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Future of clean energy for cooking in India: A comprehensive analysis of fuel alternatives

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ABSTRACT

Household air pollution, primarily from solid fuels, globally caused 3.2 million premature deaths in 2020. India houses more than a quarter of global solid fuel users, and transitioning them to cleaner fuels offers an opportunity for global environmental and socio-economic impacts and addressing multiple sustainable development goals. This study compares cooking fuels from the perspective of health, environmental impacts, cost, supply-demand dynamics, and relevant policies. Liquefied petroleum gas (LPG) and piped natural gas (PNG) are being aggressively promoted as cleaner fuel alternatives. However, their sustained use, high reliance on imports, volatile prices, and environmental impacts remain a concern. Moreover, LPG and PNG might not be clean enough as NO_x and ultrafine particle emissions have been associated with adverse health impacts. Replacing current solid fuels with LPG will annually add about 91 million metric tons of CO_2 (just from combustion), translating to an increase of about 3.5 % of the country's CO_2 emissions. Direct and indirect imports constituted 96.5 % of the total LPG consumption in 2021-22, and the same has remained above 90 % for the last decade. Furthermore, the current subsidy-based policy promoting LPG adoption doubled the active user base in just seven years. However, annual LPG consumption has steadily declined from ~110 kg to ~85 kg per user over the same period, indicating non-sustained adoption. Unlike developed countries, electricity for cooking has not gained popularity in India, even though it has the potential to address the shortcomings of LPG and PNG. Decentralization and integration of renewables in the power generation sector can provide energy with lower carbon intensity, lesser reliance on imports, and relatively stable prices. The cooking energy portfolio of India will be a mixed bag, but more comprehensive forward-looking policies are needed to optimize its composition.

Introduction

Almost 2.4 billion people still rely on solid fuels such as biomass, dung cakes, and charcoal, burning in mostly inefficient stoves for cooking and heating (WHO, 2023), causing household and environmental air pollution (Frostad et al., 2022; Hou et al., 2022; Li et al., 2021; Pratiti et al., 2020). Solid fuel combustion emits a range of products of incomplete combustion, such as particulate matter (PM), volatile organic compounds (VOCs), and carbon monoxide (Leavey et al., 2015; Leavey et al., 2017; Puttaswamy et al., 2021; Shen et al., 2021), adversely impacting the environment (Kaur-Sidhu et al., 2020; Singh et al., 2013; Weltman et al., 2021) and human health by both direct and indirect exposure (Balmes, 2019; Balmes, 2020; Lee et al., 2020). The World Health Organization (WHO) estimates 3.2 million

Abbreviations: ACI, Aggregate Carbon Intensity; BCM, Billion Cubic Meters; BPL, Below Poverty Line; CGD, City Gas Distribution; COPD, Chronic Obstructive Pulmonary Disease; FC, Fuel cost in terms of energy content (cents/MJ energy content); GDP, Gross Domestic Product; GHGs, Greenhouse Gases; GWP, Global Warming Potential; HAP, Household Air Pollution; ICS, Improved Cookstoves; LCA, Life Cycle Assessment; LCPM, Life cycle cost per meal accounting for both capital and operational cost (cents); LNG, Liquified Natural Gas; LPG, Liquefied Petroleum Gas; MMSCMD, Million Metric Standard Cubic Meters per Day; NO_x, Nitrogen Oxides; OCPM, Operational cost per meal accounting only for fuel cost (cents); PM, Particulate Matter; PMUY, Pradhan Mantri Ujjawala Yojana; PNG, Piped Natural Gas; PPB, Parts per billion; SDGs, Sustainable Development Goals; UFPs, Ultrafine Particulates; USD, US Dollars; VOCs, Volatile Organic Compounds; WHO, World Health Organization.

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premature deaths per year related to household air pollution (HAP) (WHO, 2023).

About 44 % and 42 % of households still rely on solid fuels in China (Shen et al., 2022) and India (IIPS et al., 2021), respectively, constituting the major fraction of the HAP-affected global population. Moreover, in India, the HAP contributes 22 % to 52 % of ambient $PM_{2.5}$ concentrations (Chafe et al., 2019), and the emissions from residential energy use in the country contribute around 52 % to the population-weighted annual mean $PM_{2.5}$ concentrations and have been found to cause about 511,000 deaths annually (Conibear et al., 2018). Since both China and India are emerging economies, they are better positioned than other developing countries to address HAP by providing cleaner fuel alternatives as household income increases. Transitioning from solid fuels to cleaner alternatives will also address many sustainable development goals (SDGs) of the United Nations directly (accessibility to affordable, reliable, and sustainable energy) and indirectly (poverty; air pollution, low levels of life expectancy, and lack of access to essential healthcare services; delivering quality education; adaptation and mitigation of climate change; food production and security; economic growth and employment; sustainable industrialization; and gender inequality). However, it should be noted that all cleaner fuel alternatives, while effective in reducing HAP, have varying extents of environmental impacts, as discussed in Section 2.2. Any such initiatives to provide reliable access to clean fuels by these two countries (China and India) would have positive impacts globally, as they account for half the estimated 2.7 billion people using solid fuels. However, transitioning masses from solid fuels to cleaner fuel alternatives faces various socio-economic, cultural, and region-specific challenges and encounters multiple constraints, such as accessibility, affordability, and supply reliability (Dioha & Kumar, 2020; Hollands & Daly, 2023; Pohekar et al., 2005).

As an interim step in transitioning to cleaner fuel alternatives, improved cookstoves (ICS) have been widely explored as an option to burn solid fuels more efficiently. Current ICS have demonstrated (1) fuel savings due to improved thermal efficiency from improved heat transfer (Shan et al., 2021; Wassie & Adaramola, 2021) and (2) reduced emissions compared to traditional cookstoves, at least in a laboratory setting (Just et al., 2013; Leavey et al., 2015; Hartinger et al., 2013). However, their emission levels are still much higher than desired. The exposure-response curve is non-linear for health effects due to $PM_{2.5}$ exposure, and most changes in health effects occur at lower concentrations, resembling ambient levels (Smith & Peel, 2010). Although more research on the exposure-response curve focusing on HAP is required, a multifold reduction in emission levels from ICS is required to achieve any significant positive impact on human health. Such low levels of emissions from residential solid fuel combustion are not achievable with any ICS available to date.

Before implementing any program to promote the adoption of cleaner cooking fuels or stoves, the first step is to understand a household's complex process of fuel selection. A household's fuel choice depends on a complex interplay of multiple factors, such as price, accessibility, and supply reliability (Patel, Khandelwal, et al., 2016), which further depend on resource availability, distribution networks, subsidies, and government policies, forming a feedback loop. Therefore, it is vital to analyze the dissemination of cleaner cooking fuels from the perspectives of both (1) the user, as was done previously (Patel, Khandelwal, et al., 2016), and (2) the policymakers or government, which is the focus of this work. Fig. 1 combines a typical energy ladder diagram with the cooking fuel portfolio of India. Each pie chart shows the rural and urban usage patterns of fuel, and data is imported from the National Family Health Survey 2019-21 report (IIPS et al., 2021). While 58.6 % (165.2 million) households in India have access to clean cooking fuels (liquefied petroleum gas (LPG), piped natural gas (PNG), and biogas), 40.72 % (114.5 million) of Indian households still use solid fuels.

The present study seeks to provide a broad perspective on health and environmental impacts along with cost and supply-demand, as well as a

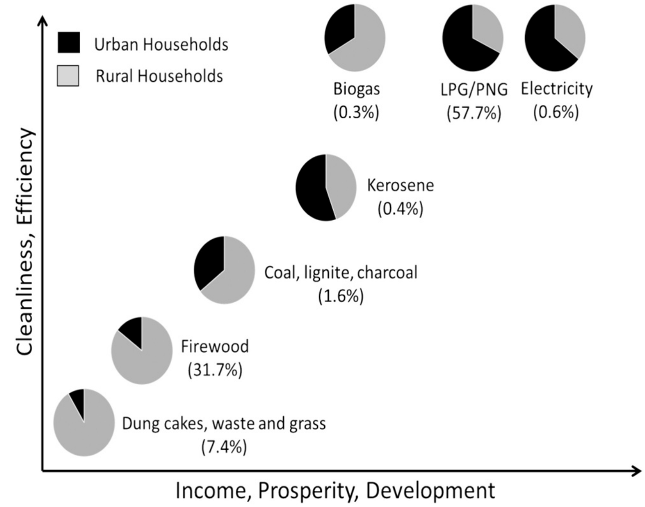

Fig. 1. Energy ladder for Indian households with the national percentage of households using various fuels (IIPS et al., 2021). In the case of electricity, generation source bifurcation is not available. LPG: liquefied petroleum gas; PNG: piped natural gas.

critical review of current policies for the present and possible future of clean cooking fuel alternatives in India. This work presents a comprehensive comparative analysis of the country's cooking fuels (solid fuels, LPG, PNG, biogas, and electricity). Firstly, emission and resultant exposure at the end use of the fuel are discussed, along with whether the cleaner fuel alternatives are clean enough to mitigate household air pollution and associated health impacts. Afterwards, life cycle environmental impacts are discussed to assess environmental sustainability in current and near-future times. After that, a cost analysis, considering both capital and operation, is performed to evaluate the affordability of different fuels. Finally, the cleaner fuel alternatives (LPG, PNG, biogas, and electricity) are critically reviewed regarding supply-demand, reliance on other countries, economics, and government policies and schemes for promoting clean cooking energy options. This work provides an overview of the current scenario of cooking fuel usage in India. Kerosene as a fuel choice has not been considered in this study, as its use as a cooking fuel is being discouraged owing to the significant environmental and health impacts associated with harmful emissions from kerosene combustion (Lam et al., 2012; Ortega et al., 2021; Pandey et al., 2014).

Comparative assessment of fuel alternatives

Multiple factors, including gender inequality, education, affordability, social status, and accessibility, govern a household's choice of cleaner fuels (Choudhuri & Desai, 2020; Timilsina et al., 2023). Among these, major determinants for adoption and sustained use are fuel cost and accessibility (Gould, Hou, et al., 2020; Gould & Urpelainen, 2018; Patel, Khandelwal, et al., 2016; Timilsina et al., 2023). From a household's perspective, health and environmental impacts do not weigh much in the fuel selection process (Ali & Khan, 2022; Aminu et al., 2024; Doggart et al., 2020; Patel, Khandelwal, et al., 2016; Paudel et al., 2018). Since cost and accessibility govern fuel selection, analysis of cost, availability, supply-demand imbalance, and relevant government policies is critical. Simultaneously, incorporating the health and environmental impacts of different cooking fuels is imperative at the policy level. Therefore, the current study has also comprehensively analyzed different cooking fuels based on their health and environmental impacts. Table 1 summarizes six different evaluation metrics along with the need and methodology of each analysis utilized for comparative assessment of fuel alternatives.

Table 1
Different evaluation criteria for the comparative analysis of cooking fuel alternatives.

Metric	Description
User-end emission and health impacts	• Literature survey to identify the pollutants emitted during the combustion of various fuel alternatives • Literature survey for the health implications arising from exposure to the emitted pollutants with a focus on recent research on NOx and UFP
Life cycle environmental impact	• Literature survey of the life cycle impacts of cooking fuels on metrics such as potential for global warming, PM formation, and eutrophication. • Environmental impacts are region-specific; thus, studies on India and other developing countries have been included. • Aggregate carbon intensity (ACI) used as the metric for electricity to account for its generation from renewable and non-renewable resources.
Cost analysis	• Accounting for both fixed (one-time) and operational (fuel) costs. • Calculation of cost per meal based on useful energy obtained after accounting for stove efficiency
Supply-demand analysis	• Estimation of resource availability or supply (production and import) • Analysis of historical supply-demand trends. • Demand, cost, and emission implications for transitioning all solid fuel users to different cleaner fuel alternatives (LPG, PNG, and electricity).
Policy and infrastructure	• Analysing current policies and their effectiveness in promoting sustained use of cleaner fuel alternatives • Critical evaluation of current growth rate and consumption trends to comment on the goals set by government policies.

User-end emissions and health impacts

Since the driving force behind most cooking fuel-oriented policies is to protect human health, this section focuses on end-use emissions that cause HAP. The emissions discussed in this section are due to fuel combustion and not from cooking activities, assuming the emissions associated with the same type of food being cooked will be similar for all cooking fuels. Although the emissions are assumed to remain the same during cooking, actual cooking practices and dietary preferences will also impact the emissions. However, including such factors is beyond the scope of this study.

Moreover, the majority of life-cycle greenhouse gases (GHGs) are emitted from fuel combustion for most cooking fuels (Afrane & Ntiamoah, 2011; Jungbluth et al., 1997). In addition to GHGs, fuel combustion emits pollutants such as fine PM, CO, nitrogen oxides (NO_x), and polycyclic aromatic hydrocarbons (Bilsback et al., 2019; Kephart et al., 2021; Patel, Leavey, et al., 2016; Wallace et al., 2008), which have significant environmental and health impacts. Emissions from solid fuel combustions and their health impacts are studied extensively. Multiple studies have reported a higher prevalence of ailments such as reduced lung function capacity, acute respiratory infections, COPD, asthma, and other health conditions among solid fuel users (Ali et al., 2021; James et al., 2020; Mahmood et al., 2017; Patel et al., 2018). Some of such studies are summarised in Table S1 in the supplementary information (SI). It should be highlighted that emissions from solid fuel combustion have impacts beyond the household level. For example, Yun et al. (2020) found that residential solid fuel consumption is only 7.5 % of total energy consumption in China but contributes 27 % of primary $PM_{2.5}$ emissions. The same study attributed 23 % of the outdoor $PM_{2.5}$ concentrations to residential solid fuel combustion, accounting for 68 % of $PM_{2.5}$ exposure in China (Yun et al., 2020). For India, Conibear et al. (2018) estimated that ~67 % of annual anthropogenic $PM_{2.5}$ emissions and ~ 52 % of total premature mortalities due to ambient $PM_{2.5}$ exposure is associated with residential energy usage, even though residential energy accounts for only 30 % of the total energy consumption. Another study by (Chowdhury et al., 2019) proposed that the transition of all households to clean fuels can avert ~13 % of premature mortality in India, and ambient $PM_{2.5}$ concentration could meet the national standards.

While the potential cleaner fuel alternatives in India, i.e., LPG, PNG, biogas, and electricity, are undoubtedly cleaner than solid fuels, there are still health impact concerns associated with their emissions. LPG and PNG are being aggressively promoted as cleaner cooking fuel alternatives in India. However, LPG, PNG, and biogas combustion emissions are not benign. LPG and PNG combustions emit NO_2, which can cause respiratory illness (Achakulwisut et al., 2019; Jiang et al., 2019; Usemann et al., 2019). Belanger et al. (2013) reported a higher risk of pediatric asthma for children exposed to NO_2 from gas stoves in households in the USA. Morales et al. (2009) studied the association between early life (first three months after birth) exposure to NO_2 from gas appliances and neuropsychological development at age four. NO_2 concentration was associated with decreased cognitive function and inattention symptoms. Kephart et al. (2021) reported that, though LPG usage substantially reduced the kitchen area NO_2 concentration compared to biomass usage, 69 % of 24-h kitchen area samples still exceeded WHO indoor air quality guideline for annual mean NO_2 (33 ppb), and 47 % of samples exceeded WHO indoor hourly guidelines. A similar study assessing the NO_2 concentrations in residential micro-environments demonstrated that the mean NO_2 concentration during summers in the kitchen area of rural households using natural gas was high (81 μg/m^3) as compared to the households using biomass (51 μg/m^3) (Colbeck et al., 2010). The same study also reported considerably higher mean NO_2 concentrations (234 μg/m^3) in urban households using natural gas owing to a combination of lower ventilation rates and higher background concentrations. Based on the current understanding of the health impacts of exposure to NO_2 from LPG and gas stoves, it is critical not to treat LPG and PNG as the ultimate solution for clean cooking. Since LPG and PNG will be a significant part of India's cooking fuel portfolio, efforts can be made to reduce indoor NO_2 concentration by altering house characteristics and stove type. For example, high-efficiency gas stoves reduce fuel consumption by around 30 %, thus lowering the NO_2 concentration (Belanger et al., 2013).

Apart from NO_2, PM emissions from gas stoves also need attention. Since mass-based PM metrics are predominantly used to determine the consequent health impacts and policy formulation, gas stoves are deemed clean and safe for users. However, the combustion of PNG and LPG in household appliances leads to very high indoor number concentrations (>1000× of background levels) of ultrafine particles (usually <20 nm) without significantly contributing to the total PM mass concentration (UFPs) (Just et al., 2013; Patel et al., 2020; Patel et al., 2021; Wallace et al., 2008; Wallace et al., 2019). The health implications of exposure to UFPs are yet to be fully understood. Limited work done so far has reported negative health implications of UFPs. Some recent studies have suggested an association between human neurodegenerative diseases and UFPs (Amouei Torkmahalleh et al., 2022; Calderón-Garcidueñas & Ayala, 2022; Flood-Garibay et al., 2023; Gan et al., 2023). Amouei Torkmahalleh et al. (2022) studied the effect of UFPs emitted from a gas stove on healthy adults using electroencephalography for brain response. The study found that the brain responses in the participants during exposure were similar to people with neurodegenerative diseases, and measured signal characteristics were similar to those observed in early-stage Alzheimer's patients.

Regarding electricity, stove-related emissions at the user end depend on the stove type as well as the type of cooking performed. Heating-coil stoves and hot plates operate at high temperatures, leading to UFP emissions (Patel et al., 2020; Wallace et al., 2008). However, it is unclear whether the emitted particles' source is the heated coil and hot plates (Wallace et al., 2015). Induction stoves have been gaining popularity among households using electricity for cooking due to their efficiency, different control settings, and safety. Since induction stoves do not transfer heat via conduction, eliminating high-temperature surfaces and hence no UFPs emission from the stove itself.

Life cycle emissions and environmental impacts of fuel alternatives

Apart from the user-end emissions, any fuel's life cycle emissions or environmental sustainability is also critical and must be accounted for by policymakers. The emissions from cooking fuel combustion have been associated with severe climatic impacts and ecosystem imbalance arising from forest degradation and soil and water contamination. Therefore, this section focuses on life cycle emissions and the environmental impacts of various fuel alternatives.

Several studies have reported life cycle emission inventory from the production and combustion of different cooking fuels (Chen et al., 2007; Kadian et al., 2007; Reddy & Venkataraman, 2002; Singh et al., 2014; Smith et al., 2000). Table 2 summarizes four such studies focussing on the life cycle environmental impact of cooking fuels under nine categories in India (Cashman et al., 2016; Morelli et al., 2017), Ghana (Aberilla et al., 2020), and multiple Southeast Asian countries (Aberilla et al., 2020). Since all studies were performed in different locations, time (which governs the state of technology), and assumptions, data summarised in Table 2 should be best for fuel trend analysis in the same study. All studies reported higher global warming potential (GWP) for solid fuels than cleaner fuel alternatives, barring electricity generated from coal and diesel. The two studies focusing on India, i.e., Morelli et al. (2017) and Cashman et al. (2016), reported the highest GWP for hard coal (963 by both) and the least for biogas derived from cattle dung (11.4 and 10.5, respectively). Barring hard coal, the GWP of solid fuels was comparable to LPG and natural gas. However, the PM formation potential of LPG and natural gas was multifold lower than that of solid fuels. PM formation potential of electricity produced from coal combustion is about ten times lower than that of hard coal, which can be attributed to better combustion efficiency and emission capture technologies at thermal power plants. Apart from a few instances, biogas demonstrated the lowest environmental impacts.

Natural gas or PNG has been projected as a clean transition fuel. Its combustion produces negligible sulfur dioxide, PM (in terms of mass),

Table 2
Summary of life cycle impact assessment of cooking fuels in different environmental impact categories reported by four studies (Morelli et al. (2017), Aberilla et al. (2020), Afrane & Ntiamoah (2012), Cashman et al. (2016)).

Fuel type	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.
	Global warming potential (g CO_2/MJ energy)				PM formation potential (g PM_{10} eq/MJ energy)				Human toxicity potential (g 1,4 dB eq/MJ energy)			
Hard Coal	963	–	–	963	19.8	–	–	19.3	–	–	–	–
Dung cake	263	–	–	191	24.3	–	–	23.6	–	–	–	–
Crop residue	119	132	–	132	11.4	10.8	–	11.3	–	38	–	–
Firewood	196	70	1031	539	5.54	1.5	–	4.72	–	38	24.9	–
Charcoal	402	225	1450	572	20.5	3.5	–	19.5	–	261	1.64	–
LPG	157	160	120	303	0.136	0.1	–	0.16	–	13	37,100	–
Natural Gas	117	–	–	292	0.019	–	–	0.12	–	–	–	–
Electricity[a]	457	502	4.425	415	1.91	2.9	–	1.69	–	41	2.33	–
Biogas	11.4	124	163	10.5	0.21	-0.1	–	0.077	–	−15	0.017	–

Fuel type	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.
	Eutrophication potential (g P eq/MJ energy)				Terrestrial acidification potential (g SO_2/MJ energy)				Water depletion potential (L/MJ energy)			
Hard coal	0.0024	–	–	0.0021	1.87	–	–	1.87	0.397	–	–	16.6
Dung cake	0.189	–	–	3.82	0.736	–	–	0.75	0.0017	–	–	1.19
Crop residue	0.0098	0.131	–	0.19	0.598	0.41	–	0.62	0.000087	5	–	0.058
Firewood	0.0074	0.153	0.013	0.16	0.377	0.4	0.094	0.40	0.000065	4	–	0.049
Charcoal	0.014	0.154	0.03	0.28	0.209	0.22	0.168	0.21	0	5	–	0.63
LPG	0.0038	0.005	1400	0.0029	0.256	0.44	0.0225	0.33	0.193	40	–	31.7
Natural gas	0.00007	–	–	0.0021	0.027	–	–	0.31	0.039	–	–	26.7
Electricity	0.0037	0.019	0.0028	0.0034	4.54	5.46	0.0147	4.00	3.25	95	–	515
Biogas	–	-0.301	0.0019	0	0.106	-1.97	0.0257	0.11	1.02	-54	–	1.04

Fuel type	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.	Morelli et al.	Aberilla et al.	Afrane et al.	Cashman et al.
	Photochemical oxidation formation potential (g NMVOC/MJ)				Ozone depletion potential (g CFC-11 eq/MJ energy)				Black carbon and short-lived pollutants (g BC eq/MJ energy)			
Hard coal	7.87	–	–	7.86	3.01e-08	–	–	8.2e-07	4.10	–	–	3.91
Dung cake	18.8	–	–	18.7	1.40e-09	–	–	6.2e-08	5.27	–	–	5.01
Crop residue	8.22	10.8	–	8.75	7.28e-11	5.0e-08	–	3.1e-09	2.48	–	–	2.42
Firewood	5.38	1.5	–	6.02	5.46e-11	4.0e-08	–	2.6e-09	1.22	–	–	1.04
Charcoal	10.4	3.5	–	10.5	1.03e-11	1.0e-07	–	4.5e-09	4.58	–	–	4.27
LPG	0.341	0.1	–	0.76	6.56e-08	3.3e-05	–	2.0e-06	0.012	–	–	0.014
Natural GAS	0.046	–	–	0.62	7.25e-08	–	–	2.3e-06	0.002	–	–	0.0005
Electricity	2.66	2.9	–	2.01	4.24e-07	9.5e-05	–	1.4e-06	-0.016	–	–	-0.019
Biogas	0.114	-0.1	–	0.11	–	-4.0e-06	–	0	0.035	–	–	0.0068

[a] Morelli et al. (2017), and Cashman et al. (2016) considered electricity from a coal-fired thermal power plant, Aberilla et al. (2020) considered electricity from a diesel generator, and Afrane & Ntiamoah (2012) considered hydro-electricity.

and mercury; hence, it is less polluting than coal or oil and thus benefits health relative to solid fuels (Saunders et al., 2016). Nevertheless, natural gas is linked to various health and environmental hazards. The emission of toxic and carcinogenic chemicals from gas compressor stations, leakage from pipelines, NO_x emitted during combustion, and increased atmospheric methane levels might outweigh the advantages of natural gas (Landrigan et al., 2020; Howarth, 2019; Intergovernmental Panel on Climate Change (IPCC), 2018).

All three gaseous fuels (LPG, PNG, and biogas) have similar combustion and emission characteristics. Biogas production from organic waste or biomass restricts methane emission, with a global warming potential of 25 times more than CO_2, which otherwise would have been released into the atmosphere through natural decomposition. Further, biogas, a dung derivative, can be carbon neutral regarding CO_2, whereas LPG and PNG are not. Therefore, any increases in the use of PNG and LPG would contribute to global warming by adding CO_2 to the environment. Apart from the CO_2 emissions during combustion, the production-to-distribution process of LPG, encompassing feedstock recovery, import, fuel production, and distribution, also has a significant carbon footprint (Kim et al., 2021). Altogether, LPG usage and promotion as a cleaner fuel alternative are not without their disadvantages.

The end-use emissions of electric induction stoves are the easiest to assess because none are associated with induction stove usage. However, the emissions at the source vary significantly due to the range of resources from which electricity is produced. The centralized electricity generation and grid-based distribution make it challenging to attribute electricity used for cooking to any specific source. Therefore, emissions from electricity used explicitly for cooking cannot be calculated like those of other cooking fuel alternatives. In such a scenario, metrics such as aggregate carbon intensity (ACI) (Ang & Su, 2016) can be used. ACI is CO_2 emissions from electricity generation normalized by the electricity produced from all sources. So, the minimum ACI of 0 kg CO_2/kWh can be achieved using 100 % renewables. As reported by Ang & Su (2016), the ACI of India in 2013 was 0.793 kg CO_2/kWh, just 4.75 % lower than the ACI in 1990 (0.832 kg CO_2/kWh), mainly due to improvements in thermal efficiency. In contrast, China reduced its ACI by 23.96 % (0.909 kg CO_2/kWh in 1990 to 0.692 kg CO_2/kWh in 2013). Fig. 2 presents the evolution of annual CO_2 emissions from electricity and ACI. While the annual electricity generation has been increasing (Fig. S1A), the corresponding CO_2 emissions have remained relatively flat (Fig. 2). These trends can be attributed to the decreasing ACI (Fig. 2). The most recent ACI for electricity generation in India was 0.715 kg CO_2/kWh in 2021-22 when renewables accounted for ~25 % of total generation (Fig. S1B) (CEA, n.d.). A comparative LCA study by Hertwich et al. (2015) also indicated that renewable electricity has significantly lower pollution-related impacts in terms of greenhouse gases, particulate matter, freshwater ecotoxicity, and freshwater eutrophication. With the integration of more and more renewables in the Indian power generation sector (summarised in Section S2), ACI will further decrease, making electricity even more attractive.

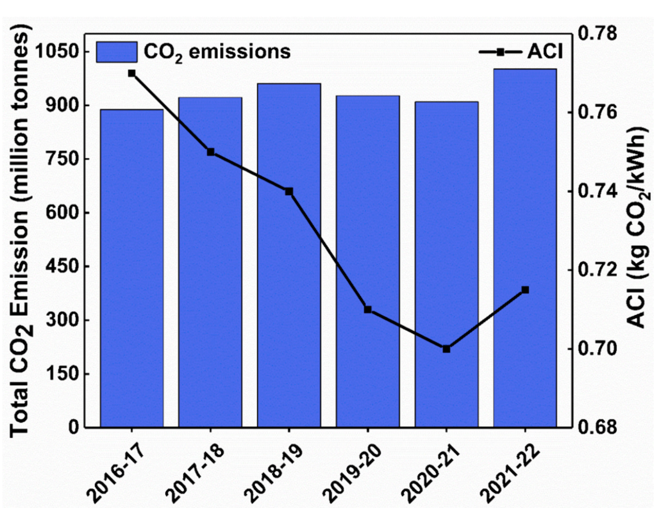

Fig. 2. Evolution of annual CO_2 emissions from electricity generation (left y-axis) and corresponding aggregate carbon intensity (ACI on right y-axis) in India (CEA, n.d.).

Cost analysis of fuel alternatives

Previous studies have already ascertained that cost is one of the primary governing factors for adopting any cooking fuel. This section compares different fuel alternatives based on the cost of cooking for multiple scenarios: (i) fuel cost in terms of energy content (FC: cents/MJ energy content), (ii) cost per meal accounting for only fuel cost (OCPM: cents), and (iii) cost per meal over the stove's lifetime accounting for both capital and operational cost (LCPM: cents). The cost analysis presented in this work is based on the Indian market price of the fuels in 2023. The indirect environmental and health costs discussed in the previous sections do not significantly affect a household's fuel preference (Patel, Khandelwal, et al., 2016). This section discusses the direct costs of the fuels under consideration. Table 3 combines firewood, crop residue, dung, coal, lignite, and charcoal as solid fuels. Any government subsidies for commercial cooking fuels (LPG, PNG, and electricity) have not been considered. More details on the subsidies and their implications for fuel adoption and the government budget are discussed in Section 2.4. Commercial fuel costs vary by region due to different tax structures and transportation costs from the production facility. Moreover, the electricity price within the same region varies inversely with the monthly usage to incentivize lower electricity consumption. Therefore, a national average of the pre-subsidized prices of these fuels was used for the cost analysis.

In the case of electricity, induction stoves were considered owing to their higher efficiency compared to typical coil-type electric stoves (Banerjee et al., 2016; Smith & Sagar, 2014). For biogas, the capital cost is based on 1 m^3 capacity, and dung is assumed to be free. Two types of stoves (improved and traditional) were considered for the cost analysis of the solid fuels. In urban areas, 9.5 % of households (6.9 million households) use solid fuels (Fig. 1) (IIPS et al., 2021), which are not readily available for free. Therefore, the analysis incorporated scenarios for solid fuels obtained at a cost (cases a-d). Fuel or operational cost is calculated by normalizing the market price of the fuel by its energy content. The cost per meal is based on useful energy obtained by adjusting the operational cost for the efficiency of the stove. The highest stove efficiency (energy used for cooking/energy released during combustion), based on commercially available stoves, is 84 % (electric induction stoves), followed by 60 % (both PNG and LPG) and 55 % (biogas) (Reddy, 2003). Solid fuel stoves demonstrate the lowest efficiency, which varies with stove and fuel type (Jetter et al., 2012). An average efficiency of 10 % for traditional stoves and 20 % for ICS were used.

Among the clean commercial fuels (LPG, PNG, and electricity), the fuel or operational costs (Table 3) are the lowest and highest for PNG (1.57 cents/MJ) and electricity (2.43 cents/MJ), respectively. LPG cost is a close second at 1.90 cents/MJ. Because similar stoves are used for LPG and PNG, the higher fuel cost is responsible for the higher per-meal cost associated with LPG. A detailed analysis of LPG and PNG, which are considered the top contenders for cleaner cooking fuel alternatives in India, is provided in the following sections. The cost per meal is zero for biogas (from dung), and a nominal cost of dung cake is assumed. The cost per meal discussed so far factored only the fuel and operational costs of the stove. Next, the average cost per meal, obtained by calculating the capital costs over the lifetime of the cooking system, is also presented in Table 3. Factoring in the capital costs over the lifetime of the cooking system did not significantly increase the cost per meal for LPG, PNG, electricity, and kerosene due to the long lifetime of the

Table 3
Different costs (capital, operation, and per meal) associated with using cooking fuels in India.

Fuel	Capital cost ($)[a]	Lifetime (years)	Stove efficiency (%)	FC (cents/MJ)[a]	OCPM (cents)[b]	LCPM (cents)[c]
Cleaner fuel alternatives						
LPG	25.00	15	60	1.90	31.67	31.89
PNG	25.00	15	60	1.57	26.17	26.39
Electricity[d]	37.50	12	84	2.43	28.93	29.36
Biogas[e]	162.50	15	55	0.00	0.00	1.48
Solid fuels[f]						
a) Firewood (freely available)	37.50	5	20	0.00	0.00	1.03
b) Dung Cake[g]	37.50	5	20	0.54	26.80	27.83
c) Coal	37.50	5	20	0.76	38.00	39.03
d) Firewood (commercial)	37.50	5	10	0.42	42.00	43.03

[a] All cost data is converted to USD with an exchange rate of INR 80 per USD.
[b] Calculated based on 10 MJ per meal per household after accounting for stove efficiency.
[c] Assuming two meals per day.
[d] Average cost of electricity.
[e] Estimates based on 1 m^3 capacity.
[f] Average price of a forced draft gasifier improved cookstove.
[g] Average cost of dung cake taken from (*Economics of cow dung - A commercialized VC with a huge green jobs potential*, n.d.)
Data sources (MNRE, 2023; Patel, Khandelwal, et al., 2016; Petroleum and Natural Gas M, 2023; Reddy, 2003).

cooking system, the low capital costs, or both. The cost per meal for biogas is the second lowest (1.48 cents per meal), assuming that feedstock is available for free, with freely available firewood being the lowest (1.03 cents per meal). All other cleaner fuel alternatives, i.e., LPG, PNG, and electricity, demonstrated comparable costs per meal. However, a definitive comparison between these three cannot be made as fuel prices differ throughout the country.

Cooking fuels: resource availability, demand, and policies

This section discusses the current status and future projections for LPG, PNG, biogas, and electricity in India, focusing on their supply (current production and imports) and demand (consumption). Government priorities, made evident by the current policies and various schemes, are also discussed. Based on the discussion, kerosene is not a suitable replacement for solid fuels; therefore, it will not be discussed in this section. However, a brief discussion on kerosene is available in Section S3.

Liquefied petroleum gas (LPG)

Many countries, including India, are aggressively promoting LPG to replace solid fuels using different strategies. The Brazilian government promoted the adoption of LPG through subsidies to reduce deforestation due to the high demand for fuel wood (Jannuzzi & Sanga, 2004). In contrast, the Indonesian government reduced subsidies on kerosene to promote LPG adoption and reduce the burden on the exchequer (Andadari et al., 2014; Budya & Yasir, 2011). Regarding increasing LPG adoption in India, subsidies have been used widely because a lack of purchasing power is perceived as the most common deterrent in transitioning from solid fuels to LPG. Nevertheless, studies have shown that other factors, such as improved fuel accessibility and a reliable supply, are critical too and sometimes more effective than subsidies (Dutta & Sahu, 2022; Patel, Khandelwal, et al., 2016; Sharma et al., 2020). The fraction of LPG in the cooking energy portfolio of India has increased from 24.7 % in 2005-06 to 57.7 % in 2019-21 (IIPS et al., 2006; IIPS et al., 2021), and recent data shows that almost every household has an LPG connection (Petroleum and Natural Gas M, 2023). However, the fuel stacking behavior in households using LPG (Gupta et al., 2020; Jha et al., 2021) is still significant. The main reasons are the unaffordability of LPG, freely or cheaply available biomass, taste preferences for cooked food, and a shortage in LPG supply.

The authors' analysis of the historical data obtained from the Ministry of Petroleum and Natural Gas, Government of India (Petroleum and Natural Gas M, 2023) indicates that LPG consumption in India has been increasing at an average annual rate of 7.7 % since 1997 (Fig. 3). However, LPG production (5.1 % annual increase) has not kept pace with the consumption. This shortfall has been met by LPG imports, increasing by 13.8 % annually (Fig. 3). In 2021-22, imported LPG fulfilled >60 % of the LPG consumption. Moreover, India imported 87.7 % of the crude oil; therefore, a significant fraction of domestic LPG production can be attributed to imported crude oil. After accounting for imported crude oil, Fig. 3 demonstrates the net LPG imports, i.e., direct and indirect imports. For 2021-22, the net imported LPG (after accounting for imported crude oil) constituted 96.5 % of the total consumption. The net imports of LPG have remained above 90 % for the last decade, demonstrating a high reliance on fuel imports to fulfill basic cooking needs. The LPG imports will tend to increase further as more and more households switch to LPG. For example, the sharp increase in consumption and import of LPG post-2015 (Fig. 3) is due to the implementation of PMUY (Pradhan Mantri Ujjawala Yojana) (Petroleum and Natural Gas M, 2023), which increased the LPG user base by 80 million within four years.

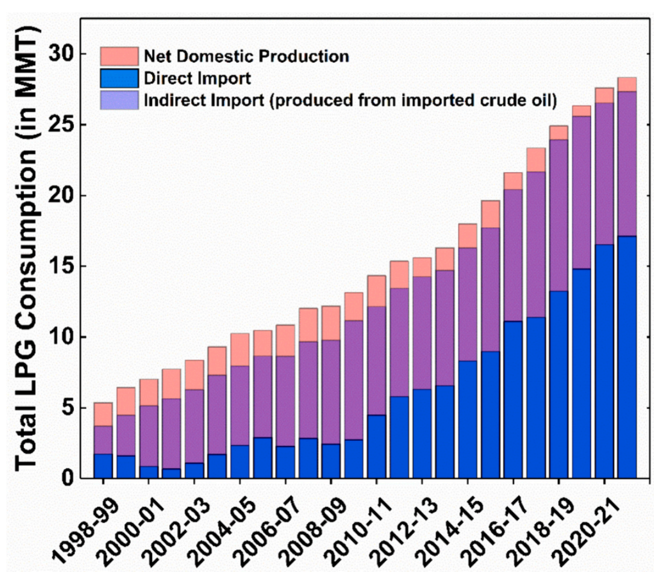

Fig. 3. Year-wise statistics of LPG consumption and net import. Net LPG import is the sum of LPG imported and LPG produced from imported crude oil as per the authors' analysis of data obtained from the Ministry of Petroleum and Natural Gas (Petroleum and Natural Gas M, 2023).

Fig. 4 presents the required amount of a fuel (LPG, PNG, electricity) in terms of its energy content and cost for two scenarios: (1) if all households were supplied these given fuels for cooking, and (2) if only those households currently using solid fuels were supplied the fuel. The analysis is based on the annual energy requirements of households for cooking and considers the energy efficiency of stoves and fuel calorific values that are also used in Table 3. If all households using solid fuels were to be provided with LPG (Case LPG2), the LPG supply would need to be more than doubled relative to the 2021-22 consumption level. Moreover, replacing solid fuels with LPG will annually add about 91 million metric tons of CO_2 to the environment, an increase of about 3.5 % on the current CO_2 emissions of India. It should be noted that the additional CO_2 emissions are just due to the combustion at the user end and do not include emissions related to LPG production and transportation.

From the policy perspective, the government of India started PMUY, which translates to Prime Minister's Bright Scheme, in May 2016. The PMUY targeted poor households categorized as below the poverty line (BPL) and aimed to provide LPG connections to 50 million households in the coming three years from its inception. Currently, 93.4 million active LPG connections have been distributed under the PMUY scheme (Fig. 5). This is the first-ever scheme by the government of India on this scale, explicitly targeting HAP for the welfare of women and children. Nevertheless, it is essential to understand what an active LPG connection in India means. A household consuming at least one cylinder per six months is categorized as an active user (Deccan Herald, n.d.). However, two cylinders per year for a family as small as four may be insufficient, indicating either fuel stacking or discontinued use of LPG. Thus, even though government records showed 136.5 million LPG connections in 2011 (Petroleum and Natural Gas M, 2023), only 70.4 million households reported using LPG for cooking regularly as per the 2011 Census of India (Government of India, 2011). More recent fuel usage patterns indicate that only 162.7 million households reported using LPG (IIPS et al., 2021), even though the reported LPG active users are >300 million. Fuel stacking or partial transition from LPG to solid fuels is also evident in Fig. 5, demonstrating a downtrend in LPG consumption per active user. One probable reason for this observation can be unaffordability as the BPL or even the low-income households will find it hard to afford even subsidized LPG.

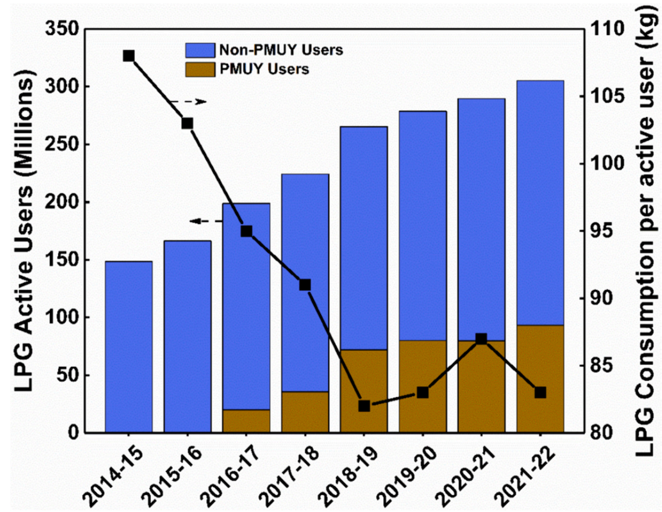

Fig. 5. Evolution of the LPG user base (left y-axis) and normalized LPG consumption (right y-axis) in India. The LPG user base is further bifurcated into PMUY and non-PMUY users after the PMUY was implemented in 2016-17 (Petroleum and Natural Gas M, 2023).

Similar schemes promoting LPG adoption and usage across the globe have not helped much in elevating energy poverty (Andadari et al., 2014; Coelho & Goldemberg, 2013; Jannuzzi & Sanga, 2004). The LPG program in Indonesia, a country with one-seventh the population of India and almost twice the per capita GDP, failed to reduce overall energy poverty substantially. However, such programs have effectively alleviated extreme energy poverty (Andadari et al., 2014). Similarly, in Brazil, the consumption of LPG increased in the early stages when the government encouraged the adoption through subsidies. However, subsidy removal led to declining LPG consumption and increasing fuelwood consumption (Coelho & Goldemberg, 2013).

In summary, while LPG will remain a part of India's clean cooking energy portfolio for the foreseeable future, in the long run, LPG may turn out to be accessible and affordable to households only at the upper end of the income spectrum. Though an important tool to manipulate consumer choice, subsidies might be unsustainable on the scale India envisions in the long run. Several other things to keep in mind: (1) India relies heavily on imports (>90 %) to fulfill the LPG demand, (2) mass usage of LPG will significantly increase India's GHG emissions, (3) the target households are susceptible to price changes, and finally, (4) the government initiative to promote LPG (PMUY) was not as effective as envisioned in reducing the energy poverty.

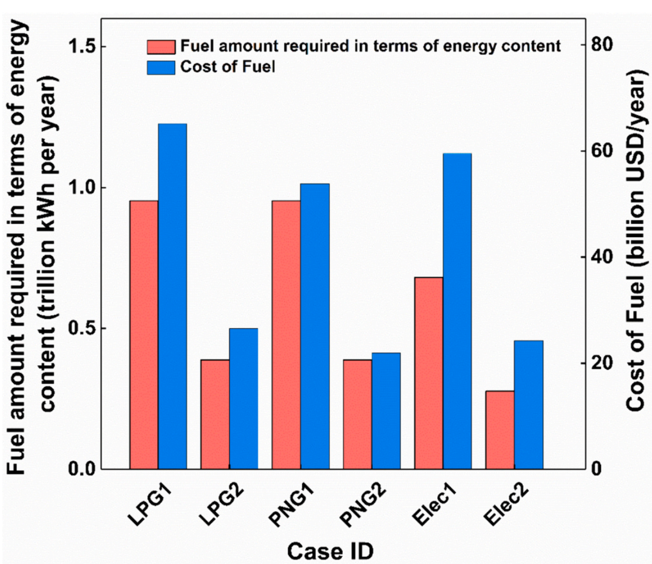

Fig. 4. Estimated amount (in terms of energy content) and cost of LPG, PNG, and electricity for two cases – (1) if all households are provided one of the fuels and (2) only solid fuel using households are provided one of the fuels. The cost estimations are based on the current (2022–23) pre-subsidy market price of LPG, PNG, and electricity. Case X1 and Case X2 mean if fuel X is provided to all and only solid fuel using households, respectively.

Natural Gas or Piped Natural Gas (PNG)

Natural gas or piped natural gas (PNG) is another potential cleaner cooking fuel alternative for India. PNG's combustion and emission characteristics are similar to those of LPG, but the cost per meal for PNG is lower (Table 3) based on dynamic market rates.

In 2021-22, only 6.3 % of the total primary energy consumption came from natural gas (Petroleum and Natural Gas M, 2023). Further, about 80 % of the natural gas in India in 2021-22 was consumed by industries such as fertilizer (29.4 %), refineries (8.6 %), and power (16.5 %) (Petroleum and Natural Gas M, 2023). The remaining 20 % was channelled via City Gas Distribution (CGD), which overlooks both the compressed natural gas (CNG) used as automobile fuel and piped natural gas (PNG) for domestic, commercial, and industrial use. Sector-wise bifurcated data for CGD distribution is not available. However, it can be reasonably said that only a small fraction of total PNG consumption is used for domestic cooking. From an infrastructure perspective, the length of the operational gas pipe network (as of September 2022) is

21,102 km, with a capacity of ~330 million metric standard cubic meters per day (MMSCMD) to supply both domestic and industrial consumers (Petroleum and Natural Gas M, 2023). In 2022, CGD operated in almost all the states and union territories and supplied PNG to 10.4 million households (Petroleum and Natural Gas M, 2023).

Based on 2022 data, India has a reserve of 1138.67 billion cubic meters (BCM) of natural gas, and 34.02 BCM was extracted in the same year (Petroleum and Natural Gas M, 2023). With the current reserves and extraction rate, domestic natural gas will last for only around 33 years. In terms of energy content, 35.17 BCM of natural gas, worth 21.93 billion USD, would be required every year if all households currently using solid fuels were to be transitioned to PNG for cooking (Fig. 4). Unless more domestic reserves are discovered importing more natural gas in the long-term is inevitable if PNG is to be considered as a viable cooking fuel alternative. Moreover, the analysis of the data obtained from the Indian Ministry of Petroleum and Natural Gas reports (Petroleum and Natural Gas M, 2023) demonstrates that the domestic production of natural gas has been declining steadily (annual average decline of 2.9 % since 2011-12), barring a few years where domestic production increased. At the same time, LNG imports have been increasing with an average annual rate of 5.9 % since 2011-12 to keep pace with declining domestic production. Reasons for declined production include natural depletion, underperformance, and closure of some wells due to technical issues and lower consumption. The government has planned to increase the share of natural gas in the energy basket from 6.3 % to 15 % by 2030 (Petroleum and Natural Gas M, n.d.). A fraction of this increase of PNG's share in the total energy portfolio might also be reflected in the domestic use of PNG as the government targets to connect ~120 million households through CGDs by 2030 (Petroleum and Natural Gas M, n.d.). The targeted penetration of PNG in the domestic sector is on par with the targets set up for LPG penetration under PMUY, which resulted in the addition of 80 million active users of LPG in four years.

The discussion indicates that even though the net consumption of natural gas is declining, India seems prepared to increase the natural gas supply to meet the targeted increase in the demand for cooking. However, capital-intensive infrastructure (pipe distribution network) can challenge realizing the set targets. As the penetration of PNG increases, a shift from LPG to PNG might occur, thus relieving some pressure from the constrained LPG supply. It would be interesting to observe whether current targets for PNG penetration in the cooking sector are realized and to analyze its impact on the overarching cooking energy portfolio. In summary, PNG is expected to grow its share in the cooking energy portfolio. However, it is subject to the same constraints as LPG: (1) energy security risks arising from the projected increase in imported natural gas, (2) the highly fluctuating price of natural gas, and (3) increased GHG emissions.

Biogas

In India, most residential-scale biogas systems are targeted to those households with bovines that provide a continuous supply of dung (MNRE, 2023). Biogas produces much lower emissions than burning dung directly (Pandey et al., 2014; Patel, Leavey, et al., 2016) due to its higher combustion and thermal efficiencies. The amount of energy generated per unit mass of dung burned directly is more than double that generated by the combustion of biogas produced from the same quantity of dung. However, the useful cooking energy per kg of dung is more than double that of biogas due to the much higher efficiency of a biogas stove (Rao et al., 2010). Moreover, the by-product of anaerobic digestion is manure, used to enrich the soil for agriculture, thus demonstrating commercial value and explaining the lowest (even negative) values for various environmental impact parameters discussed in Table 2. Previous studies have discussed the advantages, significant potential, and challenges associated with biogas (Aggarwal et al., 2021; Bhatia et al., 2020; Kothari et al., 2020; Talevi et al., 2022). A cost-benefit analysis model from the perspective of Indian households demonstrated that the benefits of biogas are the highest among all cooking fuel alternatives (Patel, Khandelwal, et al., 2016). However, households perceive the high capital cost of anaerobic digestor setup as critical when selecting fuel, and therefore, the one-time initial cost deters households from adopting biogas. Nevertheless, the long-term per-meal cost for biogas is lower than for any other clean cooking fuel due to the free availability of dung (Table 3).

The biggest factor against adopting biogas is the high capital cost and space required for the anaerobic digester (Patel, Khandelwal, et al., 2016). Apart from financial barriers, other variables, such as social and cultural, infrastructural, and informational barriers, limit the adoption of biogas (Hasan et al., 2020; Mittal et al., 2018; Mukeshimana et al., 2021). An adequate supply of water and substrate is critical for the effective functioning of biogas plants. Moreover, under-feeding or incorrect feeding ratios result in suboptimal performance of the biogas plants, resulting in dysfunctional plants. These failures create a negative perception of biogas technologies that discourage potential users. Large community and industrial-scale biogas plants are better equipped to ensure sustained operation. A summary of large-scale biogas plants and relevant policies is discussed in Section S4. However, household-scale biogas holds massive potential for clean cooking in India. As a part of the National Biogas Programme initiative, the government of India has set a target of installing ~29,700 subsidized small biogas plants in 2022-23 (Ministry of New and Renewable Energy, n.d.). This relatively modest target is not commensurate with the number of potential users. The subsidy level varies with factors such as the anaerobic digester size, region, and caste of the household members. The subsidies help households partially cover the high capital cost, an initial barrier to switching to biogas.

Given that the average cost per meal over the lifetime of the digester is the lowest among all cleaner commercial fuels (Table 3), even a non-subsidized biogas plant can be a profitable option for many households. Therefore, public outreach and awareness programs alone can lead to increased adoption of biogas as it is already the least expensive long-term fuel choice, even without subsidies. Several studies have highlighted the role of community empowerment, awareness, training, and education, focusing on women, in accelerating the adoption of biogas (Ahmad Romadhoni Surya Putra et al., 2017; Hasan et al., 2020; Mukeshimana et al., 2021; Raha et al., 2014). However, the current focus of government policies seems to be on LPG and PNG. In addition, policies to ensure sustained biogas use still need improvement.

In summary, biogas seems an ideal fuel for both cost and emissions. Freely available animal waste in rural households presents an excellent opportunity. Nevertheless, the rate of biogas adoption is low. Unlike continuous subsidies for other fuels, biogas subsidy is one-time financial assistance to cover the capital cost required for the anaerobic digester partially. It would be unrealistic to expect the government alone to realize the full potential of biogas generation. Though private companies have started entering this sector, the government can do more by formulating policies that fully exploit market forces to further disseminate biogas plants at centralized and decentralized levels (Raha et al., 2014; Schmidt & Dabur, 2014).

Electricity

As demonstrated in Section 2.3, the cooking cost per meal using electricity is comparable to that for LPG and PNG. End-use emissions are minimal for electric induction stoves (Section 2.1). Moreover, electricity has flexibility in its source, which could be both renewable and non-renewable, opening the possibility of energy self-sufficiency and carbon neutrality (Section 2.2). Electric cooking devices, i.e., induction stoves, are a mature technology, and many choices of manufacturers and models are now available at affordable prices on the Indian market. Therefore, electricity should be considered critical in India's clean cooking energy portfolio. In Ecuador, albeit a much smaller country than India, with a population of only 17.8 million, <1 % of households use solid fuels (Gould, Schlesinger, et al., 2020). However, Ecuador promoted electric induction stoves to reduce reliance on fossil fuels and LPG, aiming to provide 3.5 million units by 2023 (Gould, Schlesinger, et al., 2020). In developed nations like the USA, 63 % of households use electricity for cooking, and the remainder use natural gas and propane (U.S. Energy Information Administration (EIA), n.d.).

Electricity as a cooking fuel alternative has yet to receive much attention from India's government and policymakers. Although 98 % of Indian households have access to electricity, only 0.6 % (0.9 % urban and 0.5 % rural) use electricity for cooking (IIPS et al., 2021). Unlike all other cleaner fuel alternatives, the fraction of electricity in the cooking portfolio has been more or less stable in the last decade, signifying low adoption of electricity for cooking. One of the reasons for low adoption could be required changes in cooking style and transition to induction-compatible utensils. However, such hurdles can be overcome by outreach, support, and awareness programs.

An unreliable power supply in many states could be a crucial reason for the low adoption of electricity for cooking, even though all Indian states have achieved almost 100 % electrification (Agrawal et al., n.d.; Khanna & Rowe, 2024). Poor quality from the electricity grid discourages the customers from connecting more devices and using more electricity, resulting in low demand. Power outages due to shortages are common in many regions, especially in rural areas. Studies have also found that willingness to pay for electricity correlates strongly with supply reliability (Lee et al., n.d.; Grimm et al., 2020) and that satisfaction with electricity supply strongly correlates with reliability (Aklin et al., 2016). In Himachal Pradesh, among India's most electrified states, only 5 % of the households given an induction stove used it as their primary cooking stove (Banerjee et al., 2016). The observed trend was attributed to an unreliable supply of electricity.

As demonstrated in Fig. 4, the amount of energy required to supply all solid fuel using households is the lowest for electricity, which can be attributed to the high efficiency of induction stoves. India would require an extra 0.68 trillion kWh of electricity annually, worth 59.54 billion USD (based on the 2023 average market price), if all households were provided electricity for cooking (Fig. 4). The amount of electricity required by all households just for cooking is around 45 % of the current electricity production of India. It would require 0.28 trillion kWh of additional electricity annually, around 19 % of the current electricity production, to transition all households from solid fuels to electricity. From an emissions perspective, based on the ACI in 2022 (0.715 kg CO_2/kWh) in Fig. 2, an additional generation of 0.28 trillion kWh would lead to annual emissions of 200.2 million metric tons of CO_2, an underestimated figure since transmission and distribution losses are not accounted. If CO_2 emissions presented above were to be lower than those generated after transitioning all solid fuel users to LPG (91 million metric tons), the ACI needs to be lower than 0.325 kg CO_2/kWh. This steep reduction of almost 55 % might not be achievable if India continues to increase its reliance on coal and gas for electricity. In such a scenario, increasing the share of renewables in the electricity generation portfolio is the only option. Section S2 in SI briefly discusses the current scenario and future projections for renewable energy in India.

Apart from emissions, power distribution challenges associated with peak demand fluctuation and grid infrastructure are other challenges that need to be addressed for the mass adoption of electricity-based cooking devices. If the additional electricity requirement is evenly spread throughout the day, India's installed capacity is enough to fulfill the demand. However, cooking is short but energy-intensive, making it a high-power activity. Therefore, a surge in the peak demand for electricity, a critical parameter for power generation and grid management, will occur due to the small-time window in which most households cook their meals. A well-engineered power generation system and a smart grid will be necessary to tackle this issue. It is reasonable to say that centralized power generation and distribution systems might not be able to cope with the cooking-induced electricity demand. Therefore, decentralized power generation and storage must be considered as a tool for encouraging the adoption of induction stoves for cooking.

Decentralized power generation, especially renewable, has been growing fast in India and has many advantages over centralized power generation. Reduced transmission and distribution losses, lower infrastructure costs, and accessibility to remote areas are a few of them. The decentralized power generated can be used for cooking. Multiple studies have focused on the techno-economic feasibility of using PV arrays for cooking using induction stoves (Atmane et al., 2021; Lombardi et al., 2019; Ochoa Avilés et al., 2020; Sibiya & Venugopal, 2017). An Indian government initiative 'Surya Nutan' has developed a hybrid solar cooker that can work with solar energy and alternative fuels.

Moreover, off-grid solutions for cooking using electricity avoid load on already strained grids, as discussed previously. In addition to HAP mitigation, the biggest advantage of providing electricity, especially decentralized, is its indirect contribution to the growth of local economies. Though energy poverty does not always imply financial poverty, it usually does. Increased access to a reliable electricity supply and its consumption drives income growth (Coelho & Goldemberg, 2013; Shakouri et al., 2023; Shao, 2017). For example, decentralized power generation using biomass gasifiers generates direct employment opportunities and creates a market for solid fuels at a local level (Bhattacharya & Jana, 2009; Hiloidhari & Baruah, 2011; Somashekhar et al., 2000).

To summarise, electricity seems to be the best candidate among all the fuel alternatives for a long-term sustainable cooking energy option in all aspects. As the share of renewables increases in the electricity portfolio, the ACI will decrease further and achieve a level that is environmentally sustainable and reduces reliance on fossil fuels, thus increasing India's energy sovereignty. Decentralized electricity generation presents a ripe opportunity to target HAP.

Conclusion and policy implications

This paper presents a comparative analysis of solid fuels and cleaner cooking fuel alternatives (LPG, PNG, electricity, and biogas) in India from different perspectives, including emissions, health impacts, environmental impacts, cost, supply-demand imbalance, and relevant policies and regulations. Based on the usage pattern, projections, and government policies, LPG, PNG, and biogas are being promoted as cleaner alternatives to solid fuels. Among these, LPG and PNG are getting the most attention from the government and policymakers. Under PMUY, the active LPG user base has doubled in the last seven years since its inception. However, the annual LPG consumption per user has steadily declined from ~110 kg to ~80 kg in the same duration, possibly due to non-sustained use (complete abandonment or fuel stacking), owing to accessibility and affordability. While PMUY has promoted LPG consumption among middle-income households, low-income households still rely on solid fuels for cooking.

Though LPG and PNG are cleaner than solid fuels, their emissions can still have health implications. The mass-based PM emissions from LPG and PNG combustion are significantly lower than those of solid fuels. However, LPG and PNG emit ultrafine (mostly <20 nm) particles whose health effects are not yet fully understood. Further, LPG and PNG result in elevated NOx levels in indoor spaces, and exposure to them has been associated with respiratory and cognitive ailments. LPG and PNG are fossil fuels emitting GHGs during production, transportation, and end-use phases. Replacing current solid fuels with LPG will annually add about 91 million metric tons of CO_2 (just from combustion), translating to an increase of about 3.5 % of the country's CO_2 emissions. Besides health and environmental impacts, high reliance on imports for LPG (96.6 % import in 2021-22 accounting for imported crude oil) and PNG (48.4 % import in 2021-22) poses a national energy security risk and makes end users vulnerable to price volatility and supply reliability. The government has planned to increase the share of natural gas in the energy basket from 6.3 % to 15 % by 2030. The target is to connect ~120 million households through CGDs by 2030. However, with the current reserves and extraction rate, domestic natural gas will last for only around 33 years. High reliance on imports is inevitable unless more domestic natural gas reserves are discovered. While LPG and PNG will be a part of the cooking energy portfolio for the foreseeable future, the analysis indicates that both fuels are not suitable for playing a long-term role in the future of clean cooking.

From the perspective of Indian households, the benefits of biogas are the highest among all cooking fuel alternatives. However, the high capital cost, low feedstock availability and aggregation, and the upkeeping of anaerobic digestors deter households from adopting biogas. Nevertheless, the long-term per-meal cost for biogas is lower than for any other clean cooking fuel due to the free availability of dung. Biogas, due to its high methane content, can be directly used for cooking, electricity, and heat. The upgraded biogas with increased methane content (around 90 %) is equivalent to natural gas in calorific value and can be compressed for transportation like CNG and LPG. According to the Government of India, about 5 million biogas plants had been installed in the country by 2017-18. However, only 0.84 million Indian households reported using biogas in 2019-21. Compared to the number of households using biogas for cooking, the number of households using dung cakes is >13 times higher. India has massive potential for biogas generation with livestock of ~512 million. Therefore, biogas can potentially capture a significant share of the cooking energy portfolio, especially in rural India, and it offers India a cleaner alternative to its dependence on imported natural gas. However, its growth rate is too low, potentially due to the high capital cost of setting up, low feedstock, and upkeep of the anaerobic digestor. Since biogas is the cheapest cooking option in the long term, even without subsidies, public awareness and education can go a long way to promote its use.

Electricity is currently the least used for cooking (only 0.6 % of households in 2019-21), even though the per-meal cost for electricity is comparable to that for LPG and PNG based on the prevalent market prices. Electric induction stoves have the highest efficiency and zero emissions at the user end, primarily due to the lack of hot surfaces. Unreliable power supply and grid limitations are the major detriments of adopting electricity as cooking fuel. Even though the carbon intensity of electricity generation in India has been declining with the integration of renewable resources, the carbon intensity is still high. Electricity distribution is also challenging as the already strained electricity grid might not cope with cooking-induced excess peak demand. Despite these challenges, specific characteristics make electricity a promising option to achieve the goal of clean cooking that is sustainable in the long term. The carbon intensity of electricity can be further reduced by increasing the share of renewables. The central grid limitations can be overcome by decentralized power generation based primarily on renewables. Apart from a cleaner cooking fuel, electricity has the advantage of being useful for many other applications. Electrification with a reliable supply can act as an engine of growth, enabling the development of commercial activities at a local level.

Supply-demand analysis indicates that no single fuel alone can meet all the cooking energy requirements, at least in the near future. The cooking energy portfolio of India will be a mixed bag for a significant time to come. If the transition to cleaner fuel alternatives succeeds, cascading improvements on multiple fronts, such as health, environment, and economy, will positively translate to India's GDP in the long run. Further, transitioning more than a quarter of the world's solid fuel user population will have global implications, which might well outweigh the cost incurred. This analysis highlights multiple concerns over current energy policies and their implementation. Due to the scale and scope of the energy poverty leading to HAP, any initiative targeting it will necessarily be complex. Any fuel to mitigate HAP should be promoted based on a holistic and robust science-based assessment of fuel alternatives. While LPG and PNG are relatively cleaner, they might not be clean and sustainable enough. Biogas and electricity are promising yet untapped.

While this work does not address socio-cultural aspects that also affect a household's fuel choice, approaches such as in this work should be the guide for policies on fuel adoption. Socio-cultural aspects must be addressed for successful adoptions and retentions of cleaner fuel alternatives.

CRediT authorship contribution statement

Nishchaya Kumar Mishra: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Pratim Biswas:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Sameer Patel:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could potentially influence the reported work.

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Appendix A. Supplementary data

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