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Review of Cooking Fuel and the Level Of Carbon Imprint Associated with the Fuelling System Adopted

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Abstract: The choice of cooking fuel is a critical yet often overlooked aspect of our daily lives, with significant implications for both personal health and the environment. As households around the world seek efficient and accessible means to prepare meals, the impact of these fuel choices on carbon emissions and climate change becomes increasingly evident. This article aims to review various cooking fuels, ranging from traditional options like wood and charcoal to modern alternatives such as liquefied petroleum gas (LPG) and electricity. By examining the carbon imprints associated with each fuelling system, we will highlight the urgent need for sustainable alternatives and explore the broader implications for policy and community health. Through a comprehensive analysis that includes methodologies for assessing carbon emissions, case studies of successful fuel adoption, and recommendations for future practices, this article seeks to contribute to the dialogue on reducing our carbon footprint in the kitchen and beyond.

1. Introduction to Cooking Fuels and Their Environmental Impact

Cooking is an indispensable daily activity for billions worldwide, providing sustenance and cultural connection. However, the energy sources and technologies used for cooking vary widely, from rudimentary open fires to highly efficient electric induction stoves. This diversity in fuelling systems translates into a vast spectrum of environmental and health impacts, most notably concerning greenhouse gas (GHG) emissions and the associated carbon footprint. Globally, approximately 2.4 billion people still rely on polluting fuels such as wood, charcoal, animal dung, crop residues, and kerosene for cooking (IEA, 2023). This reliance on traditional biomass and inefficient combustive systems leads to severe indoor air pollution, causing millions of premature deaths annually, particularly among women and children, due to respiratory and cardiovascular diseases (WHO, 2022). Beyond health, the carbon imprint associated with these fuelling systems is a significant contributor to climate change and environmental degradation.

This paper aims to review the prevalent cooking fuels and their associated fuelling systems, analyzing their respective levels of carbon imprint. It will categorize the fuels, discuss the primary emissions from each system, and assess their environmental implications, providing a foundational understanding for policymakers, researchers, and practitioners working towards sustainable energy access and climate mitigation.

2. Literature Review and Theoretical Framework

Kimutai, Dushengere, and Muchilwa, (2025) emphasised that the Kenya's Kesses region, Uasin Gishu county, feasibility of a hybrid solar photovoltaic (PV)-biogas system with the aim of addressing the persistent shortage of energy access in rural communities. Energy demand, economic and environmental effects, resource potential, hybrid system modeling, and data collection from 100 families are all part of the study's objectives. With maize residues and bovine dung having biogas potentials of 88.08 and 309.7 m3/day, respectively, against the minimal need of 141.8 m3/day, an estimated 780 kg of firewood per day is required. There is a daily electrical requirement of 114.75 kWh.

An 18.20 kW converter, a 25.50 kW photovoltaic module, a 143-kWh battery, and a 3-kW biogas generator comprise the optimal HOMER (Hybrid Optimization of Multiple Energy Resources) configuration. The Levelized Cost Of Energy (LCOE) is 0.171$/kWh, and the Net Present Cost (NPC) is USD 183,558. Furthermore, research revealed that using biogas for cooking lowers CO2 emissions by 60,193.39 kg per year. Sensitivity analysis demonstrates that while a higher inflation rate has a double effect, biogas generating prices have no influence on NPC or LCOE. PV-Biogas hybrid systems offer a practical means of improving household livelihoods and electrifying rural areas.

Mangeni et al.(2025) observed that notwithstanding the well-known detrimental health impacts, almost 85% of people in sub-Saharan Africa (SSA) cook using polluting fuels like biomass and kerosene. To improve public health and safeguard the environment by halting deforestation, some countries in Sub-Saharan Africa are working to increase the use of liquefied petroleum gas (LPG), a fuel that burns cleaner in terms of black carbon and fine particulate matter emissions. By giving LPG a zero rating, the Kenyan government has been encouraging its quick expansion as a domestic fuel. More than 2000 families in a rural and peri-urban sub-county of Uasin Gishu County were given a census survey to identify the elements related to the major cooking fuel (biomass versus LPG) and cooking characteristics. About 28% (n = 629) of the families utilize clean fuels (86.8% LPG, 12.9% biogas/solar, and 0.3% electricity), whereas the majority (72%; n = 1619) use biomass as their primary fuel (86% wood, 12% charcoal, 1.5% wood chips, and 1% kerosene). The likelihood of using LPG was up to 2.5 times higher among peri-urban dwellers than among those in the rural sub-county. The number of days that LPG is used each week is influenced by supply considerations including simple access to refills. The government is urged to pass laws that would make more LPG refills available to remote areas, cutting down on travel time and expenses that could hinder access and lead to low usage.

Mekonnen (2025) stated that despite being mostly traditional, biomass fuel is still the main source of energy for households and requires careful development. Population expansion and the effects of deforestation make biomass fuels physically and financially limited. The researched work examined the energy consumption patterns of households, price trends, and the tree species that people prefer for wood fuel in Ziway town and the surrounding preurban areas. For the household survey, 120 households were chosen at random, 60 from each of the urban and preurban areas. For 15 days in a row, the town's biomass fuel input rate was also noted. According to the findings, a preurban home consumed 943 kg of biomass fuel annually, while an urban household consumed 726 kg. Firewood accounted for the majority of this fuel.

Davis, (2025) opined that In 1950, only 1% of American houses were heated by electricity; by 2020, that number had risen steadily to 40%. 90% of the rise can be explained by geography, climate, income, house characteristics, and energy prices, with energy prices being by far the most significant driver. The cost of requiring new dwellings to be electrified is then estimated in the report. Warm-state households would typically be less than $350 worse off each year since they prefer electricity nonetheless. However, those in colder states would be worse off by more than $1,000 a year because they tend to prefer natural gas.

Examined the prevalence of household solid fuel consumption in Somaliland and the characteristics related to this practice using data from the 2020 Somaliland Demographic and Health Survey. According to our data, only 2.8% of families use clean energy sources for cooking, while a startling 97.2% of households use solid fuels like wood and charcoal. To investigate the impact of both individual and community-level factors on fuel choice, we used multilevel logistic regression. The findings show that fuel choice is significantly influenced by factors such as cooking location, wealth position, gender of the family head, and educational attainment. To create a more sustainable energy landscape in Somaliland, the researched work highlights the importance of promoting clean energy alternatives, enhancing cooking techniques, and addressing the negative health and environmental effects of using solid fuels. It is in line with Sustainable Development Goal 7: Affordable and Clean Energy (Ali et al., 2025).

Table 1: Systematic literature Reviews on

Author & Year	Aim of Study	Fuel of Study	Identified Benefits	Reduction in Carbon Imprint	Location of Researchers
Kimutai, Dushengere, & Muchilwa, (2025).	Assessed the feasibility of a hybrid solar PV-biogas system	hybrid solar photovoltaic (PV)-biogas	Reduction carbon emission	Reduction of carbon imprint	Kenya
Mangeni et al.(2025)	To improve public health	Liquefied Petroleum Gas	By giving LPG a zero	Intense efforts to reduce carbon	Kenya/UK/Ghana

	and safeguard the environment.	(LPG)	rating	imprint.	
Mekonnen (2025)	Aims to evaluate the energy consumption patterns of households, and others	Biomass fuel	to reduce the amount of wood and energy lost	required high level of intervention from all stakeholders	Addis Ababa, Ethiopia
Davis, (2025)	calculates the price of requiring new dwellings to be electrified.	Electricity and other option of natural gas	Utilization is based on cost	The low sources have low carbon imprint.	USA
Ali et al. (2025)	Examined the prevalence of household solid fuel consumption in Somaliland	2.8% of families use renewable energy sources for cooking, while 97.2% of households use solid fuels	Affordable and renewable Energy highlights	Carbon imprint is high for solid fuel sources	Borama, Somaliland
Shi & Zhao, (2025).	Examined the traits and fundamentals underlying the growth of renewable energy and others	Renewable energy	Home energy transition that is low-carbon and green	Drive is on reduction of carbon imprint	Beijing, P. R. China
Eweade, Joof & Adebayo (2025).	Explores the relationship between biomass energy and economic expansion in India.	Natural gas, coal, and biomass	understanding the variables affecting India's economic growth.	The coal and biomass have high carbon imprint level compared to natural gas.	Mersin, Turkey
Ocen, Nkurunziza, Bagire, Echegu, Ssekakubo, & Atukunda, (2024).	Used a methodical approach to literature review	Solutions for clean cooking	Continued use of solid polluting fuels and technologies	High Carbon imprint is compared to clean energy	Uganda,
Mperejekuman, Shen, Gaballah & Zhong (2024).	Examined the possibilities /difficulties of energy transition in Sub-Saharan Africa.	Firewood and charcoal for cooking	Environmental deterioration due to various emissions	High Carbon imprint /negative health implications	China/USA
Ma et al.(2023)	China's efforts to improve air quality	Drive towards clean energy	The costs and health benefits	Project neutral carbon reduction	Beijing China
Farghali et al.(2023)	A call for an urgent need for new energy-saving technologies,	Hybrid heat pumps, geothermal heating, biomass boilers and and	Energy-saving measures revealed	Drive is to reduce carbon imprint	Japan/Egypt/UK/China

	stressed	others			
Khavari, Ramirez, Jeuland & Fuso Nerini, (2023).	Under Sustainable Development Goal (SDG) 7, for clean cooking fuel usage.	Cleaning cooking energies compared to biomass fuel utilization	Exploring the cost and benefits of clean fuel and others	clean energy carbon compared to dirty fuel	Sweden/USA
Ogundari, (2023).	Investigated the techno-economic parameters for a Waste-to-Suburban Cooking Energy	Waste to Energy	Environmental, and socioeconomic viable factors studied	Low Carbon imprint/solid waste to biogas revealed	Ile-Ife, Nigeria
Stritzke et al. (2023)	Examines in depth two novel strategies	Modern Energy Cooking (MEC)	benefits of switching from dirty to clean fuels	beam its searchlight carbon imprint reduction	UK
Hakam, Nugraha, Wicaksono, Rahadi, & Kanugrahan, (2022).	gives the economic assessment of induction stoves compared to others	Liquefied Petroleum Gas (LPG) and Electricity	Studied clean energy strategies	Studied means of reducing carbon imprint	Indonesia
Li, Wang, & Zhang (2022)	Evaluates the effects of different kinds of cooking fuels	Electricity comparison with Natural Gas	cut down on emissions	Electric cooking mode compared to Natural gas	China
Boudewijns et al. (2022)	In order to: assess the develop two useful implementation strategy to clean fuels	Transiting from solid fuels to cleaner solutions	Enhancing results related to gender equity plus other factors	l high carbon imprints compared to cleaner energy	Netherlands/Uganda
Endalew et al. (2022)	ascertained Ethiopia's level of solid fuel use and the elements that impact it.	Fuels classified as solids include coal, biomass, charcoal, wood, and straw.	Studied increase in public knowledge on the effects of solid fuels	High Carbon imprint / negative health impact shown	Gondar, Ethiopia
Leary, Leach, Batchelor, Scott & Brown (2021)	Examines a potentially revolutionary new strategy to use various cooking fuels	Lithium-ion batteries and solar PV	Benefits varies versus competitive market prices.	Carbon imprint compared to other sources of energy.	UK
Petrokofsky, Harvey, Petrokofsky,, & Ochieng, (2021).	systematic study on Modern Energy adoption.	Modern Energy	Cleaner fuel adoption strategies studied	Very High	UK/ Ireland;
Leary, Menyeh, Chapungu & Troncoso (2021)	Considers the main program that are far from cooking behavioral changes	electric Cooking, (eCooking)	Considers the main program that are far cooking behavioral	High level of carbon imprint reduction	UK

			changes		
Shupler, et al. (2021)	Examine a population-based survey on cooking habits in peri-urban areas	Use of LPG and other biomass fuel	Supply-side factors' significance in promoting clean cooking	Carbon imprint is very low as compared to biomass fuel	UK/ Kenya/ Ghana/ Cameroon
Billah, Islam, Tasnim, Alam, El Arifeen & Raynes-Greenow, (2020)	evaluated the characteristics that influence LPG uptake and usage	Migration from biomass fuels to Liquified Natural Gas(LNG) and dual usage	LPG consumption and its positive impact revealed.	Carbon imprint is low as compared to biomass fuel.	Bangladesh/ Australia
Gould et al. (2020)	A recent government initiative promoted the use of induction stoves and LPG.	Induction stoves and LPG.	significant health, climate, and environmental advantage revealed	serious drive to reduce carbon imprint revealed	USA/ Ecuador
Jagoe et al.(2020)	examined the effects of implementing a more effective biomass cooking	Biomass cooking fuel	The use of traditional means of cooking was the order of the day.	High level carbon emission/ negative health and environmental impacts.	USA/UK/Kenya
Simkovich et al. (2019)	Comprehensive analysis of clean fuel solutions	Reviewed of mix energy sources	Conserve time and money.	Observed mixed performance toward energy sources	USA/UK
Pradhan, Limmeechokchai& Shrestha, (2019)	examined how cooking with electricity and biogas affects energy consumption	Electricity and Biogas	Cost varies with fueling system used.	Carbon imprint with renewable energy sources compared	Thailand/ Nepal
Bhallamudi & Lingam (2019).	non-renewable energy sources and policies	Non-renewables (with national LPG initiatives revealed	Significant benefits for livelihoods, health, and climate change	Non renewable energy sources have high carbon imprint	USA/India
Astuti, Day & Emery (2019).	Examines the adoption of LPG by homes	Adoption of LPG from wood and kerosine	Studied primary factors influencing LPG resistance and others	LPG has low carbon imprint compared to biomass fuel.	Birmingham, UK
Yasmin & Grundmann (2019).	uses hybrid model to investigate users' ongoing attentions	Drive for energy transition from fossil fuel to renewable energy like biogas.	examined the adoption phenomenon of biogas technology with others	Biogas has lower carbon imprint as compared to fossil fuel	Germany
Bobner et al. (2019)	Analysed four residential biogas programs in operation	Biogas and other renewable energy	The results are applicable to Indonesia and other	There is serious drive toward reduction in carbon imprint in Indonesia.	UK/Canada/Sweden/Indonesia

			emerging nations		
Vigolo, Sallaku & Testa (2018)	to determine the primary motivators and obstacles to clean cooking	Use of better cooking stoves	Awareness of the risks of traditional cookstoves and others	traditional stoves compared to improved cooking stoves.	Verona, Italy
Goldemberg, Martinez-Gomez, Sagar, & Smith (2018).	aimed to increase household fuel economy by lowering exposure to air pollution	Transiting from biomass fuel to Liquefied Petroleum Gas(LPG)	Today's household energy access debate	High Carbon imprint from biomass fuel compared to LPG	Brazil/ Ecuador/ India/USA

Deduction from the systematic literature reviews:

1. The United Nation Sustainable Development Goal -7 which emphasize about access to affordable and clean energy for all, highlight where government and individuals with the awareness are working on having access to clean cooking energy.
2. The drive for clean and modern energy is a globally call to action and that why the studies about clean energy cut across researchers from different countries.
3. Carbon imprint if it is high has negative health and environmental effects, which we are expected to reduce the carbon effects and drive towards using clean and modern energy.

2.1 Traditional Fuels: Wood, Charcoal, and Kerosene

Traditional cooking fuels – primarily wood, charcoal, and kerosene – remain the primary energy source for billions worldwide, particularly in developing countries. Despite global advancements, an estimated 2.6 billion people, predominantly in Sub-Saharan Africa and parts of Asia, still rely on traditional biomass (wood, charcoal, agricultural waste) and fossil fuels like kerosene for their daily cooking needs (IEA, 2021). This reliance is not merely a matter of convenience; it is deeply intertwined with issues of health, gender equality, environmental degradation, and economic development. This section provides a comprehensive overview of wood, charcoal, and kerosene as traditional cooking fuels, detailing their characteristics, prevalence, advantages (from a user's perspective), and the significant drawbacks. It highlights the pervasive issue of indoor air pollution, deforestation, and the disproportionate burden these fuels place on women and children, underscoring the urgent need for a global transition to cleaner cooking energy solutions

2.1.1 Wood (Biomass)

Wood, in various forms such as logs, branches, twigs, and agricultural residues (e.g., crop stalks, animal dung), is the oldest and most widely used cooking fuel globally. It is the primary energy source for cooking for roughly a third of the world's population.

- **Nature and Usage:** Wood is a raw biomass fuel, typically collected from forests, woodlands, or farmlands. It is commonly burned in rudimentary "three-stone fires" or basic, inefficient mud or metal stoves. The collection process is often labor-intensive and time-consuming.
- **Perceived Advantages (from user perspective):**
  - **Availability:** Often locally available and free for collection, especially in rural areas.
  - **Affordability:** Low direct cash cost, making it accessible to the poorest households.
  - **Cultural Acceptance:** Deeply ingrained in many cultures and traditions, with established cooking practices and recipes optimized for wood fires.
  - **Renewability:** If harvested sustainably, wood is a renewable resource.
- **Disadvantages:**
  - **Inefficient Combustion:** Open fires and traditional stoves are highly inefficient, resulting in significant energy loss and the release of large quantities of smoke and harmful pollutants.

- **Indoor Air Pollution (IAP):** Burning wood produces high levels of particulate matter (PM2.5), carbon monoxide (CO), volatile organic compounds (VOCs), and other toxic substances. This IAP is a leading cause of premature deaths globally, particularly among women and young children who spend more time indoors.
- **Deforestation and Environmental Degradation:** Unsustainable harvesting of wood for fuel contributes to deforestation, forest degradation, loss of biodiversity, and soil erosion, exacerbating climate change through the release of greenhouse gases (GHGs) and black carbon.
- **Time Poverty:** Women and children, who are typically responsible for fuel collection, spend several hours daily gathering wood, detracting from education, income-generating activities, and leisure.
- **Safety Risks:** Open flames pose a risk of burns and house fires.

2.1.2. Charcoal

Charcoal is a solid fuel made by heating wood (or other biomass) in the absence of oxygen, a process called pyrolysis or carbonization. This process removes water and volatile compounds, resulting in a more carbon-dense fuel.

- **Nature and Usage:** Charcoal is essentially carbonized wood, appearing as black, porous briquettes or lumps. It is more compact and has a higher energy density per unit weight than raw wood, making it easier to transport and store. It is predominantly used in urban and peri-urban areas where wood collection is impractical, and income levels might allow for purchasing fuel. It is typically burned in metal stoves (e.g., jikos) or ceramic cookstoves.
- **Perceived Advantages:**
    - **Higher Energy Density:** Burns hotter and more consistently than wood, requiring less fuel by weight for the same cooking task.
    - **Less Smoke (during use):** Produces less visible smoke during combustion compared to raw wood, though it still emits significant amounts of CO and fine particulate matter.
    - **Transportability and Storage:** Easier to transport and store in urban settings due to its concentrated form.
    - **Quick Ignition and Sustained Heat:** Ignites relatively quickly and holds heat well, making it suitable for various cooking methods.
- **Disadvantages:**
    - **Inefficient and Polluting Production:** The traditional production of charcoal is highly inefficient, wasting up to 70-90% of the energy content of the wood. The kilns themselves are major sources of particulate matter, methane, and black carbon emissions.
    - **Intensified Deforestation:** The demand for charcoal drives significant commercial logging and deforestation, often more rapidly than direct wood usage for cooking, as it caters to densified urban populations.
    - **Cost:** Charcoal is a purchased fuel, representing a substantial economic burden for many low-income urban households.
    - **Indoor Air Pollution:** While less smoky than wood fires, charcoal combustion still releases harmful pollutants like CO, PM2.5, and polycyclic aromatic hydrocarbons (PAHs), contributing significantly to IAP and associated health issues.
    - **Safety Risks:** High carbon monoxide concentrations and the risk of burns are prevalent.

2.1.3. Kerosene

Kerosene, a petroleum-based liquid fuel, is another widely used traditional cooking fuel, particularly in urban and peri-urban areas where solid fuels may be scarce or perceived as less convenient. It is also extensively used for lighting.

- **Nature and Usage:** Kerosene is a clear, flammable liquid derived from crude oil. For cooking, it is typically used in wick stoves or pressure stoves, which are relatively compact and portable.
- **Perceived Advantages:**
  - **Convenience and Cleanliness (initial perception):** Liquid fuel, easy to store, pour, and ignite. Perceived as "cleaner" than solid fuels due to less visible smoke.
  - **Availability:** Readily available in many markets and shops, even in remote areas due to its use for lighting.
  - **Portability:** Kerosene stoves are generally small and lightweight.
  - **Quick Cooking:** Heats up relatively fast.
- **Disadvantages:**
  - **High Flammability and Safety Risks:** Kerosene is highly flammable, posing significant risks of accidental fires, explosions, and severe burns. Accidental ingestion, particularly by children, can be fatal.
  - **Indoor Air Pollution:** Despite less visible smoke, kerosene combustion produces significant levels of fine particulate matter (PM2.5), sulfur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), and black carbon. These pollutants contribute to respiratory illnesses, eye irritation, and cardiovascular problems.
  - **Cost Volatility:** Kerosene prices are subject to global oil market fluctuations, making it an unpredictable and often expensive fuel for low-income households.
  - **Fumes and Odor:** Emits a distinct, often unpleasant odor, and its fumes can cause headaches and nausea.
  - **Environmental Impact:** As a fossil fuel, its combustion contributes to greenhouse gas emissions and climate change. Black carbon emissions from kerosene lamps and stoves are also potent short-lived climate pollutants.

2.1.4. Cross-Cutting Impacts and Challenges

The continued reliance on wood, charcoal, and kerosene for cooking creates a nexus of interconnected challenges:

- **Health Crisis:** Indoor Air Pollution (IAP) from these fuels is the fourth leading risk factor for premature death globally, responsible for an estimated 2.3 million deaths annually (WHO, 2022). It causes acute respiratory infections (ARIs) in young children, chronic obstructive pulmonary disease (COPD), lung cancer, cardiovascular disease, and adverse birth outcomes in adults.
- **Environmental Degradation:** Unsustainable biomass harvesting leads to deforestation, habitat loss, and reduced carbon sequestration. The black carbon emitted from inefficient combustion is a potent climate forcing agent, second only to CO2 in its warming impact.
- **Socio-Economic Burden:** The time spent collecting fuel or the money spent purchasing it creates a significant economic drain on impoverished households. The health impacts reduce productivity and increase healthcare costs. Girls, often burdened with fuel collection, miss out on education.
- **Gender Inequality:** Women are disproportionately affected by the health consequences of IAP due to their primary role in cooking and spend countless hours on fuel collection, perpetuating a cycle of poverty and limiting their empowerment.

2.2 Modern Fuels: LPG, Natural Gas, and Electricity

The 20th and 21st centuries have seen the widespread adoption of specific triads modern fuels that have revolutionized domestic and commercial kitchens: Liquefied Petroleum Gas (LPG), Natural Gas, and Electricity. These fuels offer a significant departure from traditional methods, providing enhanced convenience, superior control, and often improved indoor air quality. However, each of this modern fuel sources presents a unique set of characteristics regarding availability, cost, convenience, environmental impact, and safety. This section provides a comprehensive overview of these three contemporary cooking fuels, examining their fundamental properties, advantages, disadvantages, and the broader implications of their use. By analyzing their respective profiles, this paper aims to illuminate the complex considerations involved in fuel selection for residential and commercial cooking applications globally.

2.2.1 Liquefied Petroleum Gas (LPG)

LPG is a flammable mixture of hydrocarbon gases, primarily propane and butane, or a mixture of the two, used as fuel in heating appliances, vehicles, and increasingly as an aerosol propellant and refrigerant. It is a by-product of natural gas processing and petroleum refining. At normal atmospheric pressure and temperature, LPG is a gas, but it can be liquefied at relatively low pressures, enabling its storage and transport in liquid form in cylinders or bulk tanks.

(i). Production and Supply Chain

LPG is obtained from two main sources: extraction from natural gas streams (approximately 60%) and as a by-product of crude oil refining (approximately 40%). Once produced, it is typically transported via pipelines, ships, or trucks to distribution centers, where it is bottled into cylinders of various sizes or loaded into bulk tanks for commercial and industrial users. The cylinder-based distribution model makes LPG highly portable and accessible even in areas without pipeline infrastructure.

(ii). Advantages

- **Portability and Accessibility:** Stored in cylinders, LPG can be readily transported and used in homes, remote areas, and for outdoor activities like camping. It is the dominant modern cooking fuel in many developing countries without extensive natural gas grids.
- **High Energy Density:** LPG offers a high energy content per unit volume, making it efficient for cooking and heating.
- **Instant Heat and Control:** Similar to natural gas, LPG provides instant flame ignition and precise temperature control, appealing to professional chefs and home cooks alike.
- **Clean Burning:** Compared to solid fuels like wood or coal, LPG burns much cleaner, reducing indoor air pollution (soot, particulate matter) and associated health risks.

(iii). Disadvantages

- **Safety Concerns:** Being highly flammable and heavier than air, LPG can accumulate in low-lying areas in case of a leak, posing a significant explosion risk. Safe storage, handling, and ventilation are paramount.
- **Refilling Inconvenience:** Users are dependent on a supply chain for cylinder refills, which can be inconvenient and lead to interruptions in supply.
- **Price Volatility:** LPG prices are often linked to global crude oil prices, making them subject to fluctuations.
- **Carbon Emissions:** While cleaner than solid fuels, LPG is still a fossil fuel and releases carbon dioxide (CO_2) upon combustion, contributing to greenhouse gas emissions.

2.2.2. Natural Gas

Natural gas is a naturally occurring hydrocarbon gas mixture consisting primarily of methane (CH_4), with varying amounts of other higher alkanes, and sometimes a small percentage of other gases like carbon dioxide, nitrogen, helium, and hydrogen sulfide. It is formed deep beneath the Earth's surface from the decomposition of organic matter over millions of years.

(i). Production and Supply Chain

Natural gas is extracted from underground reservoirs through drilling. Once extracted, it undergoes processing to remove impurities and higher hydrocarbons, making it pipeline-quality gas. It is then transported through extensive networks of pipelines directly to homes and businesses. This "on-demand" delivery system is a key differentiator from LPG.

(ii). Advantages

- **Continuous Supply:** Unlike LPG, natural gas provides an uninterrupted supply directly to the appliance, eliminating the need for cylinder refills.
- **Cost-Effective:** In many regions, natural gas is the most economical cooking fuel due to its direct pipeline delivery and vast reserves.
- **Convenience:** Users do not need to manage fuel storage or worry about running out of gas.
- **Environmental (Point of Use):** Natural gas burns very cleanly, producing fewer pollutants (particulate matter, carbon monoxide) at the point of combustion compared to LPG or biomass. Methane is a potent greenhouse gas, but CO_2 emissions from methane combustion are lower than other fossil fuels per unit of energy produced.

(iii). Disadvantages

- **Infrastructure Dependent:** Natural gas requires a robust and extensive pipeline network, limiting its availability to urban and suburban areas that have been developed with this infrastructure. Rural or remote areas typically lack access.
- **Fixed Appliance Location:** Appliances powered by natural gas are permanently connected to the gas line, limiting their mobility within a kitchen setup.
- **Potential for Leaks:** While treated with an odorant (mercaptan) for detection, natural gas leaks can pose explosion risks if not addressed promptly. Methane leaks are also a significant contributor to global warming due to methane's high global warming potential.
- **Initial Hook-up Costs:** Connecting to a natural gas line can involve significant initial installation costs if the property is not already plumbed for it.

2.2.3 Electricity

Electricity, as a cooking fuel, refers to the use of electrical energy to generate heat. Unlike gas fuels which rely on combustion, electric cooking appliances convert electrical energy into thermal energy. There are primarily three types of electric cooking technologies:

- **Resistive Electric:** Coils or elements heat up when electricity passes through them, transferring heat to cookware via conduction and radiation (e.g., traditional electric coil stoves, ceramic cooktops).
- **Halogen Electric:** Similar to resistive, but uses halogen lamps to generate radiant heat quickly, often under a ceramic glass surface.
- **Induction:** This revolutionary technology uses an electromagnetic field to directly heat the ferromagnetic cookware itself, rather than the cooktop. This is highly efficient and offers precise temperature control.

(i). Production and Supply Chain

Electricity is generated in power plants using various primary energy sources (fossil fuels like coal and natural gas, nuclear, hydropower, solar, wind, geothermal). It is then transmitted through a vast grid of power lines to consumers. The environmental impact of electric cooking is therefore highly dependent on the energy mix of the local power grid.

(ii) Advantages

- **Safety:** No open flames, no risk of gas leaks, and many electric stoves include safety features like automatic shut-off and residual heat indicators.
- **Cleanliness (Point of Use):** Electric cooking produces no direct emissions or combustion by-products (e.g., carbon monoxide, nitrogen oxides) in the kitchen, leading to superior indoor air quality.

- **Temperature Control and Precision:** Especially with induction technology, electric stoves offer unparalleled temperature precision and rapid response, allowing for fine-tuned cooking.
- **Ease of Cleaning:** Flat, smooth ceramic and induction cooktops are significantly easier to clean than gas burners and grates.
- **Environmental (Grid Dependent):** As electricity grids transition towards renewable energy sources, electric cooking becomes increasingly environmentally friendly, offering a pathway to zero-emission cooking.

(iii). Disadvantages

- **Power Outage Vulnerability:** Electric cooking is entirely dependent on the continuous supply of electricity from the grid, making it unusable during power outages.
- **Energy Source Emissions:** While clean at the point of use, the upstream emissions from electricity generation (especially from coal or natural gas power plants) can be significant, making its overall environmental footprint variable.
- **Initial Heating Time (Resistive):** Traditional resistive electric coil stoves can be slower to heat up and cool down compared to gas flames. Induction technology mitigates this.
- **Specific Cookware (Induction):** Induction cooktops require ferromagnetic cookware (e.g., cast iron, stainless steel with a magnetic base), which may necessitate replacing existing pots and pans.
- **Operating Costs:** In many regions, the cost of electricity per unit of energy can be higher than natural gas or LPG, leading to higher operating costs.

2.2.4. Comparative Analysis

Shown in Table 2 is detailed comparative analysis for LPG, Natural Gas and Electricity

Table 2: Coparative Analysis of LPG, Natural Gas and Electricity

Feature	**LPG**	**Natural Gas**	**Electricity (General/Induction)**
Availability	Widespread (cylinder-based)	Grid-dependent (urban/suburban)	Grid-dependent (near universal in developed)
Convenience	Cylinder refills needed	Unlimited supply, no refills	Unlimited supply, no refills
Initial Cost	Low appliance cost, cylinder deposit	Moderate (installation & appliance)	Moderate to High (appliance specific)
Operating Cost	Moderate, price volatile	Low to Moderate, stable	Moderate to High, depends on grid rates
Heat Control	Instant, precise flame	Instant, precise flame	Slower (resistive), Highly precise (induction)
Energy Efficiency	Good	Good	Good (resistive), Excellent (induction)
Safety	Flammable gas, heavy (sinks), explosion risk	Flammable gas, lighter (rises), explosion risk	No open flame, no gas leaks, burn risk from heat
Indoor Air Quality	Low emissions (with ventilation)	Very low emissions (with ventilation)	Zero point-of-use emissions
Environmental Footprint	Direct CO2 emissions	Direct CO2 emissions (lower/unit), Methane leaks	Upstream emissions from power generation (variable)

Feature	LPG	Natural Gas	Electricity (General/Induction)
Cookware	Any	Any	Any (resistive/ceramic), Ferromagnetic (induction)
Mobility	High (portable cylinders)	Low (fixed connection)	Low (fixed connection)
Outage Impact	Independent	Independent	Dependent

2.2.5. Broader Implications

(i). Environmental Impact

The environmental footprint of cooking fuels is a critical consideration. While LPG and Natural Gas are fossil fuels that release carbon dioxide and other greenhouse gases upon combustion, their direct emissions are significantly lower than traditional biomass. However, methane leaks from natural gas infrastructure (a potent greenhouse gas) are a concern. Electric cooking, on the other hand, is emission-free at the point of use, making its overall environmental impact dependent on the utility's electricity generation mix. A grid powered by renewable sources (solar, wind, hydro) makes electric cooking the most environmentally sustainable option. The global push towards decarbonization favors electrification.

(ii). Health and Safety

Indoor air pollution from combustion of fuels like biomass, kerosene, and even poorly ventilated gas stoves is a major health concern, contributing to respiratory illnesses. LPG and Natural Gas are cleaner burning, but still produce nitrogen oxides (NOx) and carbon monoxide (CO) if ventilation is inadequate. Electric cooking eliminates these direct indoor emissions, contributing to healthier indoor environments. Safety-wise, both gas fuels pose risks of leaks, fires, and explosions, necessitating strict safety protocols. Electric appliances carry risks of electrical shock or burns from hot surfaces, but generally present fewer immediate catastrophic risks than gas leaks.

(iii) Socio-economic Factors

Access to modern cooking fuels is unevenly distributed globally. In many developing nations, LPG has been a vital bridge fuel, moving households away from traditional biomass and reducing fuel gathering burdens, empowering women, and improving health. Natural gas access is largely dictated by infrastructure development, often limited to affluent urban areas. Electricity, while more widespread than piped natural gas, can be unreliable in many regions, and its cost can be prohibitive for low-income households. Policy decisions, subsidies, and infrastructure investments play a crucial role in ensuring equitable access to clean cooking energy.

2.3 Emerging Fuels: Biofuels and Renewable Energy Sources

The world's energy landscape is undergoing a profound transformation driven by two critical forces: the escalating climate crisis, necessitated by greenhouse gas emissions from fossil fuels, and the growing demand for secure, diverse energy supplies. As a result, "emerging fuels" – novel energy carriers and sources that promise lower environmental impact and greater sustainability – are gaining unprecedented attention. While the term encompasses a broad range, including synthetic fuels, hydrogen, and advanced nuclear, this paper primarily focuses on biofuels due to their direct potential to replace liquid fossil fuels in existing infrastructure, and their intrinsic connection to the wider renewable energy portfolio.

This section provides an overview of these emerging fuels, with a specific focus on biofuels, examining their various generations, advantages, and inherent challenges. It further explores how biofuels integrate within the broader landscape of renewable energy technologies, highlighting the synergies and overarching challenges faced in the transition towards a sustainable energy future.

2.3.1 Emerging Fuels and Their Imperative

Emerging fuels are defined as energy sources or carriers that are either new in their technology or application, or are rapidly gaining prominence as alternatives to conventional fossil fuels. They are characterized by their potential to significantly reduce carbon emissions, improve energy independence, and offer more sustainable pathways for energy production and consumption. The imperative for their development stems from several pressing global challenges:

- **Climate Change Mitigation:** Decarbonization of the energy sector is crucial to limit global warming. Emerging fuels, particularly those derived from renewable sources, offer pathways to significantly reduce net greenhouse gas emissions.
- **Energy Security and Diversification:** Reducing reliance on geographically concentrated fossil fuel reserves enhances national energy security and mitigates geopolitical risks associated with energy supply chains.
- **Environmental Protection:** Beyond climate change, emerging fuels can lead to reduced air pollution, improved water quality, and minimized environmental degradation associated with fossil fuel extraction and processing.
- **Economic Opportunity:** The development and deployment of new energy technologies can spur innovation, create new industries, and generate employment opportunities.

Among emerging fuels, biofuels stand out due to their chemical similarity to conventional liquid fuels, enabling their potential use in existing transportation infrastructure, albeit with varying degrees of modification.

2.3.2 Biofuels: A Deep Dive

Biofuels are liquid, gaseous, or solid fuels derived from biomass, which is organic matter from plants or animals. Unlike fossil fuels, which are formed over millions of years, biomass is a renewable resource, theoretically replenished over short timescales. The primary goal of biofuels is to provide carbon-neutral or low-carbon alternatives to gasoline, diesel, and jet fuel, reducing lifecycle greenhouse gas emissions.

(i). Generations of Biofuels

The development of biofuels has evolved through several "generations," each addressing limitations of its predecessors and aiming for improved sustainability and efficiency:

(a) **F irst Generation Biofuels:**

- **Feedstocks:** Primarily derived from food crops rich in sugar (e.g., sugarcane, corn, sugar beet), starch (e.g., wheat, maize), or vegetable oils (e.g., rapeseed, soybean, palm oil).
- **Examples:** Bioethanol (from fermentation of sugars/starches) and Biodiesel (from transesterification of vegetable oils or animal fats).
- **Advantages:** Relatively mature production technologies, readily available feedstocks in many regions, and immediate potential for fossil fuel displacement.
- **Challenges:** The "food vs. fuel" debate (competition for land and resources with food production), significant land and water footprints, potential for indirect land use change (ILUC) leading to deforestation, and often limited net greenhouse gas reductions when ILUC is considered.

(b) **Second Generation Biofuels:**

- **Feedstocks:** Derived from non-food biomass, primarily lignocellulosic materials such as agricultural residues (corn stover, wheat straw), dedicated energy crops (switchgrass, miscanthus), forestry waste, and municipal solid waste.
- **Examples:** Cellulosic ethanol, advanced biodiesel, and "drop-in" hydrocarbon fuels (e.g., bio-jet fuel, bio-gasoline) produced via thermochemical processes like gasification followed by Fischer-Tropsch synthesis, or biochemical pathways.
- **Advantages:** Alleviate the food vs. fuel conflict, potentially offer higher greenhouse gas savings due to utilizing waste or non-arable land, and can diversify feedstock sources.

- **Challenges:** More complex and costly production processes (requiring advanced pre-treatment and conversion technologies), still require significant land and water resources, and commercial-scale production remains challenging.

(c)Third Generation Biofuels:

- **Feedstocks:** Primarily microalgae and macroalgae (seaweed).
- **Examples:** Algal biodiesel, bio-jet fuel, bioethanol, and biomethane.
- **Advantages:** High growth rates and oil yields per acre compared to terrestrial crops, do not compete for arable land, can utilize wastewater or saltwater, and can sequester CO2 from industrial sources.
- **Challenges:** High capital and operating costs, energy-intensive harvesting and processing, susceptibility to contamination, and limited commercial scalability to date.

(d) Fourth Generation Biofuels (Emerging Concepts):

- **Feedstocks:** Focus on synthetic biology and genetic engineering to enhance biomass production or convert CO2 directly into fuels. Includes advanced microbial fuels, genetically engineered algae, and "power-to-liquid" fuels where renewable electricity powers the conversion of CO2 and water into synthetic hydrocarbons.
- **Examples:** Biofuels from engineered microbes, direct CO2 utilization to produce fuels.
- **Advantages:** Potentially ultra-high efficiency, truly carbon-negative (if CO2 is captured and utilized), minimal land/water footprint, and potentially customized fuel properties.
- **Challenges:** Still in early research and development stages, high R&D costs, public acceptance issues regarding GMOs, and significant technological hurdles for commercial viability.

2.3.3. Advantages of Biofuels

Despite the complexities, biofuels offer several compelling advantages:

- **Reduced Greenhouse Gas Emissions:** When sustainably produced, biofuels can significantly reduce net lifecycle GHG emissions compared to fossil fuels, contributing to climate change mitigation.
- **Energy Security and Independence:** Domestically produced biofuels can reduce reliance on imported oil, enhancing national energy security and stabilizing energy prices.
- **Rural Economic Development:** Biofuel production can stimulate agricultural sectors, create jobs in rural areas, and provide additional revenue streams for farmers.
- **Compatibility with Existing Infrastructure:** Ethanol and biodiesel can be blended with conventional fuels, and in some cases, "drop-in" biofuels can be used without substantial modifications to engines or distribution infrastructure.
- **Waste Utilization:** Second-generation biofuels, in particular, can utilize agricultural residues and municipal waste, converting waste streams into valuable energy products.

2.3.4. Challenges and Criticisms of Biofuels

The path to widespread biofuel adoption is fraught with challenges and criticisms:

- **Food vs. Fuel Debate:** The most prominent concern, particularly for first-generation biofuels, is the competition for arable land and crops with food production, potentially leading to increased food prices and food insecurity.
- **Land Use Change and Deforestation:** Expansion of biofuel crop cultivation can lead to direct and indirect land-use change, including deforestation, biodiversity loss, and release of carbon stored in soils and forests.
- **Water Footprint:** Many biofuel crops are water-intensive, exacerbating water scarcity issues in certain regions.

- **Energy Balance (EROEI):** The energy return on investment (EROEI) for some biofuels can be low, meaning the energy input required for production (fertilizers, processing, transport) can sometimes outweigh the energy output of the fuel itself.
- **Cost Competitiveness:** Biofuels often struggle to compete with inexpensive fossil fuels without government subsidies or mandates.
- **Logistics and Infrastructure:** Reliable and efficient supply chains for diverse biomass feedstocks are essential but challenging to establish and maintain.
- **Sustainability Certification:** Ensuring that biofuels are truly sustainable and deliver genuine environmental benefits requires robust certification schemes and regulatory oversight.

2.2.5. Renewable Energy: The Broader Landscape

Biofuels are an important component of the broader renewable energy landscape. Renewable energy refers to energy derived from natural processes that are replenished constantly, such as sunlight, wind, water flow, geothermal heat, and biomass. While biofuels address the need for liquid fuels, other renewable energy technologies primarily focus on electricity generation and heat.

- **Solar Energy:** Harnessing sunlight through photovoltaic (PV) panels for electricity or concentrated solar power (CSP) for heat and power generation.
- **Wind Energy:** Converting wind kinetic energy into electricity using wind turbines (onshore and offshore).
- **Hydropower:** Generating electricity from the kinetic energy of flowing water, ranging from large-scale dams to run-of-river systems.
- **Geothermal Energy:** Utilizing heat from the Earth's interior for electricity generation or direct heating.
- **Biomass (for Heat and Power):** Beyond liquid fuels, biomass can be directly combusted for heat, co-fired in power plants with coal, or converted into biogas for electricity and thermal energy.

2.2.6 The Interconnection: Biofuels within Renewable Energy Biofuels are fundamentally a part of the renewable energy portfolio. They address the critical need for sustainable energy carriers in sectors like transportation (road, air, maritime), where direct electrification is challenging or not yet feasible. While solar and wind primarily electrify grids, biofuels offer a "drop-in" or near "drop-in" solution for liquid fuel demands.

This interconnectedness means that the success of biofuels is often tied to the overall progress of renewable energy. For instance, surplus renewable electricity could be used to produce hydrogen for advanced synthetic fuels (a form of 4th generation biofuels or e-fuels), or to power energy-intensive biofuel production processes, enhancing their overall energy balance and sustainability. A holistic approach to renewable energy aims to decarbonize all sectors, with each technology playing a complementary role.

2.3.7. Synergies, Challenges, and Opportunities for the Energy Transition

The transition to a sustainable energy future requires a multi-faceted approach, leveraging the synergies between various emerging fuels and renewable technologies while addressing common challenges.

(i). Synergies

- **Diversification:** A diversified portfolio of renewables (solar, wind, hydro, geothermal, and biofuels) enhances grid stability, energy security, and resilience against resource intermittency or supply chain disruptions.
- **Sectoral Decarbonization:** Different renewables are best suited for different sectors. Biofuels are crucial for "hard-to-abate" transport sectors, while solar and wind excel in electricity generation.
- **Circular Economy:** Advanced biofuels and biomass for energy production can integrate with waste management strategies, turning organic waste into valuable energy products.

- **Hybrid Systems:** Decentralized energy systems can combine, for example, solar PV with biomass generators or biofuel-powered generators to ensure resilient, off-grid power.

(ii) Overarching Challenges

- **Infrastructure Transformation:** The existing energy infrastructure is built around fossil fuels. Transitioning to renewable energy requires massive investments in new transmission grids, charging stations, refueling depots for alternative fuels, and smart grid technologies.
- **Cost Competitiveness:** While costs for some renewables (solar, wind) have plummeted, others, including advanced biofuels, still face higher production costs compared to fossil fuels, necessitating policy support.
- **Energy Storage:** The intermittent nature of solar and wind power necessitates robust and affordable energy storage solutions (batteries, hydrogen, pumped hydro) to ensure grid stability.
- **Policy and Regulatory Frameworks:** Stable, long-term policy incentives, carbon pricing mechanisms, and supportive regulations are crucial to de-risk investments and accelerate deployment.
- **Public Acceptance:** Addressing concerns related to land use, environmental impacts, and economic implications of the energy transition is vital for public support.
- **Global Equity:** Ensuring that the benefits of the energy transition are accessible to all nations, particularly developing ones, will be critical for a just and equitable transition.

(iii) Opportunities

- **Technological Breakthroughs:** Continuous R&D in areas like advanced catalysts for biofuel production, high-efficiency solar cells, advanced battery chemistries, and carbon capture utilization offers immense potential.
- **Job Creation:** The renewable energy sector is a significant source of new jobs in manufacturing, installation, operation, and maintenance.
- **Improved Public Health:** Reduced air pollution from burning fossil fuels leads to fewer respiratory and cardiovascular diseases, offering significant public health benefits.
- **Enhanced Geopolitical Stability:** Reduced reliance on fossil fuel imports can lead to a more stable and less conflict-prone global energy landscape.
- **Development of Biorefineries:** Integrated biorefineries can produce not only biofuels but also bio-based chemicals, materials, and other co-products, maximizing the value from biomass.

3. Analyzing Carbon Imprint:Comparisons Methodologies and Metrics

A comprehensive comparison of cooking fuels requires considering multiple factors beyond just direct combustion emissions. A "lifecycle assessment" (LCA) approach is ideal, encompassing:

- **Fuel Characteristics:** Calorific value (energy content), density, and chemical composition.
- **Combustion Efficiency:** How effectively the fuel is converted into useful heat, influenced by stove technology. Incomplete combustion leads to higher emissions of CH_4, CO, and black carbon.
- **Direct Emissions at Point of Use:** Gases (CO_2, CH_4, N_2O, CO) and particulate matter ($PM_{2.5}$, black carbon) released directly from the stove.
- **Upstream Emissions:** Emissions associated with fuel extraction, processing (e.g., refining petroleum into kerosene, gas liquefaction), and transportation to the point of sale/use.
- **Emissions from Fuel Supply Chain:** For biomass, this includes deforestation (if unsustainably harvested), land-use change, and transportation. For electricity, it's the grid's generation mix.
- **Global Warming Potential (GWP):** Converting non-CO_2 GHGs (like CH_4 and N_2O) into CO_2 equivalents (CO_2eq) over a 100-year timescale to enable comparison. Black carbon, while not a GHG, has a significant warming effect and is often considered.

While precise figures vary significantly based on regional context, stove efficiency, and measurement methodologies, this paper focuses on the relative emissions and the mechanisms by which different fuels contribute to climate change as shown in Table 3.

Table 3. Specific Comparative Analysis of Cooking Fuels

Fuel Type	Primary GHG Emissions (Direct)	Upstream/Lifecycle Emissions	Overall GHG Impact (Relative)	Health Impact (Indoor Air Quality)
Traditional Biomass	CO2 (biogenic), CH4, N2O, Black Carbon	Deforestation, inefficient charcoal production	Very High	Very Poor
LPG	CO2	Extraction, processing, transport (CH4 leakage)	Moderate to High	Good
Natural Gas (Piped)	CO2	Extraction, processing, transport (significant CH4 leakage)	Moderate to High	Good
Kerosene	CO2, CO, PM2.5, Black Carbon	Extraction, refining, transport	High	Poor
Electricity	Zero	Dependent on grid energy mix (Fossil -> High; Renewables -> Low)	Highly Variable	Excellent
Biogas	CO2 (biogenic)	Methane capture from waste, digester construction	Very Low	Good
Solar Cooking	Zero	Manufacturing and disposal of cooker	Extremely Low	Excellent

4. Broader Implications and Challenges

The choice of cooking fuel is intertwined with several global challenges:

- **Climate Change:** Reducing emissions from cooking is essential for meeting climate targets (e.g., Paris Agreement goals). The shift away from traditional biomass can reduce deforestation pressures and black carbon emissions.
- **Public Health:** The reduction of household air pollution from cleaner fuels can prevent millions of premature deaths and improve respiratory health, particularly among women and children.
- **Energy Access and Poverty:** Ensuring access to clean cooking energy is a key Sustainable Development Goal (SDG 7). The transition must be equitable, affordable, and sensitive to local socio-economic contexts.
- **Gender Equality:** Women bear a disproportionate burden of fuel collection and exposure to indoor air pollution. Cleaner fuels can free up their time and improve their health.

5. Cooking Fuel Emission: Strategies for Mitigation and Transition

Accelerating the transition to cleaner cooking fuels requires multi-faceted strategies:

- **Promoting Cleaner Fuels:** Subsidies or financing mechanisms for LPG, natural gas connections, and electric cooking appliances where grids are increasingly renewable.
- **Improving Traditional Cookstoves:** For populations still reliant on biomass, disseminating highly efficient improved cookstoves (ICS) can act as an interim solution, significantly reducing fuel consumption and emissions (CO, PM2.5, black carbon).
- **Sustainable Biomass Management:** Promoting sustainable forestry practices, commercialization of biomass briquettes from agricultural waste, and efficient charcoal production could reduce the impact of biomass use for those who cannot immediately transition to modern fuels.
- **Investing in Modern Energy Infrastructure:** Expanding electricity grids (with a focus on renewables), establishing LPG distribution networks, and promoting biogas digesters at household or community levels.
- **Integrated Approaches ("Fuel Stacking"):** Recognizing that households may use multiple fuels (e.g., biomass for some dishes, LPG for others), policies should support the gradual adoption of cleaner fuels rather than expecting an abrupt switch.
- **Research and Development:** Continuing innovation in stove technology, fuel production (e.g., green hydrogen for cooking, advanced biofuels), and energy storage.

6. Success Stories in Cooking Fuel Adoption and Carbon Footprint Reduction

This section highlights exemplary programs and initiatives from different countries that have successfully promoted the adoption of cleaner cooking fuels, yielding positive impacts on carbon footprints and public health.

6.1. India: The Pradhan Mantri Ujjwala Yojana (PMUY) – Scaling LPG Access

Context: India has historically been one of the largest consumers of traditional biomass for cooking, with millions of households suffering from the impacts of indoor air pollution. The challenge was immense, requiring a massive logistical and financial undertaking. **Intervention:** Launched in 2016, the Pradhan Mantri Ujjwala Yojana (PMUY) is a flagship government scheme aimed at providing clean cooking fuel (LPG) to women from Below Poverty Line (BPL) households. The scheme provides a financial assistance of ₹1600 (approximately US$20) for the first cylinder, a pressure regulator, and safety hose, and a deposit-free LPG connection. It also offers EMIs for stove and first refill payment. **Drivers of Success:**

- **Strong Political Will and Centralized Implementation:** The program was driven by high-level political commitment and implemented through a nationwide network of public sector oil marketing companies.
- **Targeted Subsidies:** Direct financial support significantly reduced the upfront cost barrier for vulnerable households.
- **Extensive Awareness Campaigns:** "Give It Up" campaign encouraged affluent sections to voluntarily give up their LPG subsidy, creating moral support and generating resources.
- **Infrastructure Expansion:** Rapid expansion of LPG distribution networks across the country, including in remote areas. **Carbon Footprint Impact and Outcomes:**
- **Massive Scale:** By 2023, PMUY had provided over 96 million LPG connections, significantly increasing LPG penetration across the country.
- **Reduced Biomass Consumption:** While refill rates remain a challenge for sustained use, initial connections lead to reduced reliance on solid fuels, lowering black carbon and other GHG emissions.
- **Improved Health Outcomes:** Preliminary studies indicate a reduction in IAP exposure and associated health ailments in adopting households.
- **CO2 Emission Reductions:** A shift from biomass to LPG leads to a significant reduction in non-renewable biomass combustion, thereby mitigating CO2 emissions from deforestation and unsustainable fuel collection.

6.2. China: The Rural Biogas Program – Integrated Energy Solutions

Context: In the 1970s and 80s, rural China faced severe energy shortages, widespread reliance on biomass, and environmental degradation. The government sought sustainable, decentralized energy solutions. **Intervention:** China embarked on a massive national biogas program, promoting the construction of small-scale household biogas digesters, particularly in rural agricultural communities. These digesters convert agricultural waste and animal manure into biogas (for cooking and lighting) and nutrient-rich bio-slurry (for fertilizer). **Drivers of Success:**

- **Government Subsidies and Technical Support:** Significant financial subsidies were provided for the construction of digesters, coupled with extensive technical training and support for farmers.
- **Integrated Approach:** Biogas was integrated into agricultural practices, offering dual benefits of energy production and improved fertilizer, appealing to farmers' economic interests.
- **Community Engagement and Local Implementation:** Programs relied on local cadres and technicians to promote adoption and provide maintenance support. **Carbon Footprint Impact and Outcomes:**
- **Scale and Impact:** By the early 2000s, over 40 million rural households had adopted biogas, making China the world leader in domestic biogas use.
- **Methane Capture:** Biogas digesters capture methane (a potent GHG) that would otherwise be released into the atmosphere from decomposing organic waste, significantly reducing overall GHG emissions.
- **Reduced Biomass Consumption:** Decreased reliance on firewood and coal for cooking and heating, leading to reduced deforestation and associated CO2 emissions.
- **Improved Waste Management:** Enhanced sanitation and waste management in rural areas.

6.3. Kenya: Promoting Improved Cookstoves (ICS) and Market-Based Approaches

Context: Kenya, like many Sub-Saharan African countries, faces high rates of deforestation and health impacts from traditional charcoal and firewood use. **Intervention:** While not a single government program, Kenya has seen a vibrant, market-driven growth in the adoption of improved cookstoves (ICS) by various private companies and NGOs (e.g., BURN Manufacturing, Envirofit, Equity Bank). These stoves are designed to be significantly more fuel-efficient than traditional open fires or inefficient charcoal jikos. **Drivers of Success:**

- **Market-Based Solutions:** Focus on designing affordable, durable, and aspirational ICS that meet consumer needs, often with financing options (e.g., pay-as-you-go).
- **Quality Standards and Certification:** Development of national standards (e.g., by Kenya Bureau of Standards) to ensure the quality and performance of stoves.
- **Carbon Financing:** Many ICS projects in Kenya leverage carbon credits (e.g., through Gold Standard or Verified Carbon Standard) to subsidize stove costs or expand distribution, making clean cooking economically viable.
- **Local Manufacturing and Distribution:** Establishment of local manufacturing facilities creating jobs and ensuring availability. **Carbon Footprint Impact and Outcomes:**
- **Fuel Savings:** ICS can reduce charcoal/wood consumption by 30-60%, leading to significant cost savings for households and reduced pressure on forests.
- **Reduced Black Carbon and Methane:** More efficient combustion reduces emissions of black carbon and methane, contributing to both climate mitigation and improved air quality.
- **Scalability:** The market-driven approach has enabled millions of ICS to be distributed, reaching a wide demographic.
- **Carbon Credit Generation:** Kenya is a global leader in utilizing carbon finance to support clean cooking, with millions of tonnes of CO2e reduced through ICS projects.

6.4. Indonesia: Kerosene to LPG Conversion Program

Context: In the early 2000s, Indonesia heavily subsidized kerosene for cooking, leading to a massive fiscal burden and environmental concerns. The government aimed to shift households to a cleaner, more efficient fuel. **Intervention:** Beginning in 2007, Indonesia embarked on a nationwide program to convert households from kerosene to LPG. This involved providing free starter LPG packages (3kg cylinder, stove, and regulator) to millions of households, particularly targeting low-income segments. **Drivers of Success:**

- **Phased Rollout:** The program was implemented in phases, starting with specific regions, allowing for learning and adaptation.
- **Strong Government Commitment:** Political will to eliminate expensive kerosene subsidies and embrace a cleaner alternative.
- **Public Awareness Campaigns:** Extensive campaigns educated the public on the benefits and safe use of LPG.
- **Supply Chain Development:** Robust efforts to expand LPG distribution networks to ensure availability of refills. **Carbon Footprint Impact and Outcomes:**
- **Rapid Transition:** Within a few years, millions of households switched from kerosene to LPG, making it one of the fastest energy transitions globally.
- **Significant GHG Emission Reduction:** LPG combustion produces fewer GHG emissions than kerosene, especially considering the lifecycle emissions and the carbon intensity of kerosene production.
- **Fiscal Savings:** The program eventually led to substantial savings for the national budget by eliminating kerosene subsidies.
- **Health Benefits:** Reduced exposure to kerosene fumes led to improved indoor air quality.

6.5. Cross-Cutting Lessons and Enabling Factors

The success stories from India, China, Kenya, and Indonesia, while distinct in their approaches and contexts, reveal several common enabling factors crucial for accelerating the clean cooking transition and reducing carbon footprints:

- **Strong Political Will and Policy Support:** High-level commitment from governments, reflected in clear policy targets, dedicated funding, and regulatory frameworks, is paramount. Subsidies (for stove or fuel), tax incentives, and financing mechanisms (e.g., carbon credits, microfinance) play a pivotal role.
- **Tailored Financial Mechanisms:** Affordability remains a major barrier. Innovative financing models, including direct subsidies, installment plans, microfinance, and leveraging carbon finance, are essential to make clean cooking accessible to low-income households.
- **Robust Supply Chains and Infrastructure:** Reliable access to fuel refills (LPG cylinders, biogas feedstock) or spare parts for stoves is critical for sustained adoption. This requires investment in distribution networks, local manufacturing, and maintenance services.
- **Technological Appropriateness and Quality Assurance:** Stoves and fuels must be culturally acceptable, safe, durable, efficient, and meet local cooking needs. Establishing national quality standards and certification processes builds consumer trust.
- **Effective Awareness and Behavioral Change Campaigns:** Addressing entrenched cultural practices and perceptions requires sustained public education campaigns that highlight health benefits, economic savings, and ease of use. Community engagement and peer-to-peer learning are vital.
- **Multi-Stakeholder Partnerships:** Collaboration between governments, private sector companies (manufacturers, distributors), NGOs, research institutions, and local communities maximizes reach and impact.
- **Data-Driven Monitoring and Evaluation:** Continuous monitoring of adoption rates, fuel consumption, and environmental/health impacts allows for program adjustments and demonstrates concrete results, which can attract further investment.

6.6. Challenges and Future Directions

Despite the successes, significant challenges persist. Sustaining subsidy programs, ensuring consistent fuel supply in remote areas ("last-mile delivery"), and overcoming behavioral inertia remain ongoing hurdles. Furthermore, achieving full "stacking" of clean fuels (where households use clean fuels exclusively) rather than "fuel-stacking" (using traditional and modern fuels concurrently) is crucial for maximizing benefits. Future efforts must focus on:

- **Scalable and Sustainable Business Models:** Moving beyond sole reliance on subsidies towards market-driven solutions that are economically viable for both providers and consumers.
- **Diversification of Clean Energy Options:** Promoting a portfolio approach that includes not only LPG and improved biomass stoves but also electric cooking, ethanol, and advanced biogas systems, tailored to local resource availability and consumer preferences.
- **Integration with Broader Energy Planning:** Embedding clean cooking initiatives within national energy access strategies and climate change mitigation plans.
- **Enhanced Research and Development:** Investing in R&D for more efficient, affordable, and culturally appropriate cooking technologies.
- **Stronger International Collaboration:** Facilitating knowledge sharing, technology transfer, and financial support from developed to developing countries.

7. Conclusion

The transition to clean cooking is an imperative for global health, environmental sustainability, and climate action. The success stories from India, China, Kenya, and Indonesia unequivocally demonstrate that widespread adoption of cleaner cooking fuels is achievable. These experiences underscore the critical role of political commitment, innovative financing, robust infrastructure, technological adaptation, and sustained public engagement. By learning from these diverse national triumphs, the international community can accelerate efforts to ensure that every household has access to clean, affordable, and sustainable cooking energy, significantly reducing the global carbon footprint and fostering a healthier, more equitable future

The comparative analysis of cooking fuels reveals a complex interplay between energy efficiency, fuel source, and environmental impact. Traditional biomass, particularly when unsustainably harvested and used in inefficient stoves, stands out as having the highest carbon footprint and severe health consequences due to its non-CO2 GHG and black carbon emissions. While fossil fuels like LPG and natural gas offer cleaner combustion, their lifecycle impact remains significant due to upstream emissions. Electricity, especially when sourced from renewable energy, emerges as the most promising long-term solution for low-carbon cooking. Biogas and solar cooking offer niche, yet highly sustainable, alternatives where applicable.

Achieving universal access to clean cooking by 2030, as envisioned by SDG 7, is not merely about energy access but also about climate action and public health. A just and equitable transition necessitates integrated policies that combine technological innovation, financial incentives, infrastructure development, and community engagement to move billions away from polluting cooking methods towards cleaner, healthier, and more sustainable alternatives.

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