Design and Simulation of a Hybrid Renewable Energy Grid for Low-Carbon Urban Communities

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Abstract. This research assessed the energy conservation advantages of Renewable Energy (RE) generating systems by integrating solar energy in a metropolitan area. The solar city idea was executed using photovoltaic (PV) and Solar Thermal (ST) technology. The National Pilot Smart City (SC) was chosen as a case study to assess the green energy adoption rate. The power and ST demands of the SC were assessed using field measurements to evaluate the suggested RE solutions for low-carbon urban communities. The city's RE adoption rate was assessed. The HomerPro program was implemented to evaluate the gas-powered generator's PV production and operational electrical consumption inside a district heating system. The heating and cooling capacity of the ST systems was assessed using the TRNSYS program. The findings indicated that the suggested urban integrative RE systems could achieve an RE adoption rate above 31%, with the leveled cost of power and overall net current cost being 8% cheaper than the baseline systems (i.e., natural gas generators). The suggested system demonstrated a 39% reduction in CO2 emissions compared to the baseline system for low-carbon urban communities.

1 Introduction

Urban regions account for about 76% of global energy use and are responsible for 70% of global carbon dioxide emissions [1]. Currently, most metropolitan areas globally depend significantly on the concentrated energy supply of non-renewable fossil fuels. Accelerated industrialization and population expansion are subjecting cities, particularly in emerging nations, to heightened challenges from escalating energy requirements, depleting fossil fuels, limited land resources, and significant environmental contamination. Scattered Renewable Energy (RE), characterized by reduced greenhouse gases, decreased transportation and distribution expenses, and deferred investments, is efficient for attaining decarbonization objectives and promoting equitable growth for low-carbon urban communities [2]. The optimal planning and oversight of hybrid electrical systems, including dispersed RE production, remains a complicated and demanding endeavor due to the distinct local resource circumstances and the competitive edge of diverse technologies from several viewpoints.

Research on urban hybrid energy systems has begun to include trends from the building to the city level [3]. An extensive study has been conducted on the techno-economic-environmental evaluation and optimum design of urban energy systems using novel technologies. The survey of hybrid energy sources mainly focuses on photovoltaic (PV) arrays [13], windmills, storage systems, and Combined Heat and Power (CHP) units, including turbines, combustion engines, or fuel cell technology for low-carbon urban communities [4]. The research created a financial framework and optimization technique for a grid-connected RE system, including PV panels, wind turbines, and fuel cells, to meet households' heating and electricity requirements [10]. The research used the modeling program to focus on the ideal configuration of a hybrid energy system integrating PV, biomass gasification, and diesel technologies for a rural region [5]. The research introduced an optimization framework for the techno-economic evaluation of a combination of energy sources, including PV technology, diesel-fired and gas-fired thermal and electrical power systems, and electric preservation for low-carbon urban communities [11]. It was implemented at an exhibition centre. The research examined the best energy scheduling for a hybrid PV and wind energy system, including batteries and hydrogen car storage methods for a high-rise residential structure [6].

Alongside the integration of diverse distributed energy production on the supply side, hybrid energy sources encounter management issues on the consumer side, particularly owing to smart devices and efficient building control systems [9]. Flexibility Demand-Side Response (DSR) [7] end-users' activities are crucial in balancing the intermittent production from RE sources. Financial incentives and regulatory actions are the primary demand reaction plans for mitigating peak load or modifying the demand curves for low-carbon urban communities. Certain studies have integrated DSR technology into administering home RE sources and emphasized its

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efficacy in frequency regulation. The research optimized a single-family residence's integrated RE system using a two-step DSR method. The study revealed that a DSR technique might lower the investment cost of the combined energy system by reorganizing the deferrable loads.

Few studies have assessed the viability of a hybrid system that concurrently considers Rooftop (RT) solar panels and waste-to-energy technologies as power-generating choices and DSR strategies. This paper proposes an extensive structure for the optimum design and dispatching of a hybrid power plant, emphasizing the combination of RT PV and biomass-based power production, motivated by the research gaps identified for low-carbon urban communities [15]. The prospective evaluation of local RE at the regional scale is usually undertaken from the energy supply viewpoint within the unified structure [8]. This paper primarily contributes by: (1) assessing the possible benefits of RT PV systems and solid waste plant matter at the community level using a mapping tool; (2) formulating a mixed-integer linear programming approach to the best possible layout and operation of an integrated energy system that leverages localized clean energy sources to meet electrical demands; (3) analyzing and contrasting the effects of RE policies and DSR techniques on the layout of the system, total costs, and unit dispatch tactics; and (4) investigating the effects of unknowns in capital costs and electricity tariffs through a sensitivity analysis for low-carbon urban communities [12][14].

2 Proposed Hybrid RE Grid for Low-Carbon Urban Communities

To evaluate the effects of various electric load characteristics on the financial and emission efficiency of hybrid electric structures, the research selected three distinct neighbourhood sizes representing the city's household (case a), business (case b), and manufacturing (case c) electrical consumption. This study will refer to them as home, commercial, and industrial for low-carbon urban communities. For a more effective comparison of the effects of load trends from the city's residential, business, and corporate electrical demands, their average electrical power need and daily mean energy demand should be comparable in size, within a 10% variance. The research established three distinct power scenarios according to (i) 100% fossil fuels (e.g., freestanding natural gas plants); (ii) hybrid natural gas/renewables; (iii) entirely clean energy (e.g., wind, solar energy, and compost). Afterwards, the most financially viable solutions were derived and evaluated by reducing the overall expenses of supplying electricity to the three neighbourhoods based on their techno-economic and environmental capabilities.

Fig 1 illustrates the simulation method. The present research examined nonpresidential structures using measurements from the Sustainable Energy Town for low-carbon urban communities. In contrast, residential buildings were examined through simulation information obtained from measurements to determine the buildings' consumption of electricity, heating load, and hot water system load. Weather information was analysed using the Metronome program. The capacity needed for a small combination plant for a new city was determined using Homer software.

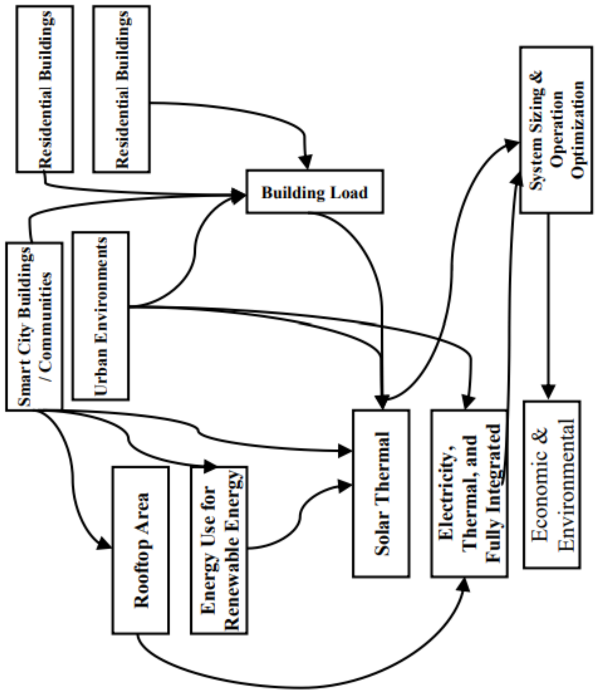

Fig 1. Process overview

2.1 Optimization Approach

This research aimed to minimize the overall net present costs (NPC) of the SC's energy and heat supply network by serving as the goal function for maximizing the combined costs and capacity of diverse systems for low-carbon urban communities. The power output of the NG generation was computed, and optimization research determined the PV structures, converter, and battery setup capabilities. The HomerPro software's optimizing tool enhanced the system's capability. A financial efficiency study was performed comparing the installation of ST installations with PV systems. Concerning optimization, Natural Gas (NG) generation offers a cheap initial cost. Still, it incurs significant running expenses owing to NG consumption, while other RE systems provide a low cost of operation despite their elevated initial investment. A comprehensive long-term life-cycle cost study is necessary**.**

This work is crafted in such a manner that the energy grid framework is recreational and can be critically assessed. Each of the components involved in the hybrid renewable energy grid design has been broken down into specific details with a step-by-step breakdown of the software tools, models, parameters, and assumptions applied in the simulations.

Software Tools: HomerPro software was employed in the evaluation of the power generation of PV systems and gas-powered generators in the district heating system. The heating and cooling of the solar thermal (ST) systems had been simulated by the TRNSYS program. These models were characterized by specific configurations, including PV panel efficiency, type of battery, and other generator specifications.

Model Specifications: PV panels, which are commercially available with an 18% efficiency, were chosen in the HomerPro model, and Lithium-Ion batteries with an 85% round trip efficiency were chosen. The biomass generator model was developed using the conventional data on the efficiency of combustion and the consumption of fuels in a typical biomass system. Standard heat pump technology was used in the incorporation of thermal storage based on literature sources.

Assumptions: There were assumptions regarding capital costs, operation and maintenance (O&M) costs, and fuel costs, which are very important in the optimization process. Such assumptions are in line with the industry standards on renewable energy (RE) systems.

Scenarios and Constraints: Four scenarios (Base, S1, S2, S3) were considered, and the penetration of RE was different. Such scenarios were well spelled out, involving renewable energy integration objectives and the capacities that RT PV systems and biomass generators should have. All the scenarios were meant to be geared towards the general decarbonization goals.

2.2 Model Specifications and Cost Assumptions

In the hybrid renewable energy system evaluation and optimization, HomerPro and TRNSYS were used in the research. The models built, along with the specific components and their specifications, and the cost assumptions, are listed below:

HomerPro Model Components:

PV Panel Type and efficiency: They were modelled with a commercially available monocrystalline panel, which is highly efficient with 18% efficiency.

Battery Chemistry: Li-Ion batteries were selected as a source of energy storage, and their round-trip efficiency is 85.

Biomass Generator Model: A conventional biomass firing technology was used to model the biomass power generation system, and the average efficiency of the combustion process was 80%. The system was made to burn the agricultural residues as the main source of fuel.

Thermal Storage: This involved the addition of thermal storage into the system by the adoption of water-based heat pump technology that is readily available in the market. The storage system was intended to satisfy the thermal energy requirements of the heating and cooling systems.

Cost Assumptions:

Capital Costs: The system components' capital costs were pegged to the industry average of each technology. The initial PV system cost was taken to be $1,200/kW installed, and the cost of the biomass generator was taken to be $3,500/kW installed. The assumption was that the capital cost of a battery storage system is 500 per installed kWh, and the thermal storage system is 800 per installed kWh.

Operation & Maintenance (O&M) Costs: It is assumed that operation and maintenance costs would be 2 % of the initial capital cost in a year on all system components. In the case of biomass systems, 1% of the capital cost was added to the cost of buying and handling fuel.

Fuel Costs: Biomass fuel cost was taken at 40 US dollars per tonne, and the fuel efficiency was 90 % in the biomass generator. The operating prices of the NG generation were pegged to the market prices of natural gas, which were estimated to be $0.07/kWh.

Scenarios and Constraints: The paper analyzes four scenarios (Base, S1, S2, and S3) that differ in the degree of integration of renewable energy. Both situations have been well articulated regarding the PV system and biomass generator potentials, and so the renewable energy penetration objectives have been achieved in accordance with decarbonization objectives.

2.3 Renewable Energy Scenarios and Penetration Targets

This paper has examined four different scenarios (Base, S1, S2, S3) to determine the effect of various renewable energy (RE) penetration on the hybrid renewable energy system design. Both situations are associated with a different level of integration of renewable energy, diverse renewable penetration goals, and constraints of operation. The description of each of the scenarios is presented below:

Base Scenario: This scenario would be the baseline one, where there is no integration of renewable energy, and all processes become based on the traditional sources of energy, like natural gas generators. It can be used as the benchmark on which the economic, environmental, and technical performance of the other scenarios can be compared.

S1 Scenario: The scenario on renewable penetration is that in this scenario, the penetration of renewable energy is pegged at 30 % of the aggregate energy requirement. This is achieved through the incorporation of solar PV systems that are installed on the roofs and biomass power, which is generated on the roofs, together with natural gas generators to fill the shortfall in demand. This scenario aims to determine the financial and environmental payoffs of a small-scale take-up of renewable energy.

S2 Scenario: The %age of renewable energy consumed in this case is 50 % of the total power requirement. There is an increased %age of the energy mix obtained through the solar PV systems, biomass generation, and solar thermal systems, and a subsequent decrease in natural gas generation as well. This case challenges the viability and effects of moderate integration of renewable energy while keeping the system reliable.

S3 Scenario: This scenario is a complete integration of renewable energy with a 75 % renewable penetration that is mainly based on solar PV systems and biomass generation of power. The other energy need is fulfilled by means of battery storage and imported grids. This situation assesses the technical difficulties and economic sustainability of a high penetration system of renewable energy.

All these scenarios were optimized to serve the electrical needs of the system and stay within the grid stability, as well as achieve the decarbonization targets of the urban community. The renewable energy penetration goals were chosen based on realistic and achievable goals towards switching to a low-carbon energy system.

3 Results and Discussions

3.1 Optimal Approaches for Case I

In the base situation, the combination system will consist of a biomass power generator of 12.37 MW and a battery of 20.30 MW, which will minimize the annual cost. Greater restrictions on RE penetration require more investments in RT PV systems and battery backup, thereby causing a huge increment in overall system costs. In the S1 and S2 cases, 39 and 68 % of the total available roof area would be covered with PV system installation, representing 32.95 MW and 57.35 MW, respectively. On the contrary, the excess power produced by the PV output during the day (9:00-17:00) would be emitted at the peak hours (18:00- 22:00) at night to ease the burden on the power supply by low-carbon urban residents. The required power of the biomass power generation would also be reduced. The overall impact would be more integration of RE that leads to increased Levelized Cost of Energy (LCOE). The LCOE of the hybrid system will be estimated at 0.094, 0.0997, 0.0935, and 0.214 of the Base, S1, S2, and S3 cases, respectively.

The biomass would be used in the production of energy since 94% of the available biomass is very cheap. It only comprises 6 % of the total electric consumption. In the absence of mandatory RE regulations, the imported energy would continue to be the majority energy provider in the community, with approximately 174.66 GWh of power supply, which is 97 % of the total energy requirement. The RT PV would generate power with a capacity of 46.74 GWh and 79.75 GWh of electricity, respectively, in the S1 and S2 scenarios, which is approximately about 27 % and 47 % of the total electricity demand in the region, respectively. When local RE (S3) is fully utilized, the production would be 136.15 GWh, which is 74% of the total power consumption. In this instance, the imports and sold power would be 131.76 GWh (72% of the total power consumption) and 72.90 Gwh (58% of the overall RE production).

Greater use of RT PV systems would also lead to a proportional increase in the amount of throughput annually of the battery. The power charge at the S3 scenario would be 34.40 GWh, which is approximately four times compared to the Base situation that recorded 9.79 GWh. The carbon emission embedded in the power supply in the Base, S1, S2, and S3 scenarios is 1.1549kg/kWh, 0.8919 kg/kWh, 0.7554 kg/kWh, and 0.6527 kg/kWh, respectively.

Under the Base situation, the biomass-based power generation would operate as an additional source at times of high demand due to constraints of energy transfer. It would be running 8 hours in the summer and greatly reduced in the other seasons of the year.

3.2. Optimal Approaches for Case II

Considering DSR, the flexible management of shiftable load might alleviate peak load and enhance the alignment of electricity availability and demand, rendering the battery unnecessary and reducing the total capacity of biomass-based power generators. Compared to Case I, the overall system expenditure of Case II would significantly diminish owing to the circumvented expenditure. The case II calculation of the overall system costs of the Base and S3 cases is 13.32 x 106 and 16.36 x 106, respectively, which is a 16 % and 14 % decrease relative to Case I. At the same time, the implementation of DSR initiatives would lead to lower Levelized Cost of Energy (LCOE), namely 0.0828 /kWh, 0.0889/kWh, 0.0934 /kWh, and 0.0 In the Base scenario, it would have imported power of 179.71 GWh, which would be one of the dominating factors of the power supply, covering more than 98% of the electricity demand. The biomass generator has an electrical capacity of 3.12 GWh, and the annual throughput of the battery is 4.96 GWh, which is due to the changing load setup. As green energy inclusion standards intensify, the electricity generation from RT PV systems will rise, while the power. Fulfilment from biomass-based generators will decline. Particularly, in the S3 situation, the power traded with the primary grid and the battery discharge of Case II would exceed that of Case I. In the Base situation, the biomass-based generation would operate from 18:00 to 1:00 throughout the summer to fulfil nighttime peak demands. The power source in other months would continue to depend on energy from the primary grid for low-carbon urban communities. In the S3 situation, enough sun irradiance in summer and spring allows RT PV systems to fulfil local daytime power demand (8:00-15:00), while surplus electricity is sent to the grid. Energy that will be obtained through the electrical grid will take into account the demand for electricity during the night (17:00-06:00). The biomass-sourced power production will work under the conditions of the lack of solar radiation, the high price of electricity, 6:00-9:00, and 17:00-20:00.

Usually, the initial movable loads in the evening peak hours are transferred to the late night as the power rates are low, and to daylight as RT PV production is more in the low-carbon urban communities. The total annual shifted load of the Base, S1, S2, and S3 cases is 10.38 GWh, 8.79 GWh, 8.36 GWh, and 14.31 GWh, respectively. In addition, the shift in the summer demand would be higher than in other months, which can be explained by the high electricity production by RT PV systems. The Base situation would mean that the daily shifted load in the summer would be 51.70 MWh, and the peak demand would be reduced by 24%.

4 Conclusion

This research sought to enhance the integration of solar energy within the RE framework of SC. Arrangements involving PV and ST structures, an ESS, thermal power storage, and NG generation were evaluated, with the dimensions of each system determined by optimization planning. Each system's yearly operational metrics were determined thereafter, and carbon emissions and financial effectiveness were evaluated. Cases 1 and 2 exhibited a 32% greater RE adoption rate than the base scenario for low-carbon urban communities. Regarding carbon dioxide emissions, Cases 1 and 2 demonstrated 37% and 39% reductions in CO emissions, respectively, compared to the base scenario, establishing Case 2 as having the smallest carbon emissions. The research indicated that compared to the base scenario, the LCOE and overall net present cost (NPC) were 8% cheaper in scenario 1 and 7% lower in Case 2. In the present scenario, Cases 1 and 2 had payback times of 7.98 and 7.01 years, respectively, relative to the base scenario, and displayed rates of 12.3% and 11.5%, respectively, indicating that Case 1 possessed superior financial effectiveness for low-carbon urban communities.

References

1. Verma, P., Kumari, T., & Raghubanshi, A. S. (2021). Energy emissions, consumption and impact of urban households: A review. *Renewable and Sustainable Energy Reviews*, *147*, 111210.
2. Flammini, F., & Trasnea, G. (2025). Battery-powered embedded systems in IoT applications: Low power design techniques. *SCCTS Journal of Embedded Systems Design and Applications*, *2*(2), 39-46.
3. Zhu, X., Zhang, X., Gong, P., & Li, Y. (2023). A review of distributed energy system optimization for building decarbonization. *Journal of Building Engineering*, *73*, 106735.
4. Chia-Hui, C., Ching-Yu, S., Fen, S., & Ju, Y. (2025). Designing scalable IoT architectures for smart cities: Challenges and solutions. *Journal of Wireless Sensor Networks and IoT*, *2*(1), 42-49.
5. Surendar, A., & Kavitha, M. (2019). Wideband Fractal Antenna For Ku Band Applications. *National Journal Of Antennas And Propagation*, *1*(1), 21-24.
6. Surendar, A. (2024). Emerging trends in renewable energy technologies: An in-depth analysis. *Innovative Reviews in Engineering and Science*, *1*(1), 6-10.
7. Skoczkowski, T., Bielecki, S., Wołowicz, M., Sobczak, L., Węglarz, A., & Gilewski, P. (2024). Participation in demand side response. Are individual energy users interested in this?. *Renewable Energy*, *232*, 121104.
8. Wiśniewski, K. P., Zielińska, K., & Malinowski, W. (2025). Energy efficient algorithms for real-time data processing in reconfigurable computing environments. SCCTS Transactions on Reconfigurable Computing, 2(3), 1–7. https://doi.org/10.31838/RCC/02.03.01
9. Usikalu, M. R., Alabi, D., & Ezeh, G. N. (2025). Exploring emerging memory technologies in modern electronics. Progress in Electronics and Communication Engineering, 2(2), 31–40. https://doi.org/10.31838/PECE/02.02.04
10. Madhushree, R., Gnanaprakasam, D., Kousalyadevi, A., & Saranya, K. (2025). Design and development of two stage operational trans-conductance amplifier with single ended output for EEG application. Journal of Integrated VLSI, Embedded and Computing Technologies, 2(1), 62–66. https://doi.org/10.31838/JIVCT/02.01.08
11. Slimani, J., Kadrani, A., El Harraki, I., & Ezzahid, E. (2024). Towards a sustainable energy future: Modeling Morocco's transition to renewable power with enhanced OSeMOSYS model. *Energy Conversion and Management*, *317*, 118857.
12. Veerappan, S. (2023). Designing voltage-controlled oscillators for optimal frequency synthesis. National Journal of RF Engineering and Wireless Communication, 1(1), 49-56. https://doi.org/10.31838/RFMW/01.01.06
13. Osmani, K., Haddad, A., Jaber, H., Lemenand, T., Castanier, B., & Ramadan, M. (2022). Mitigating the effects of partial shading on PV system's performance through PV array reconfiguration: A review. *Thermal Science and Engineering Progress*, *31*, 101280.
14. Goswami, A., & Kadao, A. K. (2025, December). Edge AI Integration for Real-Time Control in Embedded Computing Systems. In *2025 4th International Conference on Applied Artificial Intelligence and Computing (ICAAIC)* (pp. 1074-1082). IEEE.
15. Malik, P., Awasthi, M., & Sinha, S. (2021). Biomass-based gaseous fuel for hybrid renewable energy systems: an overview and future research opportunities. *International Journal of Energy Research*, *45*(3), 3464-3494.