Article

An Integrated Hybrid Methodology for Net-Zero Energy Residential Design in Rural Sindh

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Abstract

The decarbonization of the building sector should be approached in a twofold manner that includes the reduction of operational energy consumption and the removal of carbon in the building materials. The paper gives a cumulative evaluation of a net-zero energy residential structure in Garhi Yasin, Sindh, Pakistan, involving active solar energy technologies and passive and low-carbon construction. The 3.6 kWp grid-connected system with battery storage was simulated with PV*SOL premium 7.5 and will satisfy 35.3% of the annual electrical demand (3,324 kWh of 8,608 kWh) with self-consumption of 99.6% and a payback period of 10.4 years. At the same time, a comparative cradle-to-gate Life Cycle Assessment was done on material substitution with traditional concrete blocks, cement plaster and steel reinforcement being substituted with clay bricks, lime plaster and bamboo. This replacement resulted in a 73.01% reduction and saved 27,597 kg of CO2 per 150 m2 house. The integrated solution can be shown as a model that can be replicated and adapted all around the world to residential buildings in the semi-arid zone, which can be seen as both energy and materials carbon footprint. Such integrated solutions such as updated building codes, financial incentives, and local supply chain development are policy recommendations.

Keywords: Net-Zero Energy House, Photovoltaic Systems, Battery Storage, Embodied Carbon, Sustainable Construction, Clay Bricks, Bamboo Reinforcement, Life Cycle Assessment, Semi-Arid Climate

1. Introduction

Building sector is a significant source of carbon emissions to the whole world as it comprises about 40 percent of the overall energy use and corresponding CO2 emission [1], [2], [3]. This effect can be divided into two parts: the major part is operational energy, which is used to heat, cool, light, and equip a building with appliances, and the share of embodied carbon, which is the greenhouse gas emissions related to the extraction, production, transportation, and the construction of building materials, is increasing [4]. The search towards Net-Zero Energy Building (NZEBs), thus, requires the all-out approach that suppresses both origins [5]. This is simply an acute problem in developing countries where populations are quickly urbanizing like in the case of Pakistan. The traditional model of construction strongly promotes energy-consuming construction materials such as concrete and steel which cannot be used in hot-arid areas which makes them climatically unacceptable and necessitates high cooling rates in operation [6]. At the same time, electricity production is based on the ineffective and carbon-intensive national grid. The province of Sindh that has one of the best solar insulations, still experiences extensive use of the traditional high-carbon building technologies. This study addresses this gap by offering a combined case study about a prototype house in Garhi Yasin, Sindh. The paper is a unique one that uses two parallel decarbonization routes:

Active Integration of Renewable Energy: The design, simulation and the techno-economic analysis of a rooftop solar photovoltaic (PV) system including battery energy storage to replace the use of operational electricity.

Passive Material Decarbonization: A quantitative Life Cycle Assessment (LCA) of replacing standard construction materials with locally suitable materials with low-embodied-carbon.

The main aim is to prove the technical soundness, economic feasibility, and a carbon saving capability of an integrated solution to the design of NZEB in a semi-arid and rural environment. This research will provide a comprehension blueprint, which can guide policymakers, architects, and constructions in Pakistan and other areas with a similar climate because of the synthesis of discovery of energy system simulation and material LCA.

2. Methodology

2.1 Case Study Location and Climatic Context

The prototype is a 150 m2 one-story residential unit in Garhi Yasin (28 N 68.3 E), Sindh, Pakistan. The climate here is hot-arid (Kepen BWh) with hot summer temperatures of more than 40oC, low levels of precipitation (around 150 mm) and high levels of sunshine of about 5.5-6.0 kWh/m2/ day. The house at the baseline is designed with passive climatic responsive measures, such as a central courtyard to allow cross-ventilation, Jaali (lattice) screens to block sunlight and allow air to move through and their compact form factor reduces thermal envelope exposure.

Figure 1. Architectural renderings of the net-zero energy housing prototype in Garhi Yasin, Sindh, Pakistan

2.2 Photovoltaic System Design and Simulation Methodology

PV*SOL premium 7.5 which is a techno-economic software of proven validity in simulating grid connected and hybrid PV systems was used to design and analyze the active energy system [7]. The system was composed of eighteen poly-crystalline silicon panels with an individual rated capacity of 200 Wp under Standard Test Conditions (STC) with a combined nominal DC capacity of 3.6 kWp. The modules were designed architecturally into an existing terracotta-tiled roof design on the south slope (180 0 azimuth) and the tilt angle was set to 33 so as to maximize annual output at the local latitude. A battery bank of 24 V, 860 Ah lead-acid was added to provide resilience and regulate energy timing surplus daytime generation to be used in evening peak times and when the sun went down. The system is linked to the grid through the standard grid-tie inverter that handles the DC/AC conversion and allows net metering, where two-way flow of energy is possible with the national grid.

2.2.2 Simulation Parameters and Performance Metrics:

The simulation modeled the yearly system performance based on the local meteorological information. The most important output measures were the annual energy production (kWh) in AC, the ratio of self-consumption and energy autonomy, the net balance between imported and exported electricity, and the total System Performance Ratio (PR). The loss analysis was also performed in detail, counting the losses due to the temperature, soiling, wiring, and inverter losses. In financial terms, the simulation produced necessary economic parameters in terms of Levelized Cost of Energy (LCOE), simple payback period, Return on Assets (ROA) and the estimated cumulative savings in costs over a 21-year project life, with project prices of grid energy increasing at a 2 % rate per year.

2.3 Sustainable Material Substitution and Life Cycle Assessment (LCA) Methodology

A comparative, attributional cradle-to-gate LCA was conducted following ISO 14040/44 standards [8] to evaluate the embodied carbon of two construction scenarios for the same 150 m² house.

2.3.1 Scenarios Defined:

Traditional Scenario (CS): Uses standardized regional practices: Hollow concrete blocks (density 1800 kg/m3) of 230 mm used as a wall, 20 mm cement-sand plaster, reinforced concrete structural frame, and mild steel (MS) rebar.

Sustainable Scenario (SS): Uses locally sourced low-carbon substitutes: 300 mm load-bearing, sun-dried clay bricks (1,600 kg/m3) as wall material, lime-sand plaster 15 mm, and treated bamboo culms as tensile reinforcer meaning no RC frame is required.

2.3.2 LCA Scope and Inventory:

LCA used the cradle to the gate system of boundary (stages A1-A3), which included the extraction of the raw material, transportation to the manufacturing location and the manufacturing of all the materials. The total embodied carbon (expressed in kg CO2e) of the structural and envelope material that would be needed to complete one 150 m 2 house was the functional unit. The quantities of materials were calculated based on elaborate architectural drawings and quantified to meet local construction standards to produce a precise bill of quantities. The emission factors, product-specific and regionally relevant coefficients indicating kg CO2e/kg material, were systematically obtained through peer-reviewed literature and one of the established environmentally relevant databases.

Table 1: Material Quantities for 150 m² House

Material	Conventional Scenario	Sustainable Scenario
Wall Material	86,940 kg (concrete blocks)	100,800 kg (clay bricks)
Plaster	16,800 kg (cement)	11,340 kg (lime)
Structural Concrete	54,000 kg	0 kg
Reinforcement	1,800 kg (steel)	1,750 kg (bamboo)

Table 2: Embodied Carbon Coefficients (kg CO_2e/kg) [9]

Material	Emission Factor
Concrete blocks	0.136
Cement plaster	0.93
Structural concrete	0.15
Steel reinforcement	1.25
Clay bricks	0.013
Lime plaster	0.75
Bamboo	0.22

2.3.3 Calculation:

Following the method in [10], the total embodied carbon for each scenario was calculated with Equation 1 and Equation 2 as:

$$C_{total} = \sum (M_i \, X \, EF_i)$$

(Equation 1)

$C_{total} = total\ embodied\ carbon$

$M_i = mass\ of\ material$

$EF_i = emission\ factor$

$$\%R = (1 - \frac{C_{sust}}{C_{conv}}) \, X100$$

(Equation 2)

3. Results

3.1 Performance of the Integrated Photovoltaic System

3.1.1 Annual Energy Balance:

The model PV system produced 3,324 kWh of AC electricity per year. The aggregate household annual electricity consumption was 8,608 kWh which indicates that the PV system contributed directly 35.3% of the load. The balance demand was satisfied by importing 5,567 kWh in the grid annually. Only 13 kWh was sent back, which implied an almost perfect time damage between the on-site generation and demand in the daylight, which was based on the battery storage.

Table 3 Energy Analysis through PV*SOL premium

Global radiation - horizontal	**1,029.5 kWh/m²**	-
Deviation from standard spectrum	-10.29 **kWh/m²**	-1.00%
Orientation and inclination of the module surface	+166.56 **kWh/m²**	+16.34%
Shading	0.00 **kWh/m²**	0.00%
Reflection on the Module Interface	-52.79 **kWh/m²**	-4.45%
Global Radiation at the Module	**1,132.9 kWh/m²**	
	1,132.9 kWh/m²	
	X 30.18 m² = 34,192.4 kWh	
Global PV Radiation	**34,192.4 kWh**	-
Soiling	0.00 kWh	0.00%
STC Conversion (Rated Efficiency: 11.93%)	-30,111.90 kWh	-88.07%
Rated PV Energy	**4,080.5 kWh**	-
PV Losses (DC)		
Low-light performance	-213.24 kWh	-5.23%
Deviation from nominal module temperature	-122.40 kWh	-3.16%
Diodes	-18.72 kWh	-0.50%
Mismatch (Manufacturer Information)	-74.52 kWh	-2.00%
Mismatch (Configuration/Shading)	0.00 kWh	0.00%
PV Energy (DC) without inverter regulation	**3,651.7 kWh**	-
Regulation on account of MPP Voltage Range	-0.14 kWh	0.00%
Regulation on account of max. DC Current	-2.22 kWh	-0.06%
Regulation on account of max. DC Power	-1.34 kWh	-0.04%
Regulation on account of max. AC Power/cos phi	-0.74 kWh	-0.02%
MPP Matching	-0.47 kWh	-0.01%
PV Energy (DC)	**3,646.8 kWh**	-
Energy at the Inverter Input	**3,646.8 kWh**	-
Input voltage deviates from rated voltage	-14.16 kWh	-0.39%
DC/AC Conversion	-240.73 kWh	-6.63%
Stand-by Consumption	-0.94 kWh	-0.03%
Total Cable Losses	-67.82 kWh	-2.00%
PV Energy (AC) minus standby use	**3,323.1 kWh**	-
PV Generator Power (AC grid)	**3,324.0 kWh**	-

3.1.2 Storage and Self-Consumption:

It was essential to integrate the 24 V/860 Ah battery bank, which had an 99.6 percent self-consumption rate. The battery was charged up during the peak sunny time (10:00 - 15:00) and discharged in the late afternoon hours (17:00 - 22:00) so as to match the peak domestic load, which is generally the evening generation demand mismatch that is inherent with solar-only systems [11].

3.1.3 Technical Performance Metrics:

The simulated system recorded a Performance Ratio (PR) of 77.8% meaning that the total efficiency was strong once all the losses incurred during operations were taken into account. The site-specific yield of 923.33 kWh/kWp/year was obtained that substantiates the fact that the site has a high potential of solar resources. The analysis of the loss revealed that the biggest single loss component was the difference between the Standard Test Condition (STC) module rating and actual conditions of operating the module, which represented -88.07% of the total loss. DC/AC inverter conversion (-6.63%), DC cabling resistance

(-2.00%), were the other notable losses, and justified the consideration of component choice and adequate system design.

3.1.4 Financial Viability:

The photovoltaic system proved to have a high financial viability such that the annual savings to the utility bill of the homeowner was 686.83. The forecasted Investment was expected to attain a simple payback period of 10.4 years with a Return on Assets (ROA) of 13.26. Within the 21 years period, the overall monetary benefit was immense as the PV system situation generated a total of electricity expenditures of about $1,800 as a stark contrast to the estimated expenses of about 3,000 in the case of the grid only scenario.

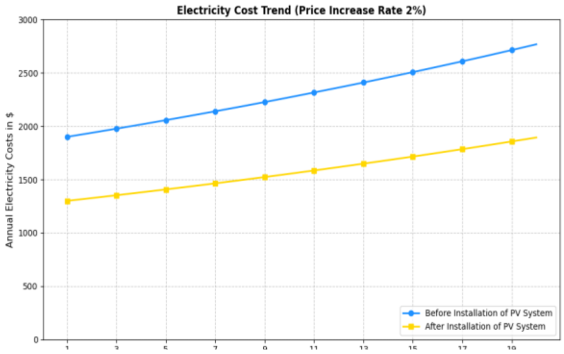

Figure 2: Comparative cumulative electricity costs with and without the PV system installation.

3.2 Embodied Carbon Reduction from Material Substitution

3.2.1 Overall Carbon Footprint:

The LCA indicated the presence of a drastic decrease in the embodied carbon of the building structure and envelope. The Conventional Scenario (CS) yielded an overall embodied carbon of 37,797.84 kg CO2e. This was cut down to 10,200.40 kg CO2e by the Sustainable Scenario (SS). This is a net saving of 27,597.44 CO2e per house, which corresponds to a saving of 73.01.

Table 4. Carbon Footprint Comparison

Component	Conventional (kg CO_2e)	Sustainable (kg CO_2e)	Reduction
Walls	11,823.84	1,310.40	88.92%
Plaster	15,624.00	8,505.00	45.56%
Structure	8,100.00	0	100%
Reinforcement	2,250.00	385.00	82.89%
TOTAL	**37,797.84**	**10,200.40**	**73.01%**

3.2.2 Per-Unit-Area Intensity:

The embodied carbon intensity fell from 251.99 kg CO_2e/m^2 (CS) to 68.00 kg CO_2e/m^2 (SS)—a reduction of 183.99 kg CO_2e/m^2.

3.2.3 Component-Level Analysis:

The value of every sustainable material to the total carbon reduction was clearly estimated. Replacing the walls using concrete block with clay bricks had a reduction of 88.92 percent that is, the emissions of 11823.84 kg CO2e reduced to 1310.40 kg CO2e, and this can be greatly attributed to the fact that energy-consuming processes of cement and kiln firing were eliminated. In this case, with the plaster element, a reduction of 45.56 percent, i.e. 15,624.00 kg CO2e to 8,505.00 kg CO2e, was obtained by using lime as an ingredient rather than cement because the calcification temperature of lime was much lower than that of Portland cement clinker (900 C versus 1450 C). When using reinforcement, when steel was substituted with bamboo, the reduction was 82.89, 2,250.00 kg CO2e to 385.00 kg CO2e, using the fact that bamboo is fast renewing and the energy used to process it is minimal in comparison to the energy used to smelt steel. The most important was that the implementation of load bearing clay walls enabled a total avoidance of the reinforced concrete structural frame which on its part would have reduced the 8,100.00 kg CO2e associated with it by 100 percent, a critical design decision that enabled the system to achieve the overall performance that it achieved.

3.2.4 Contextualization of Savings:

To put the embodied carbon reduction into perspective, the total saving of 27,597 kg CO2e / house can be put into terms that are easy to associate with: it is the total greenhouse gas emissions of an estimated six passenger vehicles in a single year [12], it is the service of one year of carbon sequestration of 32 mature temperate trees [13].

4. Discussion

4.1 Interpreting the Integrated Energy-Material Performance

The 35.3% ratio of renewable energy produced by the PV system is impressive but is indicative of how difficult it will be to fulfill 100% of demand on a roof-top solar system in an energy-intensive climate. To some extent this gap is filled by the battery, giving self-consumption 99.6%. Importantly, passive material strategy supplements the work of this active system. The use of clay bricks and lime plaster has high thermal mass and hygroscopic characteristics, which regulate the temperatures in the building and minimize the peak cooling load passively [14]. This enables the operational demand to be reduced, resulting in a smaller, more cost-effective PV system being able to achieve a fully renewable-powered house. The 10.4-year payback of the PV system is competitive on the basis of economic use in a rural residence location especially with the unstable and increasing grid tariffs in Pakistan [15]. The material substitution approach, which is not analyzed in terms of cost-benefit in this case, is usually characterized by a lowering or similar initial investment of clay and bamboo in the case of local sourcing, and possible savings in terms of the removal of expensive steel and concrete [16].

4.2 Contributions and Comparison with Literature

The reduction of carbon embodied of 73.01 percent is more than the values that are usually reported in the studies on material substitution in South Asia that usually report estimates of 30-50 percent [17]. The design shift to load bearing earthen walls at the system level can directly be credited to the result of this massive achievement. In most studies, materials have been replaced in an established structural regime; the material selection in this case inspired a re-designing of the structural rationale behind the building, the total eradication of the most carbon-intensive element - the RC frame. The PV system performance measure (PR: 77.8% Specific Yield: 923 kWh/kWp) falls within the performance of high performing systems in equivalent semi-arid climate [18]. The strategic contribution of battery storage to residential purposes is justified by the high self-consumption rate, which is confirmed by the current studies regarding the optimal use of the PV-battery systems in the off-grid and weak-grid systems to match load [19].

4.3 Implications for Policy and Practice

Such integrated solutions need to be facilitated by a supportive ecosystem, which includes policy, market, and social aspects to facilitate the mass adoption of the same solutions. The building codes in Pakistan should be first reformed to include modern standards and engineering standards on safe and dependable use of the load-bearing earth construction and treated bamboo as structural material. Second, it is necessary to provide specific financial incentives; this is through the extension of net-metering policies and soft loans to purchase PV and battery storage facilities, and other mechanisms, including property tax rebates or expedient permitting on projects using locally sourced, low-carbon materials, to stimulate market demand. Third, there should be parallel investment in supply chain and skills building to guarantee the availability of quality-controlled clay bricks, lime and preservative-treated bamboo with the support of training of the builders and engineers. Lastly, there is a need to change the established beliefs that traditional materials are backward, and this will require strong awareness campaigns and publication of evidence by the implementation of demonstration projects that will demonstrate the performance, modernity and the advantages of these sustainable alternatives.

4.4 Limitations and Future Research Directions

Several limitations have been recognized in this study that present effective prospects of future research. The cradle-to-gate Life Cycle Assessment is methodologically restricted by excluding transportation and all construction processes and the use phase; a cradle-to-grave assessment would include more information on the environmental profile. Structurally, the engineering study of seismic or long-term viability in the desert environment needs to be in-depth to comply with building codes and guarantee practicability. In addition, the socioeconomic aspect is also not very well developed; a unified evaluation of life-cycle costing, local labor considerations, and cultural acceptability would enhance the transition route. Lastly, to achieve the full realization of the synergies between the dynamic and the passive strategies discussed, the future work would utilize multi-objective optimization algorithms to optimize the PV-battery system and the material composition of the building envelope at the same time at minimal life-cycle cost and carbon footprint.

5. Conclusions

This study shows that the solution to net-zero energy settlement in semi-arid areas such as Sindh, Pakistan, is on the combined use of renewable energy technologies and material culture that explains sustainability. The technical and economic feasibility of solar energy as a source to make a substantial offset of grid reliance and achieve 35.3% renewable, 99.6% self-consumption, and payback of 10.4 years is confirmed by the simulation of a 3.6 kWp PV system with battery storage. At the same time, the systematic replacement of concrete and steel by clay bricks, lime plaster, and bamboo reinforcement was demonstrated to cut the amount of embodied carbon of a 150 m2 house by 73.01% (27,597 kg CO2e). The real meaning of this work consists in the synergy of these two strategies. The passive thermal advantage of the sustainable materials will lessen the operational energy load to the building which makes the active solar system more efficient and economical. On the other hand, electrification movement through renewables makes the process of material palette decarbonization more environmentally friendly. This comprehensive model is based on evidence, offers a quantitative model to policymakers, architects, and builders, and presents a replicable approach to the attainment of sustainable and resilient housing in Pakistan as well as in other hot-arid areas of the Global South.

References

[1] Carbon emissions in China's urban residential building sector through 2060: A dynamic scenario simulation https://doi.org/10.1016/j.energy.2022.124395

[2] Evaluating the environmental impacts of brick production from waste plastic https://doi.org/10.1016/j.mfglet.2024.09.196

[3] CO2 Emissions in Buildings: A Synopsis of Current Studies https://doi.org/10.3390/en15186635

[4] Operational vs. embodied emissions in buildings—A review of current trends https://doi.org/10.1016/j.enbuild.2013.07.026

[5] Building energy technologies towards achieving net-zero pathway: A comprehensive review, challenges and future directions https://doi.org/10.1016/j.jobe.2025.111795

[6] Study on the interfacial bond behavior of steel fibers embedded in cement-based materials under hot-dry environments https://doi.org/10.1016/j.cscm.2025.e05672

[7] A comprehensive evaluation of photovoltaic simulation software: A decision-making approach using Analytic Hierarchy Process and performance analysis https://doi.org/10.1016/j.esr.2025.101663

[8] Thematic evolution of Life Cycle Assessment in construction and demolition waste management: before and after ISO 14040 and the Paris Agreement https://doi.org/10.1016/j.jobe.2025.113482

[9] Embodied CO2 Emissions in Building Construction Materials of Hellenic Dwellings https://doi.org/10.1016/j.proenv.2017.03.113

[10]Embodied Carbon : The Inventory of Carbon and Energy (ICE) https://books.google.ru/books/about/Embodied_Carbon.html?id=_foFtwAACAAJ&redir_esc=y

[11]On the storage batteries used in solar electric power systems and development of an algorithm for determining their ampere–hour capacity https://doi.org/10.1016/j.epsr.2003.12.018

[12]Total CO2-equivalent life-cycle emissions from commercially available passenger cars https://doi.org/10.1016/j.rser.2022.112158

[13]How much more carbon could be protected in mature and old-growth forests of the United States? https://doi.org/10.1016/j.biocon.2025.111114

[14]Modified lime-cement plasters with enhanced thermal and hygric storage capacity for moderation of interior climate https://doi.org/10.1016/j.enbuild.2016.05.004

[15]Economic analysis of residential solar photovoltaic systems in China https://doi.org/10.1016/j.jclepro.2020.125297

[16]Sustainable solutions for low-cost building: Material innovations for Assam-type house in North-East India https://doi.org/10.1016/j.cscm.2025.e04461

[17]Reducing China's building material embodied emissions: Opportunities and challenges to achieve carbon neutrality in building materials https://doi.org/10.1016/j.isci.2024.109028

[18]Assessing PV inverter efficiency degradation under semi-arid conditions: A case study in Morocco https://doi.org/10.1016/j.heliyon.2024.e36906

[19]Model-based optimization of residential PV-battery systems for maximum self-consumption and cost savings https://doi.org/10.1016/j.rineng.2025.107198