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Quantifying Fossil Fuel Burden and Designing an Optimal Renewable Energy Mix for India with Local Hybrid System Validation

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Abstract: - India's growing electricity demand is still predominantly met through fossil fuels, causing severe environmental damage, escalating healthcare problems and heavy economic losses due to resultant air pollution. A shift toward renewable energy with lower carbon emissions is essential for long-term sustainability. This study evaluates the societal cost of fossil fuel dependence and proposes a two-level strategy to accelerate renewable energy adoption in India. At the national level, MCDA and a linear optimization model was used to determine a cost-effective and balanced renewable energy mix capable of generating around 1200 TWh per year. The model incorporated capital and operating costs (IRENA, CEA), regional resource availability, climatic suitability (MNRE, IMD), and policy constraints. The findings indicate that a mix dominated by solar and wind energy-together supplying about 75% of total generation-offers the most economical and scalable pathway. Hydropower and biomass improve reliability and rural access, while nuclear and green hydrogen support base-load and long-term energy security. At the local level, a grid-connected hybrid system as the most cost-effective configuration, with PV and wind turbine contribution. The optimal system consisted of 25 kW wind turbines, 65 kW solar PV, 60 kW converters, 200kWh battery and grid support achieving high efficiency with a payback period of approximately 12.8 years. It was analyzed at Poornima University, Jaipur using HOMER Pro software. Overall, this integrated strategy provides a practical roadmap for India's sustainable and self-reliant energy future.

Keywords: Renewable energy strategy; Hybrid system simulation; Solar-wind integration; Sustainable ransition

I. INTRODUCTION

India's rapidly growing energy demand, driven by industrialization, urban development, and population growth, remains heavily dependent on fossil fuels such as coal, oil, and natural gas. [1] Currently, coal, oil and solid biomass account for nearly 75% of India's energy supply with coal predominance in electricity generation and industries, while petroleum products and natural gas govern transport and industrial use respectively.[2] Although these sources have supported economic development, their environmental and health impacts are alarming. Combustion of fossil fuels releases CO_2, SO_2, NO_x, and $PM_{2.5}$, resulting in air pollution, acid rain, and global warming. [3,4] According to Greenpeace, fossil fuel-related air pollution causes nearly US dollar (USD, \$) 150 billion (B) in annual economic losses-about 5.4 % of India's GDP-and significantly contributes to premature mortality and rising healthcare costs. [5]

Global evidence reinforces this concern. The Lancet Commission and World Health Organization (WHO) identify air pollution as a leading cause of disease, while international case studies demonstrate the economic and health benefits of clean energy transitions. [6,7] For example, implementation of the U.S. Clean Air Act is projected to save up to \$250B billion per year by 2030, and policy reforms in Taiyuan, China, reduced over 2,800 premature deaths and saved \$621 million within a decade. [8,9]

India, with its abundant sunshine, strong wind corridors, hydropower resources, and biomass availability, has immense renewable energy potential. [10] Hybrid renewable systems can exploit the complementary nature of these sources to enhance reliability and reduce storage dependence. [11]

This study presents a two-level strategy:

1. Estimation of the total fossil fuel burden and development of a Transitional National Renewable Energy Optimization Model (1200 TWh/year) using MCDA and linear programming;
2. A HOMER-based hybrid system feasibility study at Poornima University, Jaipur, evaluating localized scalability and economic viability.

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II. AIM AND OBJECTIVES

AIM

To quantify the socioeconomic cost of fossil fuel dependence in India and to develop an optimized renewable energy transition strategy through national-level modelling

OBJECTIVES

1. To estimate the annual fossil fuel burden in India.
2. To determine the alternative optimal renewable energy mix at the national level through modelling and analysis.
3. To design, simulate, and economically evaluate a site-specific wind-solar hybrid power system.

III. MATERIALS AND METHODS

STUDY DESIGN OVERVIEW

This research was carried out in two distinct phases combining cost modelling of national annual fossil fuel usage and optimization of alternative renewable energy system in the first phase, and, testing the hybrid model at a local site for the feasibility and practical aspects in the second phase.

PHASE 1.1- COST ASSESSMENT OF FOSSIL FUEL DEPENDENCE

This phase quantified the economic burden of India's dependence on coal, oil, petroleum and natural gas, by including both direct cost (procurement cost) and indirect externalities -environmental degradation, public health impacts, and agricultural losses due to them considering 2023-24 as the reference year for the quantity of fossil fuels consumed.

FOR THE CALCULATION FOLLOWING FOSSIL FUEL DATA SOURCES AND CALCULATIONS WERE USED

A. Direct cost-Fossil fuel procurement and consumption data: Extracted from NITI Aayog and Petroleum Planning & Analysis Cell (PPAC) reports. [12,13]
B. Indirect cost- Environmental cost, health damage and crop loss are key components of indirect cost of fossil fuels used in the study.

- Environmental damage estimation using emission calculation:
  $\text{Emissions} = \text{Fuel Consumption} \times \text{Emission Factor}$ (Derived from the IPCC 2006 Guidelines [14]
  $\text{Monetary Valuation: Cost} = \text{SCC} \times \text{Total } CO_2 \text{ Emissions} \times \text{CPI Adjustment}$ [15,16]
  where Social Cost of Carbon (SCC): USD 2.9/ton (as per Government of India standard) and Inflation adjustment: Applied using a Consumer Price Index (CPI) factor of 1.517.
- Health related damage- involved morbidity and mortality due to particulate matter ($PM_{2.5}$) and other air pollutants.
- Crop loss estimate
  The data of health-related loss and crop loss was extrapolated from proxy models. [17,18]

Fossil-fuel mediated soil and water contamination were not estimated or extrapolated due to lack of appropriate, reliable measurement criteria and resources available.

PHASE 1.2: ESTIMATING THE ALTERNATIVE OPTIMAL RENEWABLE ENERGY SOURCE (RES) MIX

In this part of study, Multi-Criteria Decision Analysis (MCDA) and linear optimization model were used to identify the most balanced combination of renewable sources capable of offsetting the use of fossil fuels.

For MCDA of RES, the weightage given to each criterion and assumptions related to capacity factor of each RES is shown in Table 1 and 2. Data were sourced from International Renewable Energy Agency (IRENA), the Ministry of New and Renewable Energy (MNRE) (India), and the Central Electricity Authority (CEA) (India). [19,20,21] Demand baseline was considered as 1200 TWh/year and Compound Annual Growth Rate (CAGR) in demand as 3-6%.

Table 1: Criteria used for Renewable Energy Source (RES) Selection in MCDA

Criterion	Weight (%)
Levelized Cost of Energy (LCOE)	35
Resource and Land Feasibility	25
Grid Intermittency / Integration	15
Emission Reduction Potential	15
Policy and Infrastructure Readiness	10

Table 2: Capacity Utilization Factor for Key Power Resources in India (2023-2025)

Resource (India)	Capacity Factor	Primary Government Source (2023-2025)
Solar PV (Utility-scale)	25%	cea.nic.in
Wind (Onshore)	28%	cea.nic.in
Wind (Offshore)	38% (Gujarat) / 48% (Tamil Nadu)	cea.nic.in
Hydropower (Large Hydro)	~38%	Ministry of Power "Power Sector at a Glance" 2023-24
Nuclear Power	~80-87%	Press Information Bureau (PIB) press releases; NPCIL/CEA post-FY reports; WNA/IAEA global benchmarks (~81-88%).
Hydrogen-based Power	No standard CF available	Ministry of New and Renewable Energy (MNRE) - National Green Hydrogen Mission policy documents.

Optimization Model Inputs were analysed using HOMER Pro (Hybrid Optimization Model for Electric Renewables) software version 3.14

PHASE 2: TESTING HYBRID ENERGY SYSTEM (HES) DESIGN AT A LOCAL SITE: POORNIMA UNIVERSITY CASE STUDY

A technical feasibility study and hybrid energy simulation for solar and wind energy were conducted using HOMER Pro software for Poornima University, Jaipur, to evaluate localized system performance and cost-effectiveness.

The hybrid configuration consisted of:

- Solar PV Array: PV panel of 65 kW capacities.
- Wind Turbines: giving a combined capacity of 25kW
- Converter/Inverter: 60 kW converter with 90% efficiency (HOMER default) and typical operational lifespan of 25 years.

HOMER SIMULATION AND SENSITIVITY ANALYSIS

The hybrid system was modelled using hourly simulations for one full year to assess energy production, economic performance, and reliability. Key output parameters included:

- Net Present Cost (NPC)
- Levelized Cost of Energy (LCOE)
- Cost of Energy (COE)
- System Reliability Index
- Payback Period

Sensitivity analyses were performed to examine the effects of variations in fuel prices, solar irradiance, and wind speed on overall system performance and financial viability.

HOMER SIMULATION AND OPTIMIZATION

The HOMER Pro software was used to simulate and optimize the proposed hybrid energy system for Poornima University, Jaipur. After evaluating all possible combinations of solar PV, wind turbines, and converter systems, HOMER ranked each configuration according to its Net Present Cost (NPC)-the total life-cycle cost of the system. The NPC includes installation, operation, and maintenance costs, minus any revenue or savings generated during the project's lifetime.

IV. RESULTS

The total cost of fossil fuel consumption in India was \$264.87 billion with \$210.18 billion as direct procurement cost and indirect cost was \$54.69 billion in the FY 2023-24. Table 3

Table 3: Annual consumption, direct and indirect cost of major fossil fuels (FY 2023-24, India)

Fuel Type	Annual Consumption (unit)[a]	Direct price used (INR / unit) & source	Total Direct Procurement cost ($ in billion) [b]	CO_2 emissions (billion ton) [d]	Environmental damage cost,SCC @$2.9/ton after CPI ($ in billion) [e]	Health damage alloc. ($ in billion) [f]	Crop loss alloc. ($ B) [f]	Total Indirect ($ in billion)	Aggregate Socioeconomic Cost ($ in billion)
Coal	1267.8 million ton	₹1,450 / t (CIL FSA approx.)	54.87[c]	2.99	13.15				
Oil / Petroleum products	234.26 million metric t	₹47,652.61 / t	132.42	0.53	2.21				
Natural gas	68.76 billion cubic meters(scm)	₹29.55 / scm (assumed landed price based on ~USD10/MMBtu; adjustable)	22.89	0.13 million	0.53million				
TOTAL	-	-	210.18	3.54	15.40	36.8	2.49	54.69	264.87

The annual coal consumption in FY 23-24 was 1267.58 million tons. Out of them about one- fourth (264.9 million tons) was imported from various countries. As shown, coal drives the largest share of CO_2 emissions and therefore, even with a low per-tonne procurement price, coal's aggregate socioeconomic burden is large. Petroleum and oil carry the largest direct procurement bill and, hence, reducing oil dependence for transport, refining and other industries has an immediate fiscal benefit, in addition to climate co-benefits.

Morbidity and mortality due to particulate matter ($PM_{2.5}$) and other air pollutants were considered for health-related damage. The data for health burden and crop loss were abstracted from studies as $36.8B and $2.49B respectively. Again, data varies widely as no specific data source is available.

RENEWABLE ENERGY REQUIREMENT TO OFFSET FOSSIL-FUEL USAGE

To replace the fossil fuel or offset the fossil fuel-based damage, renewable energy must supply India's major part of annual electricity demand at competitive generation costs.

MCDA and linear optimization results for national-level modelling suggest that India can achieve a cost-effective and sustainable energy transition by adopting a diversified renewable energy portfolio. The proposed optimal renewable energy mix for the 2025-2030 period is shown in Table 4.

Table 4: Optimal Renewable Energy Mix for India

Source	Estimated Share (%)	Key Benefits
Solar	40-50	Highly scalable, low cost, minimal emissions, suitable for both grid-connected and rooftop systems
Wind	20-25	Strong coastal and inland potential, complements solar generation during monsoon and night hours
Hydropower	10-15	Reliable base-load power, provides energy storage and grid stability through pumped-hydro systems
Biomass	5-10	Supports rural livelihoods, utilizes agricultural residues, and promotes decentralized power generation
Green Hydrogen	~5	Key for industrial decarbonization, energy storage, and long-distance transport applications
Nuclear	~5	Suitable for urban and industrial base-load demand; ensures long-term grid reliability

This mix balances cost efficiency, scalability, reliability, and sustainability. The results emphasize that solar and onshore wind power remain India's most cost-effective and scalable renewable options, both technically and economically, for achieving a sustainable energy transition while hydro and biomass enhance grid resilience. Green hydrogen and nuclear power act as strategic long-term options to meet industrial and base-load needs.

[a]Units of consumption = tonnes (coal, oil) or standard cubic metres (scm) for gas
[b] Converted @ 1$= 83.38 INR, as on date 31/03/24
[c]22-23 data was used as last available and value differs as the rate of production and import was different
[d] Emissions in $MtCO_2$ (million tonnes CO_2).
[e] SCC was $2.9/ton;
[f] Only extrapolated direct expenses were used; indirect are 3-4 times more

Experimental Results and Analysis of Hybrid Energy System Design at Poornima University -case study

The HOMER Pro simulation identified a wind-grid hybrid system as the most cost-effective configuration, with a PV and wind turbine contribution. As shown in Table 5, the optimal system consisted of 25 kW wind turbines, 65 kW solar PV, 60 kW converter, 200kWh battery and grid support.

Table 5: System Sizing

Component	Size
Solar PV	65 kW
Wind Turbine	25 kW
Battery Bank (Li-ion)	200 kWh usable
Number of Batteries	20 units (10 kWh each)
Converter/Inverter	60 kW
Grid	Connected

The technical performance of hybrid system is shown in Table 6 and Fig.1.depicts the share of each RES used in hybrid.

Table 6: Technical Performance

Parameter	Value
Annual Load Demand	164,250 kWh/year
Solar Energy Generation	109,500 kWh/year (66.7%)
Wind Energy Generation	54,750 kWh/year (33.3%)
Total Renewable Energy	164,250 kWh/year
Wind Capacity Factor	25%
Solar Capacity Factor	19-20%
Battery Autonomy	8 hours (full night backup)
Grid Purchases	<1% (only during emergency)
Unmet Load	0 kWh/year (100% reliability)

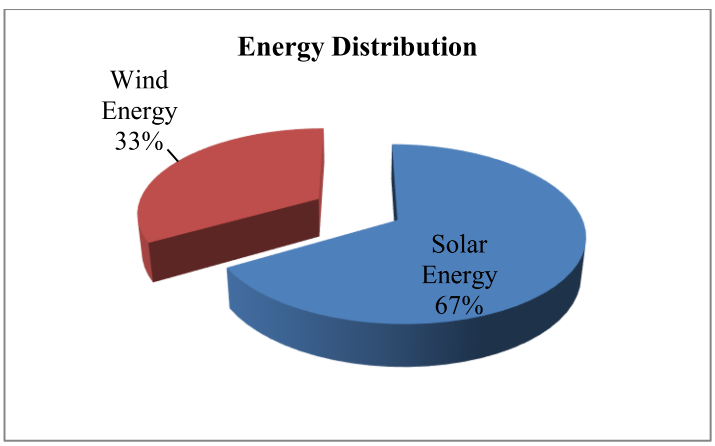

Fig. 1: Energy Distribution

The finance required for installation and annual operating cost are shown in Table 7 and 8 respectively. Fig. 2 illustrates the economic performance graphically.

Table 7: Economic Performance (USD)

Component	Cost
Solar PV (65 kW × $1,000)	$65,000
Wind Turbine (25 kW × $1,500)	$37,500
Battery Bank (200 kWh × $450)	$90,000
Converter (60 kW × $300)	$18,000
Installation & BOS (~15%)	$31,275
Total Initial Capital Cost	$241,775

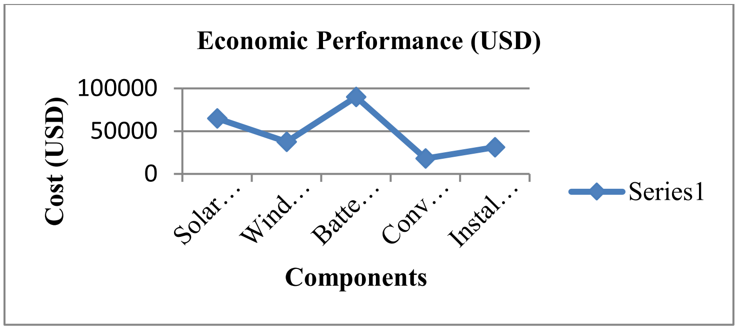

Fig. 2: Economic Performance

Table 8: Annual Operating & Maintenance (O&M) Cost

Component	**Cost/year**
Solar O&M	$1,300
Wind O&M	$1,500
Battery O&M	$2,000
Converter/Grid/Misc	$1,000
Total O&M /year	$5,800/year

1. Net Present Cost (25 years @ 8% discount rate)

$$NPC = Capital + O\&M + Replacements - Salvage$$

$$NPC \approx \$1.05 \text{ million}$$

2. Levelized Cost of Energy (LCOE)

$$\text{LCOE} = \frac{\text{NPC}}{\text{Total Energy}} = \frac{1{,}050{,}000 \text{ USD}}{4{,}106{,}250 \text{ kWh}} \approx 0.25 \frac{\text{USD}}{\text{kWh}}$$

LCOE ≈ $0.25 per kWh

3. Savings & Payback Analysis

Assuming current grid electricity price = $0.15/kWh

i. If no hybrid system:

$$\text{Annual electricity cost} = 164{,}250 \text{ X } 0.15 = \$\,24{,}637.5$$

ii. With hybrid system:

$$O\&M \text{ cost} = \$5{,}800/\text{year}$$

iii. Net annual savings:

$$\text{Annual electricity cost} - \text{O\&M cost} = 24{,}637.5 - 5{,}800 = \$18{,}837.5$$

iv. Payback Period:

$$= \frac{\text{Total Initial Capital Cost}}{\text{Net annual savings}} = \frac{241{,}775}{18{,}837.5} \approx 12.8 \text{ years}$$

Payback Period ≈ 12.8 years

This hybrid renewable energy system is designed to fully satisfy the daily load of 450 kWh using a combination of solar (66.7%) and wind (33.3%) energy, exactly as required. The battery bank provides 8 hours of backup, ensuring uninterrupted power supply during night-time or low-generation periods. The grid connection acts only as a backup, with less than 1% usage, making the system nearly independent.

From a technical viewpoint, the system delivers 100% renewable fraction, and 24/7 reliability. Economically, the initial investment is $241,775, with a Net Present Cost of $1.05 million and LCOE of $0.25/kWh, which is acceptable for an off-grid capable high-reliability system. Table 7,8 and Fig.2. The payback period of approximately 12.8 years shows long-term financial sustainability.

V. DISCUSSION

India's continued reliance on fossil fuels imposes a profound and unsustainable burden. [22,23]

FOSSIL-FUEL COST QUANTIFICATION AND GLOBAL COMPARISON

The present analysis estimated $264.87 billion as annual fossil fuel burden in India with maximum expenditure on procurement of petroleum and oil. India, world's third-biggest oil importer and consumer, spent $132.4 B importing crude oil in FY 23-24 as another study reported. [24]

The indirect cost, primarily due to CO_2 emissions in the present study was found to be $54.69 B (using a conservative Social Cost of Carbon (SCC) of USD 2.9 / ton). Comparable study by the Greenpeace Southeast Asia and CREA reported that air-pollution-related losses in India amount to $150B annually, or 5.4 % of GDP.[5] However, a study claims that India's own valuation of country-level SCC internalizes only about 5% of the global climate externality, hence, if SCC is considered as $86/ton as per that study , it surpasses the cost of procurement.[25] Previous national and global analyses highlight that fossil-fuel dependence inflicts substantial hidden costs, sometimes, far exceeding the apparent market price of energy.[17,23]

According to World Health Organization (WHO), among the world's twenty most polluted cities in the world, thirteen are in India. India has the highest levels of PM10 and PM2.5 (particles with diameter of 10 microns and 2.5 microns)., reaching up to six times more than the WHO "safe" limit of 25 micrograms. [26]

Global burden of disease (GBD) 2019 attributed 1.6 million premature deaths in India to fossil-fuel based air pollution.[17] It is projected that premature mortality due to the emissions from coal-fired- thermal- power-plants is expected to grow 2-3 times reaching 186,500 to 229,500 annually in 2030 and embracing flue gas desulphurization will cause substantial monetary benefit and 50% of health benefit. [27] A study claims that India would have benefitted by $95 billion, or 3% GDP, amounting to 150% of India's healthcare budget, if it had achieved safe air quality levels in 2019. [28]

Studies proposed that internalizing these externalities of fossil fuels make renewable power the least-cost option in most economies. [29,30] U.S. and Chinese experiences show that implementation of carbon pricing and clean-air reforms yielded measurable social and economic gains.[31]

FEASIBILITY OF NATIONAL-LEVEL ENERGY TRANSITION

The national linear optimization model in this study suggests the optimal mix-40-50 % solar, 20-25 % wind, supplemented by hydro, biomass, nuclear, and green hydrogen-aligns closely with projections from the Central Electricity Authority's Optimal Generation Mix (2023) and NREL's India Renewable Integration Study (2022), both of which emphasized solar-wind dominance supported by hydropower and flexible storage.[32,33] IRENA found that >90 % of newly commissioned renewable capacity worldwide is cheaper than the cheapest fossil-fuel option.[30]

The present study emphasizes that solar and onshore wind power remain India's most cost-effective and scalable renewable options, both technically and economically, for achieving a sustainable energy transition.

Micro-Level Validation through Hybrid Simulation

The HOMER Pro simulation conducted for Poornima University, Jaipur provides micro-scale validation of national trends. The optimal configuration the initial investment is $241,775, with a Net Present Cost of $1.05 million and LCOE of $0.25/kWh, which is acceptable for an off-grid capable high-reliability system. The payback period of approximately 12.8 years shows long-term financial sustainability.

Previous Indian campus-scale assessments, such as Serat et al. and Dhiman et al hybrid energy systems, reported payback periods of 2.5 to 7.64 years under similar resource conditions. [34,35] The payback observed in present study likely reflects higher local tariffs and location-specific variation in efficiency of hybrid system. Internationally, comparable HOMER-based case studies in Malaysia and Egypt achieved paybacks between range of 2.98-20 years, reinforcing the scalability of hybrid designs in educational and semi-urban contexts. [36,37]

GRID INTEGRATION, POLICY ALIGNMENT, AND FUTURE OUTLOOK

Large-scale renewable integration in India necessitates smart-grid expansion, distributed energy storage (pumped hydro, hydrogen), and demand-response mechanisms to manage intermittency. These requirements parallel recommendations from CEA and NITI Aayog on grid flexibility and green-hydrogen integration. [12,32] Nuclear and green hydrogen remain crucial for base-load stability as electricity demand is expected to double by 2040.[38]

STRENGTHS AND LIMITATIONS OF STUDY

The study's strength lies in its two-tier approach-linking national optimization with campus-level validation. However, the analysis assumes stable policy incentives, optimistic cost parameters, and constant capacity factors. Future work should employ dynamic carbon pricing, real-time grid simulation, and storage sensitivity analysis to refine these estimates.

VI. CONCLUSION

This study provided a comprehensive evaluation of India's renewable energy transition by quantifying the annual costs of fossil fuel dependence to be around $264.87B for the major fuels. It also explores an alternative optimized clean energy strategy suited to India's geographic and economic context with VRE-Solar and Wind (65-75%, due to favourable cost profile, scalability, and abundance required for primary power generation); Hydropower and Biomass (15-20%, for reliable base-load and rural power support) and Green Hydrogen and Nuclear (5-10%, essential for industrial use and long-term energy security).

At the micro level testing at Poornima University, Jaipur, using HOMER Pro simulation an approving NPC, favorable payback period, zero operational emissions while maintaining efficiency through grid support was noted.

Thus, the study upheld the view that India's renewable energy transition represents both an environmental necessity and an economic opportunity. With the right mix of technology, policy reform, and investment, India can achieve sustainable, affordable, and resilient energy security-serving as a global model for clean energy transformation.

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CONFLICTS OF INTERESTS

None

ETHICAL CONSIDERATION

Not Required

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