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Life Cycle Assessment of Different Energy Generation Technique "A Review"

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1. Abstract:

This study is fundamentally about energy modeling and forecasting of various renewable and hybrid systems for sustainable power generation, with a distinct focus on the specific challenges and opportunities within developing countries, as exemplified by a detailed case study from Pakistan. The scientific contribution and added value of our paper, especially for an audience interested in sustainable energy systems and their assessment, stem from its comprehensive and integrated synthesis of diverse analytical methods LCA, simulation models, and Multi Criteria Decision Making (MCDM) specifically applied to the context of developing nations. We don't merely compile individual studies; we systematically compare and synthesize findings across environmental (LCA emissions), technical (energy output, system stability), and economic (cost, resource availability) dimensions. This integrated approach highlights the most promising energy solutions and identifies critical tradeoffs for regions like Pakistan, offering insights for decision makers that are often fragmented in the existing literature.

Furthermore, a key differentiating factor and a significant contribution of our paper is the inclusion of a novel, detailed case study on the Hattar Industrial Estate in Pakistan. This case study serves as a practical, real world application that validates and demonstrates how the principles and findings synthesized from the LCA, simulation, and MCDM reviews can be effectively implemented to optimize a hybrid renewable energy system. We showcase tangible outcomes, such as significant reductions in electricity cost (to Rs.14.11/kWh) and CO_2 emissions (over 117,000 tons/year), directly translating scientific insights into practical, impactful solutions relevant to industrial and semi urban areas in developing economies. Through this combined approach, our paper delivers a unique set of insights on optimizing renewable energy mixes for improved reliability, cost effectiveness, and environmental impact reduction in developing country scenarios. This structured approach to identifying context specific optimal pathways contributes significantly to the strategic planning literature for sustainable energy transitions in these critical regions.

Keywords:
Renewable energy, Hybrid systems, Life Cycle Assessment (LCA), Solar PV, Biomass, Multi criteria decision making (MCDM), Energy Planning, Hattar Industrial Estate

2. Introduction:

The global energy sector is undergoing a major transformation as nations seek to meet rising electricity demand while simultaneously reducing greenhouse gas (GHG) emissions. Electricity generation accounts for nearly 40 % of global CO_2 emissions, making it a critical target for climate mitigation efforts **[1].** Growing concerns about climate change, volatile fossil fuel prices, and energy security have accelerated the transition towards low carbon and renewable energy systems worldwide. This transition is supported by international climate agreements and national commitments to achieve net zero emissions by midcentury **[2].**

To evaluate and compare the sustainability of different power generation technologies, Life Cycle Assessment (LCA) has emerged as a widely accepted decision support tool. LCA systematically quantifies environmental impacts across all stages of the electricity generation process from resource extraction and fuel processing (cradle) to plant operation and decommissioning (grave) [**3].** By using a functional unit such as 1 MWh of net electricity delivered, LCA enables objective comparisons between fossil fuels (coal, gas, oil), nuclear power, and renewables (biomass, hydropower, solar, and wind) **[4].** Table I summarizes the current and projected global electricity generation mix, highlighting the increasing contribution of renewables but the continued dominance of fossil fuels.

Technology	Current Share (%)	Projected 2035 Share (%)
Coal	41	36
Natural Gas	21	28
Oil	5.5	3
Nuclear	13	14
Biomass	0.8	2
Hydropower	16	14
Solar PV	0.1	3
Wind	1.1	6

Table 1 Electricity Generation Mix by Source

This growing diversification of the energy mix creates a need for harmonized, comparative assessments that consider not only direct GHG emissions but also air pollutants (NO_x, SO_2), water consumption, land use, and energy payback time. **Table II** summarizes key impact categories commonly evaluated in LCA studies.

Impact Category	Indicator	Unit
Climate Change	CO_2 equivalent emissions (IPCC GWP100)	kg CO_2eq/MWh
Acidification	SO_2 equivalent emissions	kg SO_2eq/MWh
Eutrophication	NO_3 equivalent emissions	kg NO_3eq/MWh
Photochemical Smog	VOC & NO_x precursors	kg C_2H_4eq/MWh
Cumulative Energy Demand (CED)	Primary energy use	MJ/MWh
Water Use	Blue water consumption	L/MWh

Table II: LCA Impact Categories and Indicators

3. Materials and Methods

This review investigates the **life cycle assessment (LCA)** of different electricity generation technologies and compares their environmental impacts, energy output, and system characteristics. A total of **167 expert-reviewed case studies** were considered, covering nearly 98 % of global electricity production **[5].** Data sources include international databases such as Ecoinvent v3.0, U.S. LCI, and IEA statistics, plant level efficiency and emission records, and technical reports **[6].** Studies published between 1980–2023 were included to capture modern plant designs and supply chain conditions. Modeling tools used across the reviewed studies include SimaPro 8, GaBi, and OpenLCA**,** and impact assessment methods such **as** IPCC GWP100, CML, TRACI, and Cumulative Energy Demand (CED) **[7].**

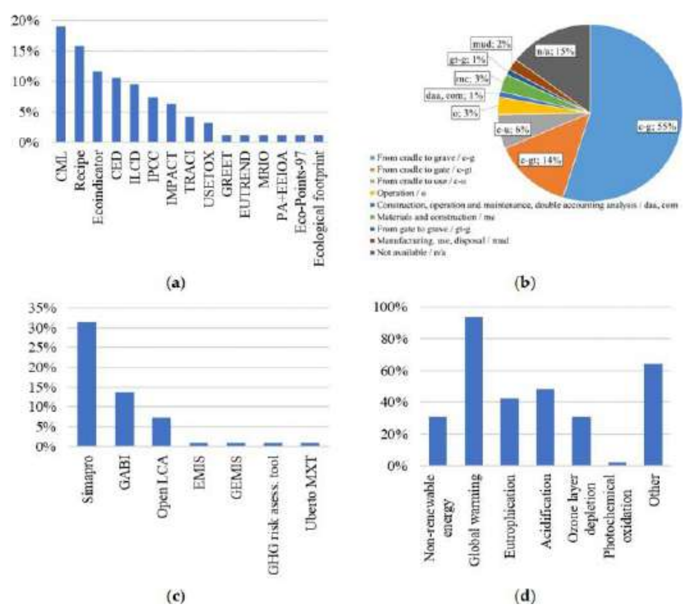

Figure 1 Methodological aspects of reviewed LCA studies impact methods, boundaries, software, categories

3.1. Technology Wise Modeling

Each generation technology was modeled using **complete life cycle boundaries** that included fuel provision, plant operation, and infrastructure phases. This ensured comparability of results across multiple studies. The primary inputs, expected lifetime, and capacity factors for each technology are summarized in **Table III**.

Technology	Main Inputs	Lifetime (Years)	Capacity Factor (%)
Coal	Coal, limestone (FGD)	40	70–85
Natural Gas	Natural gas, water	30	50–70
Oil	Heavy fuel oil	30	30–50

Technology	Main Inputs	Lifetime (Years)	Capacity Factor (%)
Nuclear	Uranium ore, enrichment energy	40–60	85–90
Biomass	Wood chips, residues	20–30	60–80
Hydropower	Cement, steel, turbines	50–100	40–60
Solar PV	Silicon, aluminum, glass	25–30	15–20
Wind	Steel, composites	20–25	25–40

Table III Key Inventory Inputs and Operational Parameters

3.2. Coal Fired Power Plants

Materials Used: Hard coal and lignite data, power plant efficiencies, and emission factors from expert-reviewed studies and IEA databases.

Method: Coal based electricity systems were modeled using complete life cycle boundaries including fuel mining, transportation, plant construction, combustion operation, and decommissioning. CO_2, NO_x, and SO_2 emissions were quantified per MWh. Byproduct allocation for fly ash was included.

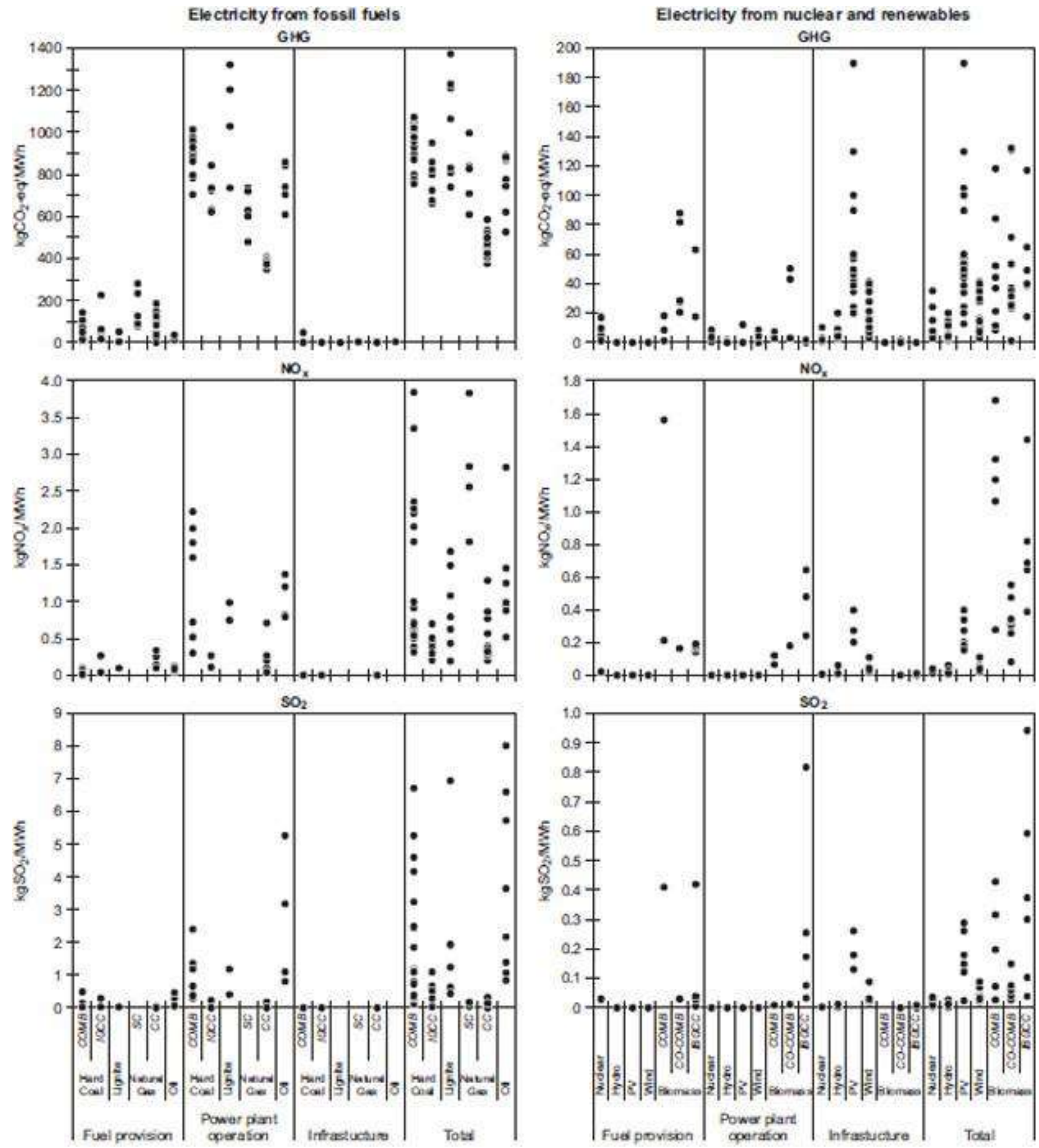

Figure 2 Life cycle emission factors for coal based power plants, divided into fuel provision, plant operation, and infrastructure [1].

3.3. Natural Gas Power Plants (3.3)

Materials Used: Combined Cycle Gas Turbine (CCGT) data, gas extraction and processing inventories.

Method: Modeled natural gas extraction, processing, pipeline transport, and combustion operation with efficiency between 50–60 %. Methane leakage was accounted for. Results were normalized to 1 MWh functional unit.

3.4. Oil Fired Power Plants

Materials Used: Heavy fuel oil combustion data, refinery operations, and global emission factors.
Method: System boundaries included crude oil extraction, refining, transport, and power plant operation. SO_2 emissions were highlighted due to high sulfur content.

3.5. Nuclear Power Plants

Materials Used: Uranium mining, enrichment data, reactor construction material inventories.
Method: The model considered uranium extraction, enrichment, fuel fabrication, reactor operation, spent fuel management, and decommissioning. Most emissions came from upstream uranium processing.

3.6. Biomass Power Plants

Materials Used: Biomass feedstock inventories (wood chips, residues), transport distances, CHP plant performance data.
Method: Modeled collection, transport, and combustion phases. Biogenic CO_2 neutrality was assumed. NO_x and particulate emissions were considered.

3.7. Hydropower Plants

Materials Used: Dam and turbine construction materials, reservoir data, and plant lifetime parameters.
Method: Life cycle emissions from cement/steel production, land use changes, and reservoir methane were included over a 50–100 year operational lifetime.

3.8. Solar Photovoltaic (PV) Systems

Materials Used: Inventories of crystalline silicon (cSi) modules, inverters, and mounting structures.

Method: Considered silicon purification, wafer/cell production, BOS components, installation, and endoflife recycling. Performance normalized using 15 to 20 % capacity factors.

3.9. Wind Power Systems

Materials Used: Wind turbine inventory including tower, nacelle, gearbox, blades, and foundations.
Method: Construction, operation, and decommissioning modeled over 20–25 years. CO_2 equivalent emissions were dominated by steel production and composite materials **[8], [9]**.

3.10. Comparative Emission Data

The harmonized life cycle emission factors for CO_2, NO_x, and SO_2 are summarized in **Table IV** enabling direct comparison across technologies **[10]**.

Technology	**CO_2eq**	**NO_x**	**SO_2**
Hard Coal	660–1050	0.3–3.9	0.03–6.7
Lignite	800–1300	0.2–1.7	0.6–7
Natural Gas	380–1000	0.2–3.8	0.01–0.32
Oil	530–900	0.5–1.5	0.85–8
Nuclear	3–35	0.01–0.04	0.003–0.038
Biomass	8.5–130	0.08–1.7	0.03–0.94
Hydropower	2–20	0.004–0.06	0.001–0.03
Solar PV	13–190	0.15–0.40	0.12–0.29
Wind	3–41	0.02–0.11	0.02–0.09

Table IV: Life Cycle Emission Factors (per MWh of Net Electricity)

3.11. Phase Wise Contributions

Infrastructure and construction emissions are particularly important for low carbon systems such as wind, solar, and hydro. The relative contributions are shown in **Table V [10]**.

Technology	Infrastructure Contribution (%)
Coal	3–7
Natural Gas	4–10
Oil	4–8
Nuclear	30–40
Biomass	5–10
Hydropower	60–80
Solar PV	70–85
Wind	75–90

Table V: Infrastructure Contribution to Life Cycle Emissions

3.12. Economic and Resource Footprint

In addition to environmental performance, economic and resource indicators were assessed. **Table VI** summarizes the Levelized Cost of Electricity (LCOE) and water use per MWh for each technology. **[11]**

Technology	LCOE (USD/MWh)	Water Use (L/MWh)
Coal	50–110	1500–1800
Natural Gas	45–90	700–1200
Oil	90–150	1000–1300
Nuclear	70–120	2000–2500
Biomass	60–120	800–1200
Hydropower	40–100	45000–70000*

Technology	LCOE (USD/MWh)	Water Use (L/MWh)
Solar PV	25–60	50–100
Wind	20–55	<10

Table VI: LCOE and Water Use for Major Technologies

4. Life Cycle Assessment (LCA) Framework

The LCA methodology was implemented in four steps:

4.1. Goal and Scope Definition:

Functional unit = 1 MWh net electricity delivered to the grid. System boundaries included fuel provision, plant operation, and infrastructure construction/decommissioning.

4.2. Life Cycle Inventory (LCI):

Collected and harmonized input/output data from selected studies, including fuel consumption, material inputs, energy use, and direct/indirect emissions. **[6]**

4.3. Life Cycle Impact Assessment (LCIA):

Applied IPCC GWP100 for climate change, CML for acidification and eutrophication, TRACI for photochemical ozone creation, and CED for energy use **[7], [10]**.

4.4. Interpretation and Harmonization:

Results normalized to per MWh, harmonized for plant efficiency and capacity factor, and cross compared to identify environmental hotspots and uncertainties.

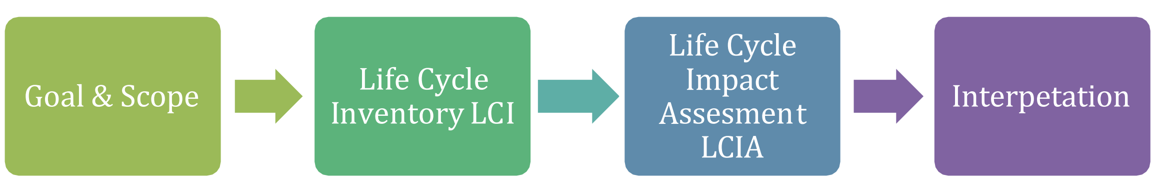

Figure 3 Flowchart of the four main stages of the LCA methodology

5. Results and Discussion

The comparative Life Cycle Assessment (LCA) of different energy generation technologies reveals stark contrasts in their environmental, technical, and economic performance. This section synthesizes the key findings drawn from over 167 reviewed case studies focusing on emissions, resource use, cost effectiveness and infrastructure contributions.

5.1. Environmental Performance

From the LCA results (Table IV), fossil fuel based technologies (coal, oil, and natural gas) exhibit the highest life cycle CO_2 equivalent emissions, ranging from 660–1300 kg CO_2 eq/MWh, primarily due to combustion emissions and upstream fuel processing. Coal fired plants, particularly those using lignite, are the most emission intensive.

In contrast, renewable technologies such as wind, hydropower, and nuclear show minimal life cycle emissions, often below 50 kg CO_2eq/MWh. Significantly

- Wind energy reports the lowest emissions (3–41 kg CO_2 eq/MWh), with steel and composites in infrastructure contributing significantly.
- Solar PV has relatively higher infra-structure related emissions (13–190 kg CO_2eq/MWh), reflecting the energy intensive manufacturing of PV modules.
- Hydropower, although low in emissions (2–20 kg CO_2eq/MWh), has high infrastructure contributions (up to 80%) and enormous water footprints (45,000–70,000 L/MWh) due to evaporation from reservoirs.

5.2. Infrastructure Contributions

Low carbon systems are significantly impacted by construction and material sourcing. As shown in Table III:

- Infrastructure accounts for 75–90% of emissions in wind and solar.
- For nuclear, infrastructure contributes 30–40%, largely due to reactor construction and fuel enrichment.
- Fossil fuel plants, on the other hand, see minimal infrastructure impacts (3–10%), as operational emissions dominate.

This indicates that improving material efficiency and recycling strategies could further reduce the life cycle impacts of renewables.

5.3. Economic and Resource Analysis

Table IV demonstrates substantial variation in the Levelized Cost of Electricity (LCOE):

- Wind and solar PV now offer the lowest costs ($20–60/MWh), supporting their rapid global adoption.
- Coal and nuclear are midrange ($50–120/MWh), while oil based generation remains the most expensive ($90–150/MWh).
- Water usage further differentiates these technologies, with wind and solar showing minimal water consumption (<100 L/MWh), compared to nuclear and coal, which consume over 2000 L/MWh.

This supports the assertion that renewables not only reduce emissions but also mitigate water stress a key issue in developing regions like Pakistan.

5.4. Integrated Case Study Hattar Industrial Estate

The case study of Hattar Industrial Estate illustrates practical application of LCA, simulation modeling, and Multi Criteria Decision Making (MCDM) in optimizing a hybrid renewable energy system. Key findings include:

- A hybrid PV wind biomass system reduced electricity cost to Rs.14.11/kWh and annual CO_2 emissions by over 117,000 tons.
- LCA validated the environmental benefits, while MCDM helped prioritize configurations based on cost, reliability, and emissions.
- Real world implementation challenges such as land availability, grid connectivity, and capital cost were evaluated in the decision making process.

This case confirms the effectiveness of an integrated assessment approach in guiding sustainable energy planning in industrial zones.

6. Conclusion

This review highlights the importance of Life Cycle Assessment (LCA) as a comprehensive tool for evaluating the environmental and economic implications of various energy generation technologies. Key conclusions are as follows:

6.1. Fossil fuel based systems especially coal and oil, remain the most environmentally and economically burdensome due to high CO_2, SO_2, and NO_x emissions, as well as significant water usage.

6.2. Renewable energy systems such as wind, solar PV, and hydropower demonstrate superior environmental performance particularly in terms of GHG emissions and water consumption. However, their environmental impact is mainly concentrated in the infrastructure phase suggesting room for improvement via circular economy practices.

6.3. Economic analysis shows that wind and solar PV are now cost competitive or cheaper than fossil fuels, reinforcing their viability in both developed and developing nations.

6.4. The case study on the Hattar Industrial Estate demonstrates how LCA, simulation, and MCDM can guide the development of optimized hybrid renewable systems tailored to local needs, delivering real reductions in both cost and emissions.

6.5. For developing countries like Pakistan, a context specific, multidimensional approach is essential for identifying optimal energy solutions that balance cost, reliability, and environmental sustainability.

Overall, this study provides robust evidence supporting the accelerated adoption of renewables through integrated LCA and decision support frameworks. These insights are crucial for policymakers, industry stakeholders, and researchers involved in planning sustainable energy transitions in resource constrained settings.

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