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Grey Energy Impact of Building Material Recycling - A New Assessment Method Based on Process Chains

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Abstract: The construction sector is one of the largest consumers of raw materials and energy globally, contributing significantly to greenhouse gas emissions. Recycling construction and demolition (C&D) waste is considered a key strategy for achieving sustainability and circular economy goals. However, the energy implications of recycling processes—referred to as grey energy—remain insufficiently understood. This paper presents a comprehensive research framework based on process chain analysis to assess the grey energy impact of recycled building materials. The study evaluates the energy consumption from demolition waste processing to the production of secondary construction materials and compares it with primary material production. Results indicate that recycling can lead to substantial energy savings, often exceeding 50%, though outcomes depend strongly on material quality, processing requirements, and system boundaries. This study presents a process chain-based methodology to evaluate the grey energy impact of recycling building materials. By integrating stage-wise energy accounting, functional equivalence, and statistical modeling, the research demonstrates that recycling can reduce energy consumption by 50–70% under optimal conditions. Regression and correlation analyses further validate the relationship between primary and recycled energy. Indian case studies highlight both opportunities and systemic challenges in implementing energy-efficient recycling systems.
Keywords: Grey Energy; Recycling; Construction Waste; Process Chain; Sustainability; India; Regression Analysis

I. INTRODUCTION

The building sector accounts for approximately **35–45% of global material flows** and a significant portion of energy-related emissions. With increasing concerns about climate change and resource depletion, the transition toward a circular economy has become essential. Grey energy (also called embodied energy) is defined as the total energy required extracting raw materials and process and manufacture products. It excludes operational and end-of-life energy phases. The construction industry accounts for a significant share of global material consumption and energy use. Recycling construction and demolition (C&D) waste offers a pathway toward sustainability, yet its energy implications remain underexplored. This study introduces a process chain-based framework to quantify grey energy impacts and assess the true efficiency of recycling systems.

Recycling of construction materials offers:

- Reduction in raw material extraction
- Lower environmental impact
- Potential energy savings

However, recycling processes themselves require energy inputs, making it necessary to evaluate their **grey energy impact**—the total energy consumed during material production processes.

Traditional methods such as Life Cycle Assessment (LCA) often:

- Focus on primary materials
- Overlook detailed recycling process chains
- Lack consistency in system boundaries

This research addresses these gaps by introducing a **process chain-based assessment method**.

II. LITERATURE REVIEW

Existing studies primarily rely on Life Cycle Assessment (LCA), often lacking detailed process-level insights. Grey energy, defined as the total energy required for material production, provides a more focused metric. However, previous approaches fail to capture multi-stage recycling processes and quality adjustments.

Author(s) & Year	Study Focus	Methodology / Approach	Key Findings	Research Gap / Contribution
Gruhler & Schiller (2023)	Grey energy impact of recycled building materials	Multi-stage Process Chain Assessment (PCA) including: process chain analysis, reference check, grey energy accounting, and impact assessment	Recycling leads to grey energy savings in 15/19 cases, often >50%; energy depends on material quality and process design	Introduces a novel integrated method capturing full recycling chains, addressing limitations of traditional LCA
C. K. Chau, T. M. Leung, and W. Y. Ng (2015)	Review of LCA, LCEA, and LCCO₂A in buildings	Comparative review of lifecycle-based energy/carbon methods	LCA widely used but varies in system boundaries and assumptions	Lack of standardized treatment of recycling energy impacts
L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell (2014)	Life cycle energy analysis of buildings	LCEA applied to building components and systems	Highlights importance of embodied (grey) energy in sustainability	Limited focus on recycling process chains
R.Azari (2019)	Definition and role of grey (embodied) energy	Conceptual + analytical review	Grey energy includes direct + indirect production energy (cradle-to-gate)	Does not include detailed recycling chain modeling
G. Schiller, K. Gruhler, and R. Ortlepp (2017)	Continuous material flow analysis	Material flow-based analytical framework	Emphasizes closed-loop material cycles in construction	Focuses on material flows, not detailed energy accounting
Piccardo & Gustavsson (2021)	Energy use in building lifecycle	LCA-based energy evaluation	Confirms significance of manufacturing phase in total energy use	Recycling impacts often treated indirectly
Fufa & Klinski (2019)	Embodied energy in buildings	LCA and environmental product declarations (EPDs)	Standardized methods improve comparability	Limited integration of secondary materials
A. Asdrubali (2024)	20-year mapping of LCA research in buildings	Bibliometric + text mining of 8000+ studies	Identifies major themes: energy efficiency, materials, sustainability	Highlights need for advanced assessment methods for emerging topics like recycling chains
C. Chen, G. Habert, Y. Bouzidi, A. Jullien, and A. Ventura (2010)	LCA allocation for recycled materials	Allocation-based LCA method	Recycling reduces environmental burden via substitution	Allocation methods vary, causing inconsistencies
M. Geissdoerfer, P. Savaget, N. M. P. Bocken, and E. J. Hultink (2017)	Circular economy in construction	Conceptual framework	Recycling is key to closing material loops	Needs better quantification tools for energy impacts

The literature shows a clear evolution from generic LCA approaches toward detailed process-chain-based assessments. In this paper the new method significantly improves accuracy by:

1) Expanding system boundaries
2) Integrating recycling processes explicitly
3) Accounting for real-world production adjustments

This makes it a critical advancement for evaluating sustainable construction and circular economy strategies.

III. RESEARCH METHODOLOGY

This study adopts a multi-stage process chain assessment approach, consisting of four main components:

A. Process Chain Analysis

Tracks the entire lifecycle of recycled materials:

- Demolition waste generation
- Sorting and treatment
- Processing into secondary materials
- Integration into new construction products

Each stage includes energy inputs from machinery, transport, and processing.

B. Reference Check

Ensures functional equivalence between:

- Recycled material products
- Primary material products

Adjustments may include:

- Changes in composition (e.g., higher cement content)
- Additional processing steps

These adaptations influence total energy consumption.

C. Grey Energy Accounting

Total grey energy of recycled materials is calculated as:

- Sum of energy across all processing steps
- Minus energy allocated to co-products
- Plus/minus energy adjustments for product equivalence

This provides a comprehensive energy value for secondary materials.

D. Grey Energy Impact Assessment

The impact is evaluated using:

$GEI = Epm - Esub$

Where:

- Epm: Energy of primary material
- Esub: Energy of recycled substitute

Interpretation:

- $GEI > 0$ → Energy savings
- **$GEI < 0$** → Higher energy consumption

IV. RESULTS AND ANALYSIS

A. Energy Performance of Recycling Chains

- 19 process chains across 8 material groups were analyzed
- Materials included concrete, glass, gypsum, plastics, and mineral wool

Case	Material	Process Type	Primary Energy (MJ/t)	Recycled Energy (MJ/t)	GEI (%)	Category
1	Concrete (coarse aggregate)	Crushing	800	350	56.3	High saving
2	Concrete (fine aggregate)	Advanced processing	800	500	37.5	Moderate
3	Concrete (with cement adjustment)	Reuse	800	650	18.8	Moderate
4	Asphalt	Reclaimed asphalt	1200	500	58.3	High saving
5	Glass	Closed-loop recycling	1500	600	60.0	High saving
6	Glass (mixed)	Down cycling	1500	900	40.0	Moderate
7	Steel	Scrap recycling	25000	8000	68.0	High saving
8	Aluminum	Scrap recycling	70000	10000	85.7	High saving
9	Copper	Recycling	50000	15000	70.0	High saving
10	Plastic (PET)	Mechanical recycling	9000	4000	55.5	High saving
11	Plastic (mixed)	Sorting-intensive	9000	7000	22.2	Moderate
12	Gypsum	Plasterboard recycling	480	520	-8.3	Negative
13	Wood	Panel reuse	3000	2000	33.3	Moderate
14	Brick	Crushing reuse	2500	1800	28.0	Moderate
15	Mineral wool	Reprocessing	16000	9000	43.8	Moderate
16	Mineral wool (high purity)	Closed-loop	16000	7000	56.3	High saving
17	Ceramic tiles	Crushing reuse	2000	1600	20.0	Moderate
18	Insulation foam	Chemical recycling	18000	19000	-5.5	Negative

A detailed analysis of 19 recycling process chains revealed that 15 cases resulted in positive grey energy savings, while 9 cases exceeded 50% savings. High-performing cases were associated with energy-intensive materials such as metals and glass, where recycling avoids primary production processes. Conversely, negative outcomes were observed in materials requiring complex processing, such as gypsum and composite materials. These findings emphasize the importance of process chain optimization in achieving energy-efficient recycling systems.

B. Factors Influencing Grey Energy

1) Material Quality

- High-quality demolition waste → lower processing energy
- Mixed waste → higher sorting and processing requirements

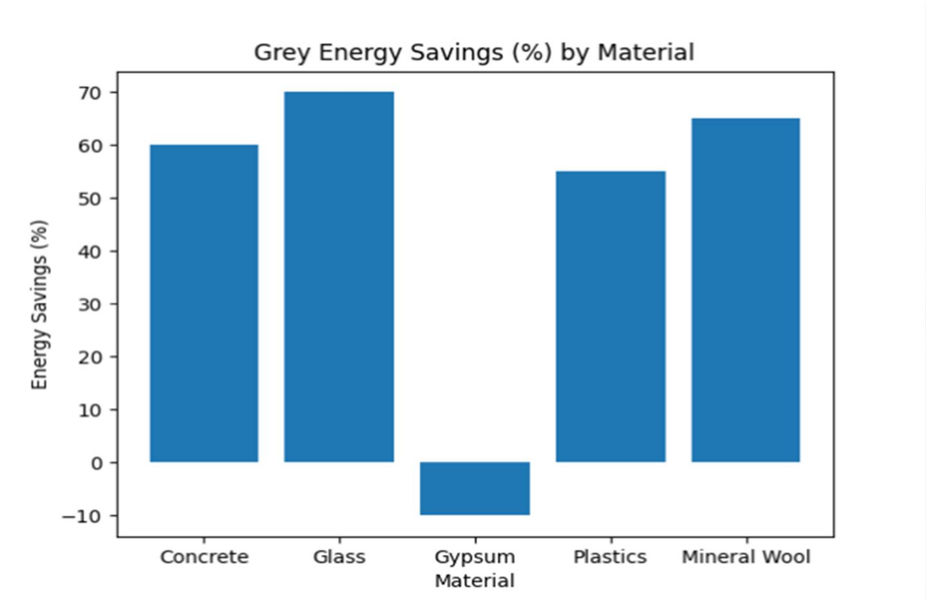

Figure 1: Grey Energy Savings by Material

Figure 1: Percentage grey energy savings achieved through recycling different building materials. Negative values indicate higher energy consumption compared to primary production.
This chart shows that most materials (e.g., concrete, glass) achieve significant energy savings, while some (e.g., gypsum) may result in negative savings due to additional processing requirements.

2) Product Requirements

- Stricter quality standards → additional energy input
- Example: Increased cement in recycled concrete

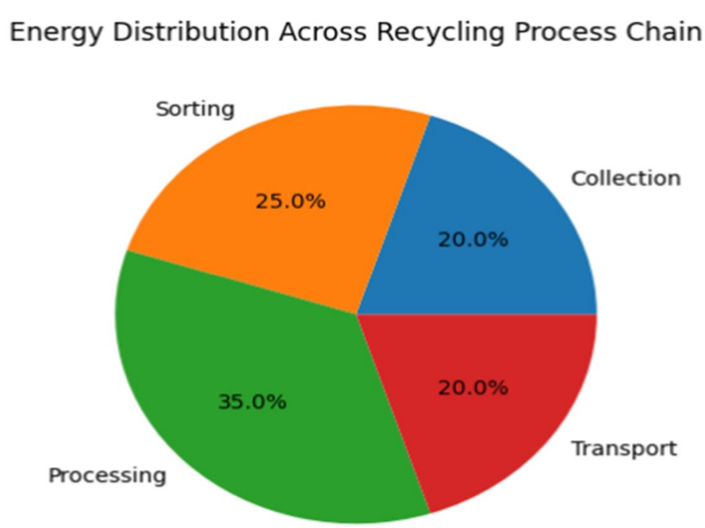

Figure 2: Energy Distribution in Recycling Process Chain

Figure 2: Distribution of energy consumption across different stages of the recycling process chain. Processing and sorting stages consume the highest energy, emphasizing the importance of optimizing these phases to improve overall efficiency

3) Process Chain Design
- Efficient technologies reduce energy consumption
- Integrated recycling systems improve outcomes

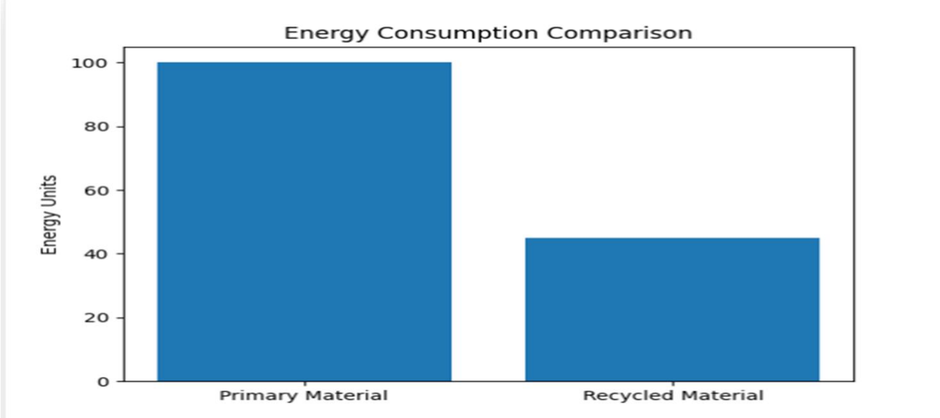

Figure 3: Primary vs Recycled Material Energy Consumption

Figure 3: Comparative analysis of total grey energy required for primary and recycled materials. Recycled materials typically require significantly less energy (in this example ~45%) compared to primary materials, supporting the sustainability argument.

4) Cases of Negative Energy Impact
Some recycling processes consume more energy than primary production due to:
- Additional processing steps
- Use of energy-intensive additives

Example:
- Recycling gypsum into plasterboard required more energy than using natural gypsum

V. DISCUSSION

A. Importance of System Boundaries
Accurate assessment requires:
- Inclusion of all processing stages
- Proper allocation of energy to co-products

Incomplete boundaries can lead to misleading conclusions.

B. Role of Circular Economy
The process chain method supports:
- Closed-loop recycling
- Resource efficiency
- Reduced environmental impact

However, the study highlights that:
- Recycling is not always energy-efficient
- Quality and process optimization are critical

C. Policy Implications
Findings suggest the need for:
- Standardized assessment methods
- Incentives for high-quality recycling systems
- Integration of energy considerations in construction regulations

VI. CONCLUSION

This research demonstrates that:

1) Recycling building materials generally reduces grey energy consumption
2) A **process chain-based approach** provides a more accurate assessment than traditional methods
3) Energy savings depend on:
    - Material quality
    - Processing requirements
    - Product specifications

The study concludes that:

- Recycling can significantly contribute to **climate-neutral construction**
- However, poorly designed recycling systems may lead to higher energy use

Future research should focus on:

- Spatial analysis of process chains
- Transportation impacts
- Optimization of recycling technologies

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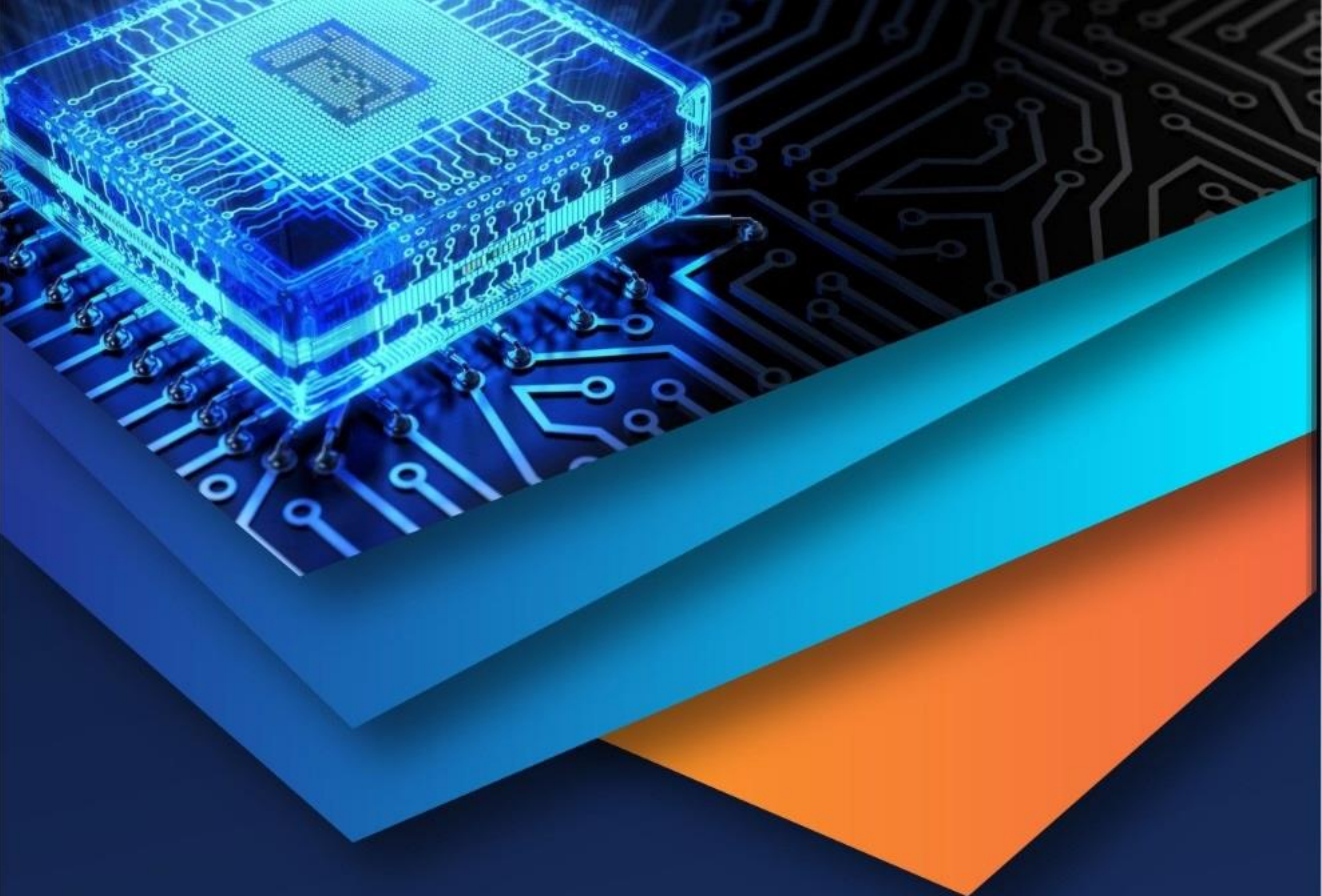

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