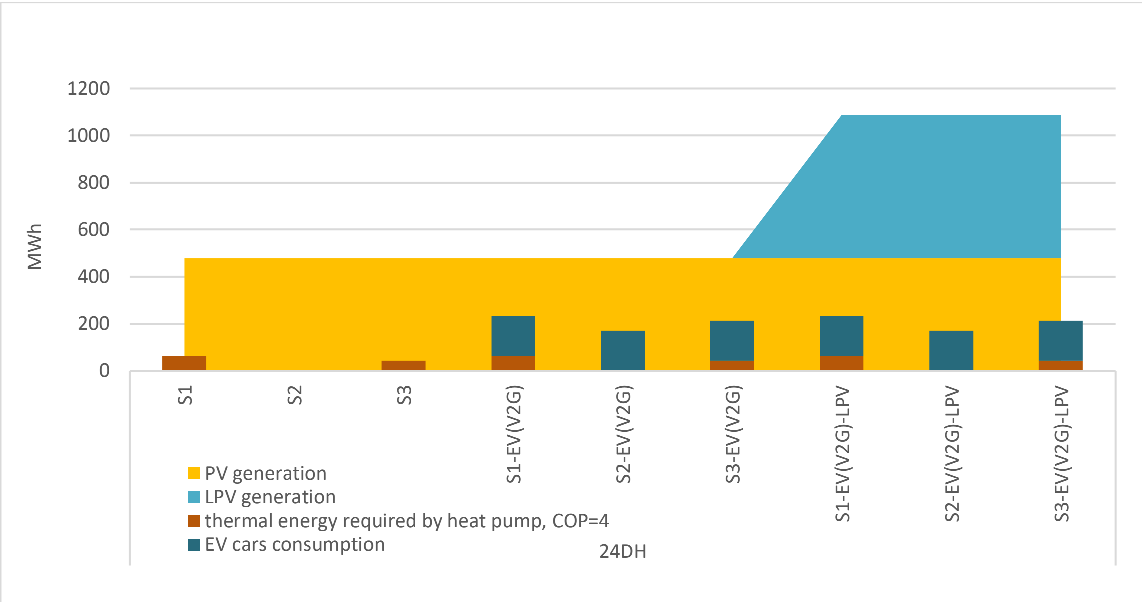
3.2. Influence of CES Scenario Configurations on Energy Performance

The integration of electric vehicles (EVs), landscape-integrated photovoltaics (LPV), and district heating strategies significantly affects the performance of Community Energy Systems (CES) across different urban typologies. This section evaluates how each of these components - EV charging and vehicle-to-grid (V2G) functions, LPV deployment, and various district heating (DH) configurations, modulates key CES metrics. **Figure 2** shows selected Neighborhood units, and their key metrics associated with various CES strategies.

Electric Vehicle (EV) Charging and Vehicle-to-Grid (V2G) Integration. Scenarios incorporating EV infrastructure with bidirectional V2G capability introduces substantial additional electrical loads due to daily charging demand. In the absence of proportional increases in local generation capacity, this leads to reduced overall performance. For instance, the transition in **MU2** from Scenario S2 (without EV) to S2-EV reduces ROP from **0.63 to 0.44** and correspondingly lowered SSI, reflecting increased reliance on the external grid. The subsequent addition of LPV in Scenario S2-EV-LPV increased ROP to **0.5**, partially mitigating the energy gap, but still well below Net-Zero Energy (NZE) thresholds.

Integration of Landscape-Integrated Photovoltaics (LPV). Across all neighborhood typologies, the addition of LPV significantly improves both the Ratio of Performance (ROP) and the net energy balance by supplementing limited rooftop and façade PV capacity. The impact is particularly significant in typologies constrained by roof area, such as medium- and high-density residential forms. For example, in 56AH, incorporating LPV into Scenario S2-EV increased ROP from 1.2 to 2.2, effectively transforming the neighborhood from marginally surplus to a significantly energy-positive performer. In the high-density typology MU1, ROP improved from 0.5 to 0.6 with an associated reduction in the annual net energy deficit of approximately 610,000 kWh.

Comparative Evaluation of District Heating (DH) Strategies. The performance of CES configurations also varied significantly depending on the selected thermal energy strategy. For instance, geothermal-assisted district heating (Scenario S3), coupled with high-efficiency heat pumps, yielded the highest ROP values in high-density neighborhoods, reflecting the lower primary energy input per unit of thermal output and reduced electrical dependency for space heating. In contrast, PV/T-integrated systems (Scenario S2) performed optimally in mid-density typologies, where space for collector integration was available and heating loads were moderate. However, their impact was limited in dense urban forms lacking surface area for thermal collectors. CES design must align thermal infrastructure selection with neighborhood typology, optimizing for density, land use, and integration potential with local renewable sources.



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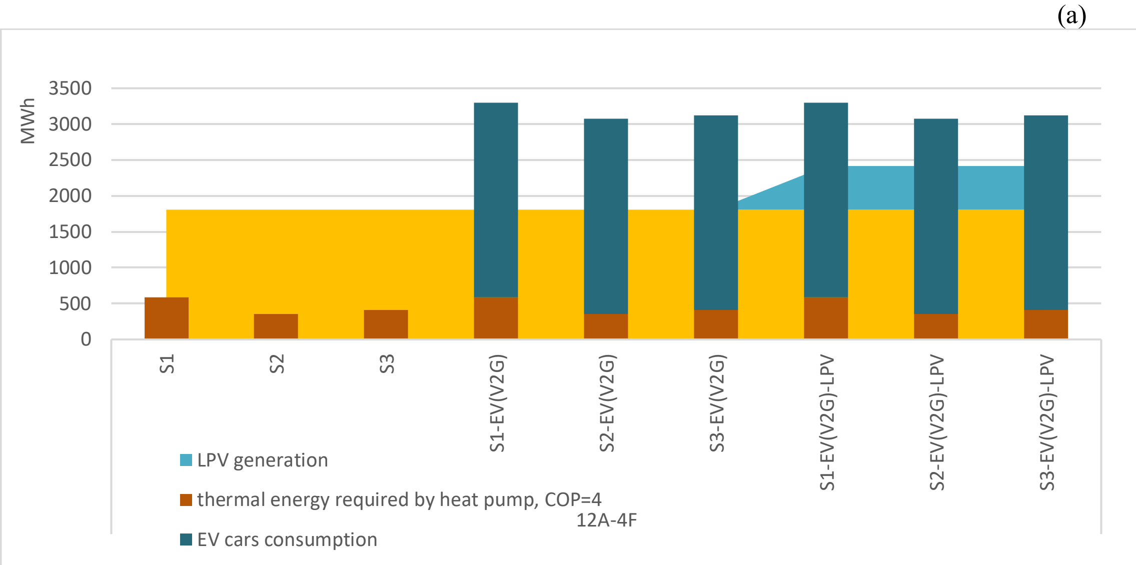

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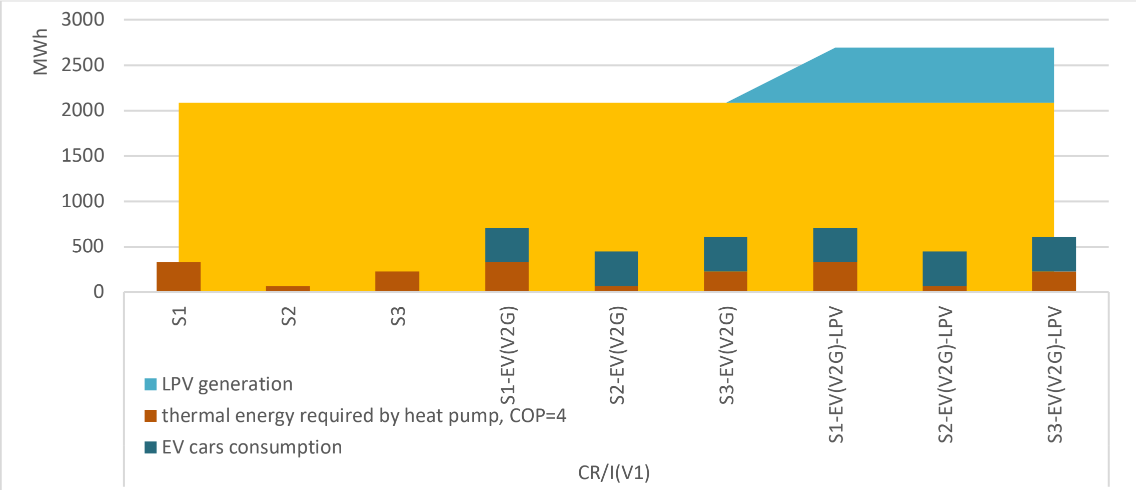

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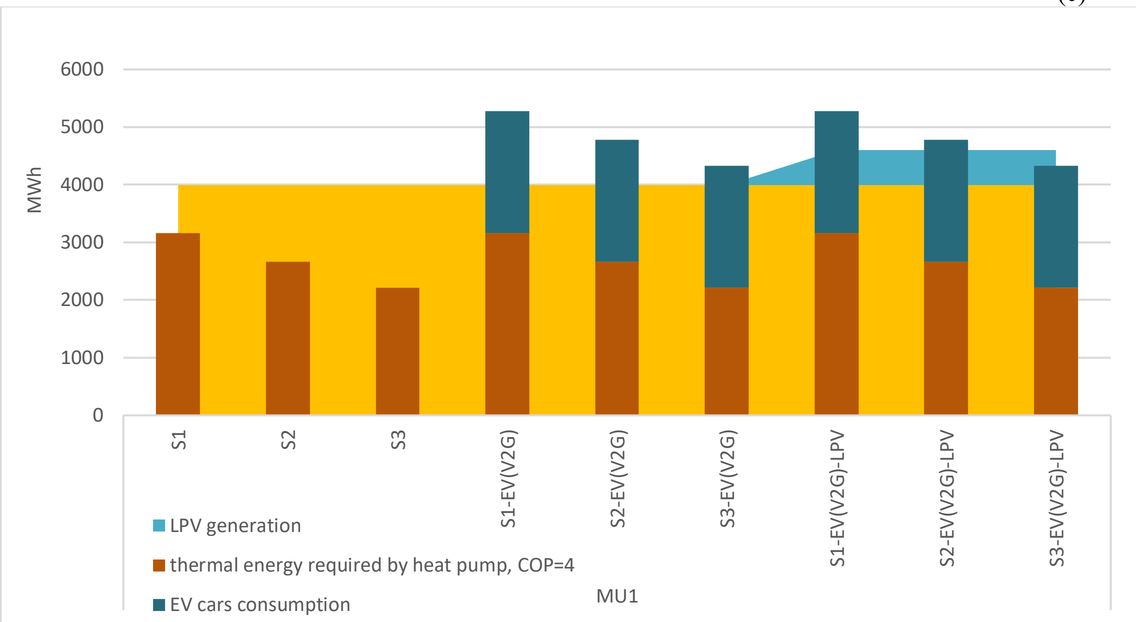

(d)

Figure 2, Performance of selected Neighborhood Units across various CES strategies

3.3. Performance Ranking and Cluster Optimization

To support CES scenario selection, all typologies and configurations are evaluated using a dual performance-ranking framework: Energy Positive Neighborhood (EPN) Score and Net-Zero Energy (NZE) Score. The EPN score prioritizes total net energy surplus and export potential, while the NZE score emphasizes energy self-sufficiency with minimal deviation from net-zero. Both scores incorporate core performance metrics, ROP, SSI, and net energy balance, and are applied across all nine CES scenarios for each of the eleven neighborhood typologies.

The EPN score directly weights energy surplus more heavily (normalized by 50,000 kWh) and filters out invalid scenarios with SSI below 0.85. Top-performing configurations under this ranking include CR/I(V1), 48DH, and CR under Scenario S2-EV-LPV, with energy surpluses exceeding 1.5 GWh annually and ROP values above 2.5. These typologies emerge as core surplus nodes.

The NZE score, in contrast, penalizes both large surpluses and deficits by using absolute net balance as a distance from zero. High-scoring scenarios under this metric are those that closely match energy demand and supply, such as CR/I(V2) under S1-EV-LPV and 56AH under S1-EV-LPV, despite not being the largest net producers.

Figures 3 and 4 show the top 20 configurations for EPN and ZEN (zero energy neighborhoods), respectively. Figures 5 and 6 present the best configuration for each neighborhood scenario.

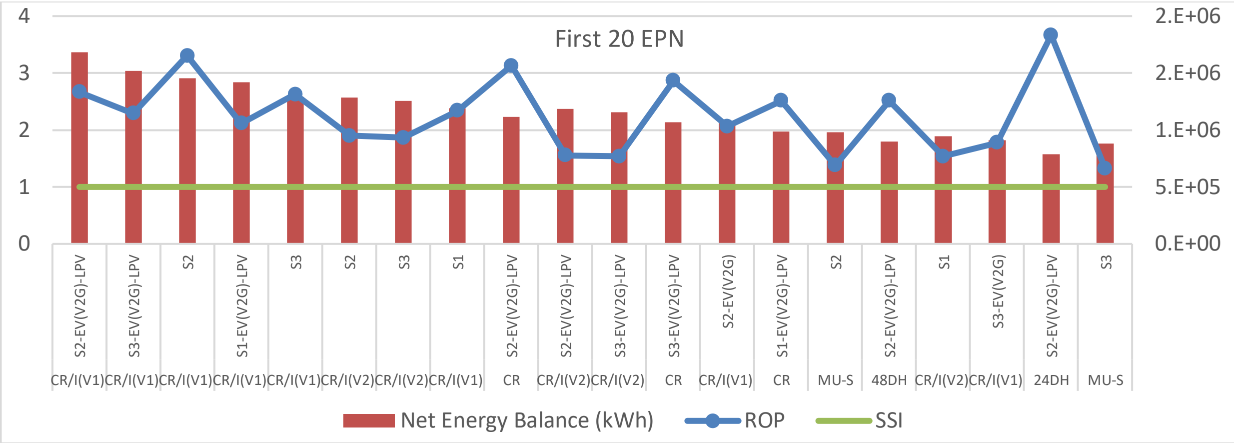

Figure 3, first best ranking 20 EPN

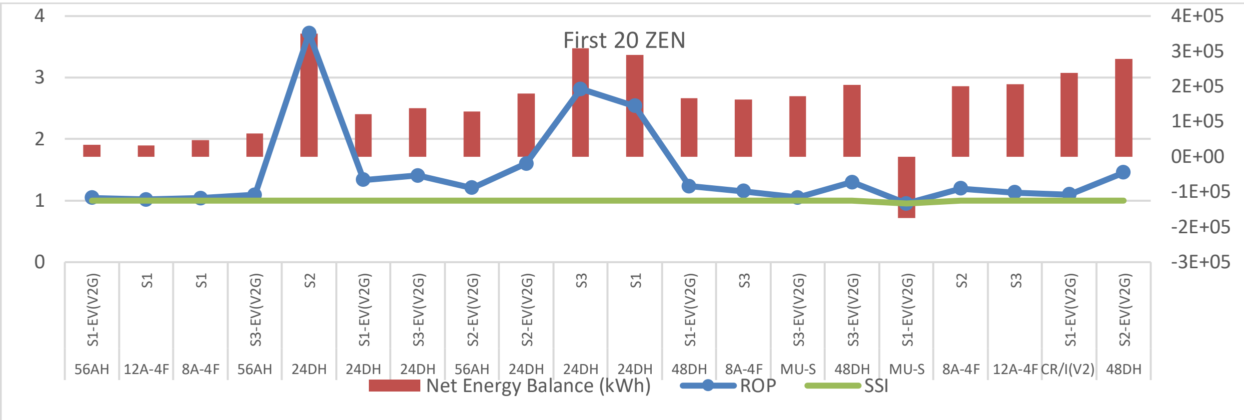

Figure 4, first best- ranking 20 ZEN

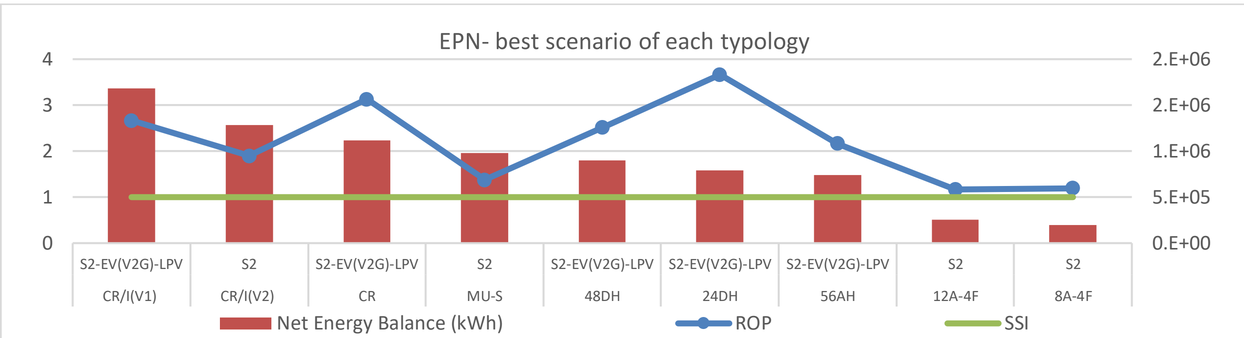

Figure 5, Best EPN configurations for each neighborhood

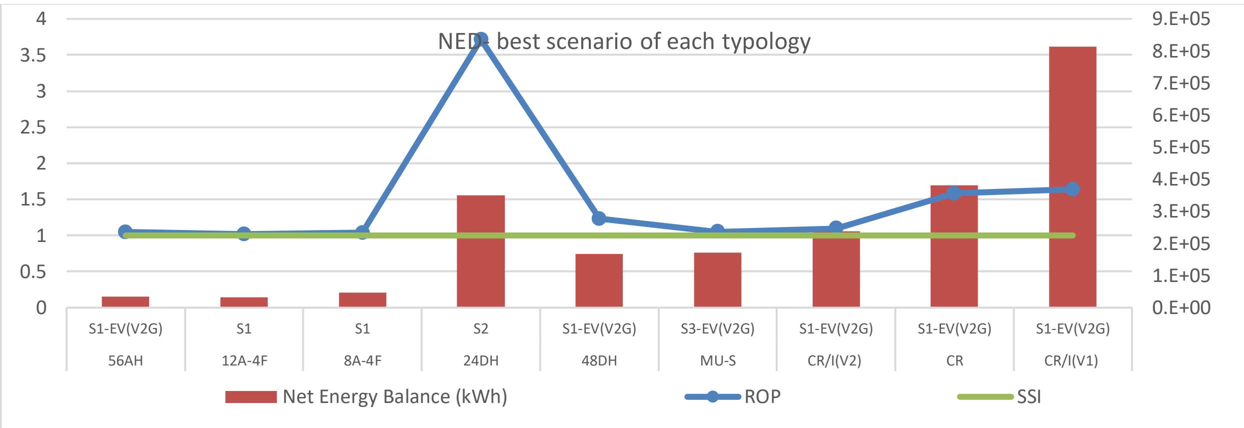

Figure 6, Best ZEN configurations for each neighborhood

4. Discussion and Conclusion

This study presents a comprehensive evaluation of Community Energy System (CES) configurations across eleven neighborhood typologies using a scenario-based simulation framework. By integrating key technologies, such as high-efficiency heat pumps, PV/T hybrid systems, geothermal district heating, V2G-capable electric vehicles, and landscape-integrated photovoltaics, the research provides a nuanced understanding of how spatial form and system design interact to shape energy performance.

Key findings highlight that urban form is a critical determinant of CES effectiveness. Low- and mid-density residential typologies consistently outperform high-density mixed-use neighborhoods under all scenarios, particularly in their ability to approach or exceed Net-Zero Energy (NZE) targets and generate energy surpluses. The addition of landscape PV (LPV) prove especially valuable in typologies constrained by rooftop area, boosting ROP and energy balance significantly, even transforming marginal performers into energy-positive systems.

The integration of electric vehicles, although under V2G scenarios, introduces substantial new loads that challenged self-sufficiency. However, when combined with enhanced on-site generation (e.g., LPV), these electrified mobility systems become more viable, underscoring the need for co-optimization between mobility and energy planning.

To synthesize results across all 99 CES simulations, a dual ranking framework, the EPN Score (energy-positive neighborhood potential) and NZE Score (net-zero energy), is developed. High-scoring configurations under EPN prioritize large surpluses and grid contributions, while NZE rankings favor balanced generation-consumption and robust self-reliance. The ability to rank and map performance directly back to neighborhood typologies enables planners to match CES configurations with spatial and infrastructural conditions, ensuring implementable outcomes.

Importantly, this approach enables hybrid clustering strategies, that can potentially pair energy-surplus typologies with energy deficit neighborhoods to create interdependent neighborhood clusters. This supports resilient modular systems capable of balancing load diversity, mitigating local deficits, and enhancing export potential.

Beyond the analytical contributions, this study offers a replicable methodology for CES planning in other urban contexts. The ranking framework supports applications in master planning, zoning codes, and municipal energy strategies by providing a scalable, performance-driven design structure that bridges simulation, policy, and spatial design.

Ultimately, this research advances the integration of spatial-energy logic into community energy systems, offering a pathway toward more resilient, net-positive, and policy-aligned urban energy transitions.

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