

Energy and Health in Low-Income and Middle-Income Countries 5



Priorities and opportunities for clean energy transitions to advance health in low-income and middle-income countries

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Energy supports health and economic prosperity, yet low-income and socially or politically marginalised populations consume the least energy and depend on the most polluting fuels (ie, biomass). Despite decades of efforts to replace biomass, which is more damaging to health and the climate than cleaner alternatives (ie, gas and electricity), hundreds of millions of people remain without the benefits of clean and modern energy. We outline four priority areas for transitions to clean energy in low-income and middle-income countries: (1) rapidly reduce use of polluting fuels; (2) leverage clean energy to deliver direct health benefits; (3) align energy transitions with climate mitigation and adaptation goals; and (4) address persistent inequalities in energy access across and within countries. We highlight strategic, cross-cutting opportunities to strengthen policy design and implementation: targeted energy subsidies for populations facing the greatest barriers to access and sustained use, bundled interventions that combine clean energy with health care and nutrition services, integrated infrastructure and urban planning, and digital tools for improving data, payments, and service delivery. Clean energy must do more than reach households; it must fully displace polluting fuels and contribute to improved health, equity, and climate resilience where the need is greatest.

Introduction

Two basic truths shape the current energy landscape. First, although energy powers economies and livelihoods, its production releases pollutants that harm health, shorten lives, and contribute to climate change. Second, the world's lowest income populations, especially those who are socially or politically marginalised, face multiple energy-related disadvantages: they use the least energy, spend the largest share of their income on it, rely on the most polluting fuels, and will bear the brunt of climate change's escalating impacts.

This inequity is a direct consequence of global political and economic structures that prioritise energy systems to drive growth and development, particularly in urban settings and largely through the combustion of fossil fuels.¹ Economic development in countries that are now high income led to near-universal household energy access—namely to electricity and natural gas—which is deemed necessary for modern life. However, 2–3 billion people in low-income and middle-income countries (LMICs) still do not have reliable access to clean energy.

Nearly one in three people globally rely on biomass, coal, or kerosene for cooking and heating,² leading to high household and ambient air pollution and more than 3 million premature deaths each year.³ Women and children bear the greatest burdens, spending the most time near these pollution sources.⁴ Electricity, which emits no pollutants at the point of use, has the potential to reduce harmful exposures across households, communities, and commercial energy services, but progress in expanding access has been slow and uneven.

As of 2023, approximately 666 million people—primarily in sub-Saharan Africa—still do not have access to electricity altogether.² Unreliable grids, underfunded infrastructure, and high costs keep many without power. Even where electricity is available, it is often insufficient, intermittent, or too expensive to displace polluting fuels.⁵ Moreover, three-fifths of the electricity available globally is generated from fossil fuels, contributing to ambient air pollution and climate change.⁶

Key messages

- Global household energy use is unequal, leaving those with the lowest incomes and those who are socially or politically marginalised reliant on the most polluting and health-damaging fuels
- The central goal is to phase out polluting fuels, not simply increase reported access to clean energy
- Lasting health impacts from clean household energy depend on sustained reductions in pollution exposure and might require progress on the underlying burdens of poverty
- Clean energy systems must be designed to advance both climate mitigation and climate adaptation
- Clean energy policy must prioritise those currently left behind, embedding gender, income, and geographical equity in targets, delivery, and accountability
- Targeted subsidies, bundled social and energy programmes, integrated infrastructure planning, and digital tools are cross-cutting levers to accelerate health-enhancing, clean energy transitions that prioritise low-income and marginalised populations

The global energy crisis does not stem from consumer preference or, in most instances, total absence of access to clean energy services; instead, it emerges from persistent shortcomings in fuel accessibility, affordability, reliability, and quality.^{7–14} This energy gap deepens health inequities, leaving the poorest and most marginalised communities without energy to support basic wellbeing and hindering economic development. It also mirrors broader disparities in access to clean water, sanitation, nutrition, health care, and education.¹⁵

A reliable and sufficient supply of clean energy—following the WHO definition, which includes electricity, solar, liquefied petroleum gas (LPG), biogas, and ethanol¹⁶—can deliver broad benefits for human health and overall wellbeing. Without dependable electricity, health-care facilities struggle to power essential equipment, from x-ray machines and oxygen generators to medical refrigerators and basic lighting. Households without clean energy struggle to regulate indoor temperatures, maintain safe food storage, and ensure lighting for education and work. Women are often tasked with collecting firewood and cooking over smoky stoves and bear disproportionate burdens that restrict economic opportunities and reinforce gender imbalances.^{7,17–19} At the community level, the lack of reliable, stable, clean power undermines business operations, deprives farmers of reliable irrigation, and hinders the operation of schools and community centres.

In this final paper in our Series on energy and health in LMICs, we issue a call to action: expanding clean, reliable energy is an urgent public health intervention. Greater access to clean energy can promote health, economic progress, and social equity while contributing to climate change mitigation and adaptation goals. Although total renewable energy production has grown by 130% in the

two decades since the previous *Lancet* Series on energy and health,²⁰ its share of total electricity generation has increased only modestly (from 35% in 2000 to 40% in 2024²¹). The global energy mix remains dominated by hydrocarbons, which have only fallen from an 85% share in 2000, to an 80% share in 2024.²² International ambitions to transition LMICs to clean energy—embodied by targets such as Sustainable Development Goal 7, which aims to achieve universal access to affordable, reliable, sustainable, and modern energy by 2030²³—are falling far short of their promises.²⁴

Several key messages have emerged from our Series. First, research and policy must move beyond binary metrics of energy access to capture the full spectrum of fuel use, including clean and polluting sources, while monitoring changes over time, gender dynamics, and the quality and reliability of clean energy.²⁵ As a result, even if global access targets are met, they are unlikely to yield meaningful health improvements if they continue to overlook the persistent reliance on polluting fuels for basic household needs and the underlying forces that drive their use. Second, transitioning households to clean fuels, especially for cooking, can dramatically reduce exposure to harmful pollutants and promote equity and wellbeing.²⁶ Third, reliable, high-quality electricity is indispensable for modern health care and its absence compromises patient safety and costs lives.²⁷ Fourth, a justice-centred strategy for climate change mitigation has the potential for transformative reductions in air pollution, delivering health benefits and acknowledging historical responsibility and current capacity to mitigate emissions and finance clean energy transitions.²⁸ Collectively, these insights show how expanding clean energy access, reliability, and use in LMICs is a crucial public health intervention with

	Targeted energy support	Packaged health-energy interventions	Integrated infrastructure and planning	Digital tools for targeting, monitoring, and finance
(1) Rapid elimination of polluting fuels in households, communities, and commercial energy services*	Provide targeted price support and fee reductions so clean fuels cost less than polluting fuels	Pair clean cooking with health and nutrition services to increase adoption and sustained use	Upgrade household wiring, replace unsafe stoves, and expand fuel distribution and delivery systems in remote regions to make clean options reliable	Use digital targeting and simple use tracking to verify displacement and support credible climate finance accounting
(2) Bridge the gap between clean energy and improved health†	Prioritise subsidies for pregnant people, infants, and clinics so that exposure reductions occur where benefits are largest	Combine clean energy with water, sanitation, hygiene, nutrition, and timely clinical care to address interacting risks	Ensure dependable power for clinics, vaccine cold chains, and water systems through coordinated planning	Link fuel use, exposure, and health outcome data to guide rapid evaluation and scale-up
(3) Combustion-free households and communities for climate and health‡	Offer time-limited support for transitional fuels while building affordable pathways to renewable electricity	Deliver cooling, safe water, and other climate adaptation services using clean power to protect health	Plan low-carbon, shock-resilient grids and avoid parallel, duplicative systems that commit infrastructure to continued fossil fuel use	Use risk maps and automated emissions accounting to target support during climate shocks and track co-benefits
(4) Understanding and addressing gender, income, and geographical disparities§	Direct benefits to women, low-income households, informal settlements, remote areas, and crisis-affected populations	Combine energy access with social protection and community outreach to reduce multiple deprivations	Map underserved areas and integrate them into formal service networks with safe, affordable connections	Provide phone-based, agent-assisted, and offline options—plus clear grievance channels—to prevent digital exclusion
References indicate illustrative sources corresponding with each priority row. Citations are grouped by the primary cross-cutting level to which each source relates. *Priority 1 sources: targeted, ^{8,29} infrastructure, ^{29–31} and digital. ^{32–34} †Priority 2 sources: packaged ³⁵ and infrastructure. ³⁶ ‡Priority 3 sources: targeted ³⁷ and packaged. ³⁸ §Priority 4 sources: infrastructure ³⁹ and digital. ⁴⁰				
Table 1: Priority areas and cross-cutting opportunities for accelerating clean energy adoption				

numerous co-benefits for livelihoods, economic development, and the climate.

We organise our call to action around four interlinked priority areas (table 1). Together, these areas underscore essential goals in accelerating clean energy use and capture the trade-offs that arise when balancing the need for affordable, reliable energy with clean air, climate risk management, and public health needs. In centring these priorities, we highlight knowledge gaps and discuss opportunities for cross-cutting programming and policy.

Priority area 1: rapid elimination of polluting fuels in households, communities, and commercial energy services

Decades of investment and economic development have increased clean fuel use, yet polluting fuels still dominate in LMICs. Modern alternatives, such as gas or electricity, often remain inaccessible, unaffordable, or unreliable. Most individuals prefer clean energy but face a trade-off: the high upfront and recurring costs of clean fuels versus the immediate affordability and proven reliability of traditional fuels. For low-income users, the benefits of polluting fuels outweigh their less tangible, long-term negative externalities (eg, worsened health from air pollution), which are often undervalued because they are less immediate and the costs are disproportionately borne by women.^{17,41} Shifting entire communities and commercial sectors poses even greater challenges.

Centrally supported, community-level planning can nevertheless transform transitions to cleaner fuels by coordinating local stakeholders, securing funding, and building reliable distribution networks. Local institutions can help balance competing priorities and ensure that essential infrastructure—such as upgraded electrical wiring, new stoves, and other energy-efficient equipment—is in place.³⁰ Without these collective initiatives, even households willing to transition to clean energy remain dependent on polluting alternatives due to the prohibitive individual costs of upgrading.

Political dynamics and historical legacies further complicate matters (see papers 1 and 2 in this Series^{25,42}). In high-income countries, coordinated policies and investments lowered infrastructure costs and created an enabling regulatory environment and market, spurring rapid electrical grid expansion. By contrast, many low-income countries inherited energy systems that continued to favour polluting fuels and were originally designed to serve foreign industrial interests. Policy makers face intense pressure to deliver short-term economic gains, discounting future health and environmental consequences and limiting long-term investments in clean energy.

Although standard data on cooking fuels and electricity access offer a crude snapshot of fuel usage, they fail to capture the short-term fluctuations and local variations that drive consumer behaviour. This gap hampers effective intervention design. Fortunately, promising

initiatives could make clean fuels more affordable and accessible. Tiered and targeted fuel subsidies, flexible payment solutions (eg, pay-as-you-go^{43–45}), and innovative pricing mechanisms (eg, dynamic pricing^{46,47}) are potential pathways. Researcher–policy collaborations using robust experimental designs to quantify the effects of new policies can help pinpoint which interventions most effectively displace polluting fuels and under what conditions.⁴⁵ Crucially, these trials should be embedded within the policy making process, rather than treated as isolated academic exercises. Doing so ensures that they are responsive to political environments, enables continuous outcome evaluation, and can lead to lasting, scalable policy change.^{48,49}

Our call to action is straightforward but difficult: sharply reduce reliance on polluting fuels. This challenge is distinct from expanding clean energy access, although the two are deeply linked. In many LMICs, rising incomes and urbanisation have driven energy transitions. But where clean fuels remain unaffordable or unreliable, polluting fuels persist. We do not call for bans on polluting fuels, which are difficult to enforce and often regressive.^{50,51} Instead, the goal is to make clean fuels the affordable, accessible, and reliable default while improving overall economic conditions, so that the transition becomes both possible and desirable.

Achieving this shift requires identifying the precise conditions under which clean fuels displace polluting ones. These thresholds vary by context, but the policy tools are clear: fuel subsidies, infrastructure investment, pricing reforms, and supply chain coordination. Delivering clean fuels at scale is not only a technical challenge but is also a collective challenge that requires coordinated action from governments, development agencies, and the private sector.

Yet global political and economic forces still favour oil and gas expansion and, despite growth in renewables, progress remains uneven.^{2,22} In the near term, LPG—although a fossil fuel—remains the most viable near-term alternative to polluting biomass in many LMICs and has driven most of the gains in clean cooking over the past two decades.⁵² Phasing in LPG in areas where it displaces polluting fuels offers health and welfare benefits, especially for those with low incomes. But without a long-term strategy, scaling LPG risks entrenching fossil fuel infrastructure. The International Energy Agency's (IEA) Net Zero 2050 roadmap makes it clear that short-term promotion of LPG must be paired with parallel investments in electrification and renewable energy systems.⁵³ Avoiding LPG altogether would delay improvements and deepen energy poverty; using it as a transitional fuel is the equitable and pragmatic path forward.

The transition to cleaner energy is shaped not just by economics, but also by power. Low-income and marginalised populations—those most reliant on polluting fuels—often have little political influence compared with

the oil and gas industry, which remains one of the most politically active and powerful sectors globally.^{54,55} Countering this imbalance requires policies that shift incentives and build institutional alternatives. Carbon pricing with revenue recycling is one such tool:⁵⁶ in Canada, British Columbia's revenue-neutral carbon tax reduced emissions without harming growth and the return of funds to households helped maintain public support.⁵⁷ Beyond pricing, grassroots and civil society activism can shape policy and amplify accountability.⁵⁸

In the long term, overcoming entrenched fossil fuel dynamics to achieve a truly clean and sustainable energy system will ultimately require substantial financial investments and robust cross-sector collaborations.

Priority area 2: bridge the gap between clean energy and improved health

Clean energy promises immediate and long-term health benefits. Yet, evaluations of clean cooking interventions and electrification have generally failed to detect benefits in the short term (see paper 3 of this Series for a discussion of evidence²⁶), prompting the question: how can we ensure that clean energy access translates into meaningful health gains?

A major obstacle is our incomplete understanding of the biochemical and physiological pathways linking clean energy to better health. Switching from polluting fuels (eg, biomass and kerosene) to LPG or electricity sharply reduces air pollution,^{59–62} which can improve mucociliary clearance, reduce systemic inflammation and oxidative stress, support lung development and function, and protect fetal growth.^{63–65} These physiological responses are plausibly linked to reductions in lower respiratory infections, chronic obstructive pulmonary disease, adverse birth outcomes, and childhood stunting.^{66–70} However, randomised evaluations of clean energy interventions have not consistently observed the anticipated declines in disease risk.^{71–74} Several factors could contribute to this insufficient decline. First, although reductions in pollutants, such as fine particulate matter (PM_{2.5}), carbon monoxide, and black carbon often meet WHO interim targets,^{59,61,62,75} these declines might be too modest or are counteracted by persistent exposures to other harmful emissions, such as ultrafine particles (diameter <0.1 µm) or nitrogen dioxide.^{76–78} Second, the timing of interventions appears crucial; for example, introducing clean energy later in pregnancy could miss vital windows for protecting birth outcomes.⁷² Third, many studies only track households for about a year, which might sufficiently capture short-term impacts (eg, reduced pneumonia) but could miss longer-term benefits (eg, improved cognition or lung development and reductions in chronic diseases). Finally, for health outcomes such as stunting, clean energy alone might not be enough to overcome broader risks associated with poverty, including malnutrition and inadequate water and sanitation. Even in randomised trials, the same

intervention can produce different outcomes depending on when it is delivered, what exposures it replaces, and whether underlying barriers like poor nutrition or little access to health care persist.

In observational studies, these poverty-related factors can confound or mediate observed links because cleaner energy is more often adopted by wealthier households.⁷⁹ Even in well-designed causal studies, these structural factors can lie downstream of energy access, complicating attribution. Clean energy might be necessary, but its health benefits depend on the broader system in which it is delivered. Despite these challenges, a broad array of studies—including natural experiments and quasi-experimental evaluations—offer encouraging evidence that under the right conditions, clean energy can yield substantial health improvements. In Indonesia, the transition from kerosene to LPG for cooking coincided with reduced infant mortality;⁸⁰ in China, phasing out coal for winter heating near Beijing resulted in measurable cardiovascular benefits⁸¹ and reduced respiratory symptoms;⁸² and in Ecuador, a nationwide shift from firewood to LPG was linked to substantial reductions in lower respiratory infection mortality among children.⁸³ Transitions from gas to electric induction stoves, especially with renewable-generated electricity, suggest a dual benefit of reducing greenhouse gas emissions and enhancing health outcomes.^{37,84}

Broader studies of electrification show that widespread grid connections can boost employment, improve livelihoods, and enhance child health, although these benefits often take years to fully materialise.^{13,85–88} Immediate health gains from electrification can be achieved by displacing kerosene lamps, a large source of air pollution in LMICs,^{89,90} although such opportunities might diminish as affordable alternatives like solar-powered light-emitting diodes become more widespread.⁹¹ Meanwhile, off-grid and mini-grid systems, intended to extend essential services to remote areas, often struggle with reliability, scalability, and financial sustainability, limiting their broader benefits.^{92,93}

A key insight from successful environmental and poverty alleviation interventions is that scale and duration are key.^{94–97} Large-scale initiatives that deploy clean energy across entire communities create positive feedback loops: as demand increases, supply becomes more stable, costs decline, and use grows. By contrast, piecemeal short-term interventions that focus on individual households might struggle to sustain momentum and fail to generate the broader cumulative benefits that emerge from community-wide transformation.

Realising the potential of clean energy to improve health will require sustained reductions in pollution and widespread, long-term, community adoption. Moreover, health benefits depend on the broader context of local nutrition, water, sanitation, and infrastructure. A clearer understanding of the causal pathways and conditions under which clean energy yields health benefits is

essential for designing interventions that effectively break the cycle of energy poverty and poor health.

Priority area 3: combustion-free households and communities for climate and health

Clean energy is essential for reducing greenhouse gas emissions and protecting public health. Fossil fuel combustion drives air pollution and global warming, causing millions of premature deaths annually and widespread morbidity^{98,99} through extreme heat, shifting disease vectors, and food supply disruptions, among other pathways.^{36,99–101} Energy is also vital for climate adaptation; it powers temperature regulation, refrigeration, essential health-care services, and communication systems that protect communities during extreme weather. In LMICs, policy makers face a dual challenge: reducing fossil fuel reliance while expanding clean, reliable energy access for both mitigation and adaptation.

Transitioning to a post-combustion world¹⁰² where renewables and nuclear energy replace fossil fuels is complex. Analyses like the *Lancet* Countdown³⁶ track correlations between fossil fuel expansion and climate impacts but, in our opinion, stop short of identifying which transition strategies yield the greatest health benefits and for whom. Traditional integrated assessment models have long informed estimates of global economic damages from CO₂ emissions,^{103,104} but they tend to oversimplify adaptation by averaging effects over large regions and overlooking key feedbacks between energy use, economic development, and adaptive behaviour.^{105,106} Emerging bottom-up analyses merge high-resolution climate models with localised socioeconomic data to estimate sector-specific outcomes—including energy,¹⁰⁷ labour (from a preprint paper),¹⁰⁸ or temperature-related mortality¹⁰⁹—but they often omit how adaptation and energy use evolve together.

Two interwoven research strands are essential for guiding energy transitions: clean energy for mitigation and for adaptation. On the mitigation side, expanding clean energy in LMICs can reduce carbon emissions and related health harms. However, blanket emission targets are unlikely to be effective. Countries need tailored portfolios of renewable technologies and infrastructure adapted to their specific geographical, social, and economic contexts. Empirical scenario modelling, such as that by Scovronick and colleagues in their Article linked to this Series,²⁸ helps clarify trade-offs among competing priorities, although finer scale research remains essential. On the adaptation side, the most severe climate impacts are projected to fall on low-income and socially or politically marginalised populations, who are particularly vulnerable due to high geographical exposure to climate hazards, limited public sector capacity to manage risks and respond to shocks, and weak social safety nets.^{36,110,111} Broadly, clean energy could enable communities to respond effectively to both immediate weather shocks and longer-term shifts in

climate.^{112–114} It can power systems that ensure safe drinking water during droughts and floods, support air conditioning and refrigeration systems that mitigate heat stress and preserve perishable foods, and sustain health-care facilities essential for treating climate-related health challenges.^{114,115} Digital communications and early warning systems, also dependent on reliable power, can further reduce risk.¹¹⁶ Yet rigorous causal evidence on the effectiveness of these adaptation strategies is scarce, especially in LMICs. Building that evidence base is an urgent priority.

Adaptation and mitigation are often treated as separate goals, but clean energy investments can support both. For example, solar-powered cold storage and clinic cooling systems reduce heat-related health risks, replace diesel or coal-based power, and cut emissions. However, although expanding access to cooling can improve resilience, it can also raise emissions if powered by fossil fuels. Global modelling projects over the past decade project that energy-based adaptation will lower emissions for most countries by 2100, reducing necessary mitigation requirements.¹¹⁷ Cross-sectoral systems analyses help to reveal these benefits and potential tensions between local and regional mitigation and adaptation approaches.^{118,119} Designing energy transitions that are both climate-smart and health-protective requires recognising where these goals align and where they might conflict.

These benefits will not be evenly distributed. In India, rising temperatures might double electricity consumption to meet increasing cooling demands, whereas in sub-Saharan Africa, persistent low incomes and weak infrastructures will likely constrain energy access.¹⁰⁷ Even in high-income countries, access to energy-intensive adaptation technologies, such as air conditioners and air purifiers, is unequal and power outages disproportionately affect low-income regions.^{120–122} Delivering meaningful adaptation will require not just boosting supply, but also ensuring the reliability and quality of energy services.

Closing the energy access gap in LMICs will require significantly more funding than is currently available.¹²³ IEA modelling indicates that universal electricity access would require annual investments of US\$45 billion and achieving universal clean cooking access by 2030 would require an additional \$10 billion a year, alongside \$100 billion per year in recurring fuel costs (most of which currently fall on users). About \$4·5 trillion per year will be needed in the early 2030s to keep the 1·5°C pathway within reach.¹²⁴ Yet annual investment in clean cooking remains at only \$130 million, much of which is directed towards biomass stoves that do little to reduce harmful exposures.⁶² Existing tools such as the Green Climate Fund and voluntary carbon markets could help close this gap, but they remain underused and hampered by weak governance, credibility concerns, and underdeveloped delivery systems.^{32,125} As climate change—driven largely by industrialised countries¹²⁶—deepens global inequalities,¹²⁷

closing these gaps demands robust financial support, improved infrastructure, and scalable adaptive solutions.¹²³

Health co-benefits can no longer be an afterthought in climate policy. Reducing emissions not only addresses long-term climate risks but also delivers immediate health benefits by lessening pollution. These dual benefits make clean energy investments more cost-effective and more politically viable when both short-term and long-term gains are considered. Policy makers must navigate the dual challenge of reducing greenhouse gas emissions while promoting social equity. For instance, investing in clean cooking solutions (eg, LPG) can quickly reduce harmful exposures among those facing the highest health risks from household air pollution, whereas grid electrification offers long-term health investments, but might reach low-income or geographically marginalised populations slowly. Supporting both immediate and gradual transition pathways creates a cycle: improved health and reduced inequality reinforce deeper climate action.

Achieving an equitable energy transition will depend on high-resolution, locally grounded evidence from economics and public health. This approach can increase the accuracy of estimates of climate change damage, identify where interventions will be most effective, and ensure that no group is left behind. It can also help identify regions ready for an immediate transition versus those that need more time and resources to secure reliable clean energy. The challenge remains to design policies that deliver both long-term climate benefits and immediate public health gains, ensuring that the transition is as just as it is essential.

Priority area 4: understanding and addressing gender, income, and geographical disparities

Widening inequities in energy access and use are at the heart of the unequal distribution of health burdens globally, regionally, within communities, and within households. Whereas most regions have expanded their energy access in recent decades, sub-Saharan Africa remains an outlier. In 2010, sub-Saharan Africa accounted for half of the world's population without electricity—a figure that rose to four-fifths in 2023, as population growth outpaced infrastructure gains.¹²⁴ Elsewhere, energy improvements have been concentrated in just a few countries: Brazil, China, India, Indonesia, and Pakistan. Even within nations, clean energy is often mainly present in urban, higher-income areas; rural communities, informal settlements, and humanitarian settings frequently lag behind. Within households, women and girls bear the heaviest burden of fuel collection and traditional cooking, facing both time poverty and substantial health risks.^{18,19,128}

The health consequences of these disparities are apparent. In countries in sub-Saharan Africa, more than 80% of the population is exposed to unhealthy levels of household air pollution, leading to mortality rates several

times higher than in industrialised countries.¹²⁹ Yet, our understanding of other consequences of these energy disparities is still limited. Many studies rely on national-level data that mask important local differences. More granular descriptive research that is focused on describing clean energy access and use among vulnerable groups—such as residents of informal settings, refugees, and women—is needed to identify and address these inequities. Furthermore, energy poverty intersects with multiple social identities, including race, caste, disability, and gender, compounding vulnerabilities. Energy justice frameworks can guide equitable energy transitions and qualitative and mixed methods research can further illuminate the drivers and barriers to clean energy use in these populations.^{130,131}

Progress in energy equity and justice in LMICs requires moving beyond theoretical frameworks and access metrics to actively assess outcomes.^{130,132–135} Future studies should prioritise equity impacts through innovative designs, such as interviewing both halves of a couple using identical questionnaires¹²⁸ to identify intra-household dynamics and differences in energy use patterns, preferences, and needs. Other efforts must target marginalised communities in informal urban settings, crisis contexts, or remote areas to test solutions for service delivery, affordability, and sustained use in remote or hard-to-serve communities.^{39,136–138} By combining qualitative insights with quantitative methods, researchers can uncover why specific interventions fail and proactively design strategies to ensure that energy policies benefit everyone.^{139,140} National energy planning that merely distinguishes between urban and rural areas fails to capture local, real-world complexity. Instead, detailed, context-specific research that accounts for local social norms, gender roles, and decision-making processes is essential to develop truly inclusive and effective energy transition strategies.

Strategic opportunities

We highlight four promising cross-cutting opportunities to design research programmes and policies that address multiple challenges simultaneously.

Targeting support: delivering clean energy where needed

Economic theory suggests that well-calibrated subsidies can address externalities (eg, air pollution) and internal misperceptions that cause households to underinvest in cleaner fuels.^{15,41,141} Unlike universal subsidies, which can be fiscally burdensome and often benefit wealthier households,¹⁴² targeted approaches raise questions about who should receive them, how much, for how long, and under what conditions. Because subsidies are politically popular, removing them can trigger backlash^{143,144} and drive households back to polluting fuels if alternatives remain unaffordable.^{145,146} Table 2 summarises key trade-offs between targeted and universal subsidies.

	Universal subsidies	Rating	Targeted subsidies	Rating	Illustrative case
Equity and reach	Broad coverage but skew towards higher-income users in areas where access is unequal ¹⁴⁷	Disadvantage	Direct resources go to vulnerable groups when eligibility criteria are inclusive and delivery systems reliably transfer benefits	Advantage	India's PMUY programme: connections prioritised for women living below the poverty line; sustained use lagged in rural areas ¹⁴⁸
Targeting feasibility and delivery capacity	Simple to administer through prices with minimal verification and few exclusion errors	Advantage	Requires identification, enrolment, and periodic verification; prone to inclusion and exclusion errors if data are weak	Context-dependent	Peru's FISE programme: utility bill proxy eased administrative burden for eligibility ¹⁴⁹
Political durability	Popular and politically durable once enacted, making reform difficult and costly	Context-dependent	Risk of backlash if perceived as unfair or error-prone; risk can stabilise with transparent rules and grievance redress	Context-dependent	India's Give It Up programme: voluntary surrender of subsidies improved feasibility of reallocating LPG support ¹⁴⁴
Risk of fuel stacking	Lower clean fuel prices increase their use but often fail to eliminate use of biomass where supplies are unreliable	Context-dependent	High and reliable benefits to households most likely to displace polluting fuels reduces stacking and raises sustained clean use shares	Context-dependent	Ecuador's LPG: universal price support raised coverage; firewood persisted where refill access and reliability were weak ¹⁵⁰
Fiscal efficiency and budget sustainability	High recurring fiscal cost with leakage to non-priority users	Disadvantage	Lower total outlay per displaced household if leakage is contained; higher admin costs	Context-dependent	Togo's digital transfers: mobile-based targeting lowered delivery costs at scale ¹⁵¹
Scalability and transferability	Technically easy to scale via existing price systems	Advantage	Performance depends on identification systems, mobile coverage, data quality, and administrative capacity	Context-dependent	Togo's digital transfers: success relied on high phone coverage and centralised administration ¹⁵¹
Objective for comparison: maximise displacement of polluting fuels per unit of public expenditure while protecting equity. FISE=Fondo de Inclusión Social Energético. LPG=liquefied petroleum gas. PMUY=Pradhan Mantri Ujjwala Yojana.					

Table 2: Trade-offs between universal and targeted energy subsidies

Targeted subsidies typically focus on vulnerable groups, such as pregnant people, older people, low-income households, and residents of informal settlements. For example, India's Pradhan Mantri Ujjwala Yojana (PMUY) programme targets subsidies on the basis of poverty status and Peru's Fondo de Inclusión Social Energético programme uses proxies, such as electricity bills. India's Give It Up programme encouraged wealthier LPG users to voluntarily surrender their subsidies for reallocation to poorer households, avoiding the potential political fallout of forced subsidy removal. This creative approach reallocated resources more equitably, fostered collective responsibility for the shift to clean energy, and helped to finance the PMUY programme, which greatly expanded LPG coverage. However, LPG use among PMUY beneficiaries has remained uneven, with persistent gaps in rural and poorer regions, thereby highlighting the need for stronger targeting in marginalised areas.¹⁵²

Digital tools from mobile-phone data to satellite imagery are increasingly used to identify vulnerable populations faster than traditional surveys, especially during crises.¹⁵³ For instance, machine-learning algorithms substantially improved targeting efficiency in Togo's COVID-19 emergency cash transfer programme, benefitting from the country's high mobile phone coverage.¹⁵¹ Yet even in this favourable setting, digital approaches can inadvertently exclude the most vulnerable households, including those with limited literacy, access to mobile phones, grid connectivity, or proper documentation. Targeting accuracy is also highly

sensitive to how poverty is measured and the quality of input data, with different measurement approaches often generating conflicting household rankings.¹⁵⁴ Blending data-driven digital targeting with traditional surveys and local outreach can help mitigate these risks and improve coverage, especially when programme budgets are small relative to the number of households targeted.⁴⁰

Despite using different tools (eg, behavioural appeals in India and algorithmic targeting in Togo), both programmes illustrate trade-offs in scalable targeting. Togo's success reflected favourable conditions: a small, centralised state with high mobile phone coverage and strong administrative control. The programme shows what digital targeting can achieve when infrastructure is in place. India's Give It Up campaign appealed to civic responsibility among middle-class LPG users, which is a specific situation that might not generalise elsewhere. PMUY's persistent gaps in rural uptake, despite formal eligibility rules, highlight the limits of energy access programmes that do not address fuel affordability and supply. These cases show that effective design depends not just on identifying what works, but also on aligning programmes with local norms, incentives, and delivery capacity.

Because clean fuels are largely unaffordable for vast parts of the population in LMICs,^{9,155} getting the level of support right is essential. Support must be high enough to induce a shift away from polluting fuels, yet low enough to preserve incentives for innovation and maintain fiscal sustainability. If too low, households might continue stacking fuels (ie, using polluting fuels

alongside cleaner ones); if too high, subsidies could crowd out private solutions or strain public budgets. Economic research and field testing are essential to establish effective pricing and targeting strategies. In parallel, more evidence is needed to assess whether focusing support on traditionally defined vulnerable groups is sufficient, or if a broader approach is required to drive widespread transitions and reduce energy poverty.

There are good reasons to be cautious about the use of subsidies. Economic analyses have shown that global fossil fuel subsidies largely benefit the wealthy, increase greenhouse gas emissions, and worsen air quality; effective strategies for fossil fuel reform are now an important area of inquiry.^{142,147,156,157} However, these same concerns might not adequately reflect the settings in which reliance on biomass is prevalent and markets do not reflect the health, environmental, and climate benefits of cleaner cooking.¹⁵⁸ In these settings, people also face barriers (eg, inadequate access to credit) that can slow adoption.

Governments have a broad policy portfolio available to promote an equitable transition to clean energy. Markets can be a powerful force for change when shaped by policies, such as tax and tariff reform, deregulation, land-use concessions, below-market loans, and targeted investment incentives. Direct benefit transfers could also provide targeted financial support. These tools can support a range of technologies, from solar arrays to microhydroelectric power generators and small modular reactors—advanced technologies designed to be more compact and efficient than traditional nuclear power plants. Because these systems are often decentralised, they can be deployed in remote or underserved areas, expanding access to clean energy and contributing to a more inclusive energy transition.

Coupling clean energy interventions with other welfare-enhancing goods and services

Energy poverty rarely exists in isolation; it is often intertwined with malnutrition, chronic stress, and inadequate access to health care.^{159–161} Even if cleaner fuels reduce air pollution, the adverse effects of poor nutrition and persistent stress can continue to undermine immune function, leaving populations susceptible to infections and stunted growth.¹⁶² By coupling clean energy with other social programming, such as nutrition programmes; improved water, sanitation, and hygiene; and enhanced antenatal care, individuals are better positioned to overcome these interrelated challenges.⁹⁶

Integrating energy initiatives with broader welfare programmes allows for shared infrastructure and synchronised service delivery, potentially reducing overall costs and maximising the impact of each dollar spent. Given the complexity of real-world settings, programme design must be exceptionally precise. Although rigorous evaluations (eg, randomised

controlled trials, quasi-experimental studies, and stepped-wedge designs) are necessary, the goal might not be to isolate each intervention's effect. Even if single interventions yield only modest benefits, an integrated package could generate substantial improvements. Although quantifying individual contributions could help refine the strategy, the priority remains delivering a comprehensive intervention that effectively addresses multiple, intertwined challenges to improve health.

Coordinating energy and infrastructure planning for resilient systems

Integrated infrastructure and urban planning can help address lagging progress on clean cooking and inadequate provision of essential energy services. In many regions, electricity grids remain unreliable, leaving households without adequate and consistent power for cooking, cooling, and refrigeration. Upgrading these grids for high-demand applications can accelerate the transition to clean energy while supporting broader socioeconomic development. Integrated planning also helps avoid redundant investments, such as maintaining parallel LPG supply chains or standalone minigrids when the main grid could be extended more efficiently.

Large-scale gains in public health and energy access will require cross-sector coordination. Ministries responsible for health, water, sanitation, nutrition, and social protection all rely on reliable energy. Yet these agencies often operate in silos, with little joint planning or shared infrastructure. Aligning priorities and investments across sectors can improve service delivery, reduce costs, and build political support for long-term infrastructure upgrades. For example, grid expansion planned jointly with water utilities and local governments can ensure power is available where it is needed most, from water pumps to health clinics.

These efforts must also reflect differences in geography and institutional capacity. In rural and remote areas, decentralised systems (eg, solar home units or minigrids) are often the most viable near-term options. But these solutions face challenges with financial viability, maintenance, and scaling beyond small populations.^{93,163} Urban and peri-urban areas, by contrast, have the demand density to justify investments in centralised infrastructure, but face their own challenges, including informal settlements that might fall outside of formal planning processes.¹⁶⁴ Strengthening grid reliability and expanding access in these areas will require coordinated planning across utilities—electricity, gas, and water—and deliberate efforts to include underserved communities.¹⁶⁵

Rapid development of resilient infrastructure is also likely to depend on aligning private sector interests with government priorities. Expanding supply chains and fostering public–private partnerships can build robust grids that meet global targets, stimulate local economies, and deliver climate change mitigation and adaptation benefits.

Digital tools for advancing clean energy and health

Expanding digital platforms for data collection is essential to understand energy access, health impacts, and policy effectiveness.^{166,167} Traditional surveys often lag behind rapid policy shifts and evolving consumer behaviour, whereas digital tracking can capture real-time fuel use patterns—including consumption, quality, and fuel stacking—and monitor sales data to improve energy use quantification for carbon reduction accounting. Improved health outcome data also enable more accurate estimations of associations across diverse risk factors and disease outcomes, enabling better estimates of public health status and benefits of specific policies.

Simultaneously, integrating digital financial services enables flexible payment systems that make clean energy more accessible to low-income households by spreading investments over time or enabling microtransactions. These systems help overcome cost barriers and provide timely, transparent data. Policy makers can use this information to fine-tune interventions, better target vulnerable populations, and assess the long-term impacts of energy policies on health and climate change mitigation.

Conditions for change

What will it take to address priority areas and make meaningful progress? Effective clean energy transitions in LMICs demand a supportive political climate, strong local commitment, and robust cross-national research capacity. Although high-income countries are responsible for most fossil fuel emissions, the resulting climate-related health and environmental harms affect low-income and socially or politically marginalised populations the hardest. These individuals consume less energy, have the lowest adaptive capacities, and rely on polluting fuels to meet basic energy needs. Still, many energy choices remain local; whether a household adopts a clean cookstove or a community invests in grid expansion depends on local infrastructure and economic realities.

The legacy of past and present energy use further complicates decision making. Decades of fossil fuel dependency have shaped climate forces that now influence households, grids, and policy choices. If persistent inequities leave basic needs unmet, energy transitions could become lower priorities, resulting in fewer job opportunities, lower incomes, and greater risk of disaster. Consistent political support is crucial. When governments tie clean energy to local priorities (eg, linking clean cooking initiatives to women's empowerment), they mobilise resources and shape policies that reflect real-world needs. However, global clean energy ambitions have stalled amid technological, financial, and political constraints.²² Shifting administrations and short-term electoral agendas risk sidelining clean energy policies, potentially reinforcing existing inequalities.

Reliable financing is another key factor. Clean energy projects in LMICs often rely on international funding, yet

changing donor commitments and the absence of a unified global financing and governance framework leaves these initiatives vulnerable. In this context, institutions like WHO and the IEA offer valuable guidance, but probably cannot replace the sustained financial backing that a cohesive global agenda once provided. Bridging the gap between research and practice also requires improved cross-national research capacity. Standardised data collection, high-quality information sharing, and collaborative studies can better illuminate the links between energy access, socioeconomic conditions, and health.

Conclusion

The promise of clean energy to improve public health depends not on increased access but on fully displacing polluting fuels—a transition that remains out of reach for many low-income and socially or politically marginalised communities. Clean energy must be reliable at all times. For low-income families, the choice between clean and conventional fuels is driven by affordability, availability, and reliability. Every dollar allocated to cleaner energy is one less dollar for food, health care, or education. Without measures to address these competing priorities and ensure a stable supply of clean energy, even the best-intentioned initiatives can deliver only modest benefits.

Furthermore, expanding clean energy access is not enough on its own. It must be integrated with complementary investments in health care, water and sanitation, and nutrition, among others. Coordinated initiatives, such as providing reliable electrification alongside improved water and sewerage infrastructure, can maximise operational efficiency and bolster system resilience. By leveraging digital tools, targeted subsidies, and robust infrastructure, community-wide energy systems can be transformed, breaking the cycle of energy poverty and delivering lasting public health and economic benefits.

Accelerating the shift away from polluting fuels is a crucial imperative both to fight climate change and address profound global inequities. Moving away from traditional energy sources will reduce greenhouse gas emissions and improve local air quality—benefits that are especially crucial for marginalised communities who bear the brunt of health and environmental harms. By aligning our goals for clean energy with those for public health, social equity, and climate action, we can lift every community into a healthier, more sustainable future.

Contributors

Conceptualisation: CFG, AG-W, and TC. Writing of the original draft: CFG and AG-W. Writing, review, and editing: all authors.

Declaration of interests

We declare no competing interests.

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References

- 1 Hall C, Tharakan P, Hallock J, Cleveland C, Jefferson M. Hydrocarbons and the evolution of human culture. *Nature* 2003; **426**: 318–22.
- 2 International Energy Agency. Tracking SDG7: the energy progress report. 2024. International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, World Health Organization. 2024. <https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2024> (accessed Feb 27, 2025).
- 3 Brauer M, Roth GA, Aravkin AY, et al, and the GBD 2021 Risk Factors Collaborators. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403**: 2162–203.
- 4 WHO. Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. World Health Organization. 2016.
- 5 Min B, O’Keeffe ZP, Abidoye B, et al. Lost in the dark: a survey of energy poverty from space. *Joule* 2024; **8**: 1982–98.
- 6 International Energy Agency. Electricity 2025: analysis and forecast to 2027. International Energy Agency. 2025. <https://www.iea.org/reports/electricity-2025> (accessed Feb 27, 2025).
- 7 Shankar AV, Quinn A, Dickinson KL, et al. Everybody stacks: lessons from household energy case studies to inform design principles for clean energy transitions. *Energy Policy* 2020; **141**: 111468.
- 8 Puzzolo E, Pope D, Stanistreet D, Rehfuess EA, Bruce NG. Clean fuels for resource-poor settings: a systematic review of barriers and enablers to adoption and sustained use. *Environ Res* 2016; **146**: 218–34.
- 9 Gill-Wiehl A, Ray I, Kammen D. Is clean cooking affordable? A review. *Renew Sustain Energy Rev* 2021; **151**: 111537.
- 10 Perros T, Allison AL, Tomei J, Parikh P. Behavioural factors that drive stacking with traditional cooking fuels using the COM-B model. *Nat Energy* 2022; **7**: 886–98.
- 11 Blimpo MP, Postepska A, Xu Y. Why is household electricity uptake low in sub-Saharan Africa? *World Dev* 2020; **133**: 105002.
- 12 Lee K, Miguel E, Wolfram C. Appliance ownership and aspirations among electric grid and home solar households in rural Kenya. *Am Econ Rev* 2016; **106**: 89–94.
- 13 Lee K, Miguel E, Wolfram C. Does household electrification supercharge economic development? *J Econ Perspect* 2020; **34**: 122–44.
- 14 Aklin M, Cheng C, Urpelainen J, Ganesan K, Jain A. Factors affecting household satisfaction with electricity supply in rural India. *Nat Energy* 2016; **1**: 16170.
- 15 Banerjee AV, Duflo E. The economic lives of the poor. *J Econ Perspect* 2007; **21**: 141–67.
- 16 WHO. Defining clean fuels and technologies. World Health Organization. 2025. <https://www.who.int/tools/clean-household-energy-solutions-toolkit/module-7-defining-clean> (accessed March 2, 2025).
- 17 Gould CF, Urpelainen J. The gendered nature of liquefied petroleum gas stove adoption and use in rural India. *J Dev Stud* 2020; **56**: 1309–29.
- 18 Krishnapriya PP, Chandrasekaran M, Jeuland M, Pattanayak SK. Do improved cookstoves save time and improve gender outcomes? Evidence from six developing countries. *Energy Econ* 2021; **102**: 105456.
- 19 Chandrasekaran M, Krishnapriya PP, Jeuland M, Pattanayak SK. Gender empowerment and energy access: evidence from seven countries. *Environ Res Lett* 2023; **18**: 045003.
- 20 Haines A. Energy and health Series. *Lancet* 2007; **370**: 922.
- 21 Ritchie H, Rosado P. Electricity mix. Our World in Data. 2020. <https://ourworldindata.org/electricity-mix> (accessed July 30, 2025).
- 22 Yergin D, Orszag P, Arya A. The troubled energy transition. *Foreign Affairs*. Feb 25, 2025. <https://www.foreignaffairs.com/united-states/troubled-energy-transition-yergin-orszag-arya> (accessed March 2, 2025).
- 23 UN. Take action for the Sustainable Development Goals. United Nations. 2025. <https://www.un.org/sustainabledevelopment/sustainable-development-goals/> (accessed March 2, 2025).
- 24 International Energy Agency. World energy outlook 2022. International Energy Agency. 2022. <https://www.iea.org/reports/world-energy-outlook-2022> (accessed Feb 27, 2025).
- 25 Gill-Wiehl A, Gould CF, Jeuland M, et al. Beyond access: clean energy use in low-income and middle-income countries. *Lancet Glob Health* 2026; **14**: e598–611.
- 26 Pillarisetti A, Daouda M, Gould CF, et al. Household energy use and health in low-income and middle-income countries. *Lancet Glob Health* 2026; **14**: e612–25.
- 27 Vinci S, Kwong LH, Miles SB, et al. Reliable electricity to advance quality health care in low-resource settings. *Lancet Glob Health* 2026; **14**: e626–39.
- 28 Scovronick N, Shiwang J, Ferranna M, et al. Global climate justice and the future of air quality co-benefits in low-income and middle-income countries: an energy, climate, and health modelling study. *Lancet Glob Health* 2026; **14**: e512–23.
- 29 Shupler M, Mangeni J, Tawiah T, et al. Modelling of supply and demand-side determinants of liquefied petroleum gas consumption in peri-urban Cameroon, Ghana, and Kenya. *Nat Energy* 2021; **6**: 1198–210.
- 30 Puzzolo E, Zerriffi H, Carter E, et al. Supply considerations for scaling up clean cooking fuels for household energy in low- and middle-income countries. *GeoHealth* 2019; **3**: 370–90.
- 31 Lee K, Miguel E, Wolfram C. Experimental evidence on the economics of rural electrification. *J Polit Econ* 2020; **128**: 1523–65.
- 32 Gill-Wiehl A, Kammen DM, Haya BK. Pervasive over-crediting from cookstove offset methodologies. *Nat Sustain* 2024; **7**: 191–202.
- 33 Pillarisetti A, Allen T, Ruiz-Mercado I, et al. Small, smart, fast, and cheap: microchip-based sensors to estimate air pollution exposures in rural households. *Sensors* 2017; **17**: 1879.
- 34 Pillarisetti A, Gill M, Allen T, et al. A low-cost stove use monitor to enable conditional cash transfers. *EcoHealth* 2018; **15**: 768–76.
- 35 Clasen T, Smith KR. Let the “A” in WASH stand for air: integrating research and interventions to improve household air pollution (HAP) and water, sanitation and hygiene (WaSH) in low-income settings. *Environ Health Perspect* 2019; **127**: 25001.
- 36 Romanello M, Walawender M, Hsu SC, et al. The 2024 report of the *Lancet* Countdown on health and climate change: facing record-breaking threats from delayed action. *Lancet* 2024; **404**: 1847–96.
- 37 Gould CF, Bejarano ML, De La Cuesta B, et al. Climate and health benefits of a transition from gas to electric cooking. *Proc Natl Acad Sci USA* 2023; **120**: e2301061120.
- 38 Chirakijja J, Jayachandran S, Ong P. The mortality effects of winter heating prices. *Econ J* 2023; **134**: 402–17.
- 39 Baldi D, Moner-Girona M, Fumagalli E, Fahl F. Planning sustainable electricity solutions for refugee settlements in sub-Saharan Africa. *Nat Energy* 2022; **7**: 369–79.
- 40 Aiken E, Ashraf A, Blumenstock J, Guiteras R, Mobarak AM. Scalable targeting of social protection: when do algorithms out-perform surveys and community knowledge? National Bureau of Economic Research. 2025. <https://www.nber.org/papers/w33919> (accessed July 30, 2025).
- 41 Jeuland M, Pattanayak SK, Bluffstone R. The economics of household air pollution. *Annu Rev Resour Econ* 2015; **7**: 81–108.
- 42 Kwong LH, Bailis R, Daouda M, et al. Powering health with energy in low-income and middle-income countries. *Lancet Glob Health* 2026; **14**: e589–97.
- 43 Perros T, Tomei J, Parikh P. Stakeholder perspectives on the future of clean cooking in sub-Saharan Africa and the role of pay-as-you-go LPG in expanding access. *Energy Res Soc Sci* 2024; **112**: 103494.
- 44 Shupler M, O’Keefe M, Puzzolo E, et al. Pay-as-you-go liquefied petroleum gas supports sustainable clean cooking in Kenyan informal urban settlement during COVID-19 lockdown. *Appl Energy* 2021; **292**: 116769.
- 45 Jack BK, Smith G. Pay as you go: prepaid metering and electricity expenditures in South Africa. *Am Econ Rev* 2015; **105**: 237–41.
- 46 Witinok-Huber R, Keller KP, Abimana E, et al. Impact of randomly assigned “pay-as-you-go” liquefied petroleum gas prices on energy use for cooking: experimental pilot evidence from rural Rwanda. *Energy Sustain Dev* 2024; **80**: 101455.
- 47 Joskow PL, Wolfram CD. Dynamic pricing of electricity. *Am Econ Rev* 2012; **102**: 381–85.
- 48 Mobarak AM. Assessing social aid: the scale-up process needs evidence, too. *Nature* 2022; **609**: 892–94.
- 49 Buera FJ, Kaboski JP, Townsend RM. From micro to macro development. *J Econ Lit* 2023; **61**: 471–503.

- 50 Barrington-Leigh C, Baumgartner J, Carter E, Robinson BE, Tao S, Zhang Y. An evaluation of air quality, home heating and well-being under Beijing's programme to eliminate household coal use. *Nat Energy* 2019; 4: 416–23.
- 51 Wekesa C, Mutta D, Larwanou M, Kowero G, Roos A. Effects of charcoal ban on value chains and livelihoods in Kenyan coast – stakeholders' perceptions. *Environ Dev* 2023; 45: 100809.
- 52 Stoner O, Lewis J, Martínez IL, Gumy S, Economou T, Adair-Rohani H. Household cooking fuel estimates at global and country level for 1990 to 2030. *Nat Commun* 2021; 12: 5793.
- 53 International Energy Agency. Net zero by 2050. International Energy Agency. 2021. <https://www.iea.org/reports/net-zero-by-2050> (accessed July 30, 2025).
- 54 Lewandowsky S. Climate change disinformation and how to combat it. *Annu Rev Public Health* 2021; 42: 1–21.
- 55 Brulle RJ. The climate lobby: a sectoral analysis of lobbying spending on climate change in the USA, 2000 to 2016. *Clim Change* 2018; 149: 289–303.
- 56 Budolfson M, Dennig F, Erickson F, et al. Climate action with revenue recycling has benefits for poverty, inequality and well-being. *Nat Clim Chang* 2021; 11: 1111–16.
- 57 Murray B, Rivers N. British Columbia's revenue-neutral carbon tax: a review of the latest "grand experiment" in environmental policy. *Energy Policy* 2015; 86: 674–83.
- 58 Green F. Anti-fossil fuel norms. *Clim Change* 2018; 150: 103–16.
- 59 Johnson M, Pillarisetti A, Piedrahita R, et al, and the Household Air Pollution Intervention Network (HAPIN) Trial Investigators. Exposure contrasts of pregnant women during the household air pollution intervention network randomized controlled trial. *Environ Health Perspect* 2022; 130: 97005.
- 60 Ye W, Campbell D, Johnson M, et al. Exposure contrasts of women aged 40–79 years during the household air pollution intervention network randomized controlled trial. *Environ Sci Technol* 2025; 59: 69–81.
- 61 Chillrud SN, Ae-Ngibise KA, Gould CF, et al. The effect of clean cooking interventions on mother and child personal exposure to air pollution: results from the Ghana Randomized Air Pollution and Health Study (GRAPHS). *J Expo Sci Environ Epidemiol* 2021; 31: 683–98.
- 62 Pope D, Johnson M, Fleeman N, et al. Are cleaner cooking solutions clean enough? A systematic review and meta-analysis of particulate and carbon monoxide concentrations and exposures. *Environ Res Lett* 2021; 16: 083002.
- 63 Beentjes D, Shears RK, French N, Neill DR, Kadioglu A. Mechanistic insights into the impact of air pollution on pneumococcal pathogenesis and transmission. *Am J Respir Crit Care Med* 2022; 206: 1070–80.
- 64 Peters A, Nawrot TS, Baccarelli AA. Hallmarks of environmental insults. *Cell* 2021; 184: 1455–68.
- 65 Al-Kindi SG, Brook RD, Biswal S, Rajagopalan S. Environmental determinants of cardiovascular disease: lessons learned from air pollution. *Nat Rev Cardiol* 2020; 17: 656–72.
- 66 Gordon SB, Bruce NG, Grigg J, et al. Respiratory risks from household air pollution in low and middle income countries. *Lancet Respir Med* 2014; 2: 823–60.
- 67 Landrigan PJ, Fuller R, Acosta NJR, et al. The Lancet Commission on pollution and health. *Lancet* 2018; 391: 462–512.
- 68 Nyadanu SD, Dunne J, Tessema GA, et al. Prenatal exposure to ambient air pollution and adverse birth outcomes: an umbrella review of 36 systematic reviews and meta-analyses. *Environ Pollut* 2022; 306: 119465.
- 69 Currie J, Zivin JG, Mullins J, Neidell M. What do we know about short- and long-term effects of early-life exposure to pollution? *Annu Rev Resour Econ* 2014; 6: 217–47.
- 70 Zivin JG, Neidell M. Air pollution's hidden impacts. *Science* 2018; 359: 39–40.
- 71 Lai PS, Lam NL, Gallery B, et al. Household air pollution interventions to improve health in low- and middle-income countries: an official American Thoracic Society Research Statement. *Am J Respir Crit Care Med* 2024; 209: 909–27.
- 72 Clasen TF, Chang HH, Thompson LM, et al, and the HAPIN Investigators. Liquefied petroleum gas or biomass for cooking and effects on birth weight. *N Engl J Med* 2022; 387: 1735–46.
- 73 Checkley W, Thompson LM, Hossen S, et al, and the HAPIN Investigators. Cooking with liquefied petroleum gas or biomass and fetal growth outcomes: a multi-country randomised controlled trial. *Lancet Glob Health* 2024; 12: e815–25.
- 74 McCollum ED, McCracken JP, Kirby MA, et al, and the HAPIN Investigators. Liquefied petroleum gas or biomass cooking and severe infant pneumonia. *N Engl J Med* 2024; 390: 32–43.
- 75 Fandiño-Del-Rio M, Kephart JL, Williams KN, et al, and the CHAP Trial Investigators. Household air pollution concentrations after liquefied petroleum gas interventions in rural Peru: findings from a one-year randomized controlled trial followed by a one-year pragmatic crossover trial. *Environ Health Perspect* 2022; 130: 57007.
- 76 Kephart JL, Fandiño-Del-Rio M, Williams KN, et al, and the CHAP Trial Investigators. Nitrogen dioxide exposures from LPG stoves in a cleaner-cooking intervention trial. *Environ Int* 2021; 146: 106196.
- 77 Shen G, Hays MD, Smith KR, Williams C, Faircloth JW, Jetter JJ. Evaluating the performance of household liquefied petroleum gas cookstoves. *Environ Sci Technol* 2018; 52: 904–15.
- 78 Shen G, Gaddam CK, Ebersviller SM, et al. A laboratory comparison of emission factors, number size distributions, and morphology of ultrafine particles from 11 different household cookstove-fuel systems. *Environ Sci Technol* 2017; 51: 6522–32.
- 79 Lewis JJ, Pattanayak SK. Who adopts improved fuels and cookstoves? A systematic review. *Environ Health Perspect* 2012; 120: 637–45.
- 80 Imelda. Indoor air pollution and infant mortality: a new approach. *AEA Pap Proc* 2018; 108: 416–21.
- 81 Lee M, Chang J, Deng Q, et al. Effects of a coal to clean heating policy on acute myocardial infarction in Beijing: a difference-in-differences analysis. *Lancet Planet Health* 2024; 8: e924–32.
- 82 Liao L, Kong S, Du M. The effect of clean heating policy on individual health: evidence from China. *China Econ Rev* 2025; 89: 102309.
- 83 Gould CF, Bejarano ML, Kioumourtoglou MA, et al. Widespread clean cooking fuel scale-up and under-5 lower respiratory infection mortality: an ecological analysis in Ecuador, 1990–2019. *Environ Health Perspect* 2023; 131: 37017.
- 84 Smith KR. In praise of power. *Science* 2014; 345: 603.
- 85 Ratledge N, Cadamuro G, de la Cuesta B, Stigler M, Burke M. Using machine learning to assess the livelihood impact of electricity access. *Nature* 2022; 611: 491–95.
- 86 Burlig F, Preonas L. Out of the darkness and into the light? Development effects of rural electrification. *J Polit Econ* 2024; 132: 2937–71.
- 87 Lee K, Miguel E, Wolfram C. Electrification and economic development: a microeconomic perspective. University of California Berkeley Center for Effective Global Action. 2017. <https://escholarship.org/uc/item/6bd7t9ng> (accessed March 3, 2025).
- 88 Stern DI, Burke PJ, Bruns SB. The impact of electricity on economic development: a macroeconomic perspective. University of California Berkeley Center for Effective Global Action. 2019. <https://escholarship.org/uc/item/7jb0015q> (accessed March 3, 2025).
- 89 Lam NL, Smith KR, Gauthier A, Bates MN. Kerosene: a review of household uses and their hazards in low- and middle-income countries. *J Toxicol Environ Health B Crit Rev* 2012; 15: 396–432.
- 90 Barron M, Torero M. Household electrification and indoor air pollution. *J Environ Econ Manage* 2017; 86: 81–92.
- 91 Ankel-Peters J, Schmidt CM. Rural electrification, the credibility revolution, and the limits of evidence-based policy. *Environ Dev Econ* 2025; 30: 70–81.
- 92 Aklin M, Bayer P, Harish SP, Urpelainen J. Does basic energy access generate socioeconomic benefits? A field experiment with off-grid solar power in India. *Sci Adv* 2017; 3: e1602153.
- 93 Peters J, Sievert M, Toman MA. Rural electrification through mini-grids: challenges ahead. *Energy Policy* 2019; 132: 27–31.
- 94 Brouwer AF, Zahid MH, Eisenberg MC, et al. Understanding the effectiveness of water, sanitation, and hygiene interventions: a counterfactual simulation approach to generalizing the outcomes of intervention trials. *Environ Health Perspect* 2024; 132: 127003.
- 95 Bouguen A, Huang Y, Kremer M, Miguel E. Using randomized controlled trials to estimate long-run impacts in development economics. *Annu Rev Econ* 2019; 11: 523–61.

- 96 Banerjee A, Duflo E, Goldberg N, et al. A multifaceted program causes lasting progress for the very poor: evidence from six countries. *Science* 2015; **348**: 1260799.
- 97 Egger D, Haushofer J, Miguel E, Niehaus P, Walker M. General equilibrium effects of cash transfers: experimental evidence from Kenya. *Econometrica* 2022; **90**: 2603–43.
- 98 Lelieveld J, Haines A, Burnett R, et al. Air pollution deaths attributable to fossil fuels: observational and modelling study. *BMJ* 2023; **383**: e077784.
- 99 Pörtner HO, Roberts DC, Tignor MMB, et al, eds. Climate change 2022: impacts, adaptation and vulnerability. Intergovernmental Panel on Climate Change. 2022.
- 100 Haines A, Ebi K. The imperative for climate action to protect health. *N Engl J Med* 2019; **380**: 263–73.
- 101 Carleton TA, Hsiang SM. Social and economic impacts of climate. *Science* 2016; **353**: aad9837.
- 102 Nazaroff WW. Previsualizing a post-combustion world. *Indoor Air* 2015; **25**: 569–71.
- 103 Moore FC, Drupp MA, Rising J, Dietz S, Rudik I, Wagner G. Synthesis of evidence yields high social cost of carbon due to structural model variation and uncertainties. *Proc Natl Acad Sci USA* 2024; **121**: e2410733121.
- 104 Rennert K, Erickson F, Prest BC, et al. Comprehensive evidence implies a higher social cost of CO₂. *Nature* 2022; **610**: 687–92.
- 105 Rising J, Tedesco M, Piontek F, Stainforth DA. The missing risks of climate change. *Nature* 2022; **610**: 643–51.
- 106 Andrijevic M, Schleussner CF, Crespo Cuarema J, et al. Towards scenario representation of adaptive capacity for global climate change assessments. *Nat Clim Chang* 2023; **13**: 778–87.
- 107 Rode A, Carleton T, Delgado M, et al. Estimating a social cost of carbon for global energy consumption. *Nature* 2021; **598**: 308–14.
- 108 Rode A, Baker R, Carleton T, et al. Is workplace temperature a valuable job amenity? Implications for climate change. *SSRN* 2024; published online July 2. <https://papers.ssrn.com/abstract=4882247> (preprint).
- 109 Carleton T, Jina A, Delgado M, et al. Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *Q J Econ* 2022; **137**: 2037–105.
- 110 Burke M, Hsiang SM, Miguel E. Global non-linear effect of temperature on economic production. *Nature* 2015; **527**: 235–39.
- 111 Callahan CW, Mankin JS. Globally unequal effect of extreme heat on economic growth. *Sci Adv* 2022; **8**: eadd3726.
- 112 Callahan CW. Present and future limits to climate change adaptation. *Nat Sustain* 2025; **8**: 336–42.
- 113 Berrang-Ford L, Siders AR, Lesnikowski A, et al. A systematic global stocktake of evidence on human adaptation to climate change. *Nat Clim Chang* 2021; **11**: 989–1000.
- 114 Carleton T, Duflo E, Jack BK, Zappalà G. Adaptation to climate change. In: Barrage L, Hsiang S, eds. *Handbook of the Economics of Climate Change* volume 1. Elsevier, 2024: 143–248.
- 115 Barreca A, Clay K, Deschenes O, Greenstone M, Shapiro JS. Adapting to climate change: the remarkable decline in the US temperature-mortality relationship over the twentieth century. *J Polit Econ* 2016; **124**: 105–59.
- 116 Wu X, Weinberger KR, Wellenius GA, Dominici F, Braun D. Assessing the causal effects of a stochastic intervention in time series data: are heat alerts effective in preventing deaths and hospitalizations? *Biostatistics* 2023; **25**: 57–79.
- 117 Abajian AC, Carleton T, Meng KC, Deschênes O. Quantifying the global climate feedback from energy-based adaptation. *Nat Commun* 2025; **16**: 3928.
- 118 Berry PM, Brown S, Chen M, et al. Cross-sectoral interactions of adaptation and mitigation measures. *Clim Change* 2015; **128**: 381–93.
- 119 Grafakos S, Trigg K, Landauer M, Chelleri L, Dhakal S. Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities. *Clim Change* 2019; **154**: 87–106.
- 120 Pavanello F, De Cian E, Davide M, et al. Air-conditioning and the adaptation cooling deficit in emerging economies. *Nat Commun* 2021; **12**: 6460.
- 121 Barreca A, Park RJ, Stainier P. High temperatures and electricity disconnections for low-income homes in California. *Nat Energy* 2022; **7**: 1052–64.
- 122 Davis L, Gertler P, Jarvis S, Wolfram C. Air conditioning and global inequality. *Glob Environ Change* 2021; **69**: 102299.
- 123 Pachauri S, Pelz S, Bertram C, et al. Fairness considerations in global mitigation investments. *Science* 2022; **378**: 1057–59.
- 124 International Energy Agency. Tracking SDG7: The Energy Progress Report, 2025. International Energy Agency. 2025.
- 125 West TAP, Wunder S, Sills EO, et al. Action needed to make carbon offsets from forest conservation work for climate change mitigation. *Science* 2023; **381**: 873–77.
- 126 Callahan CW, Mankin JS. National attribution of historical climate damages. *Clim Change* 2022; **172**: 40.
- 127 Chancel L, Mohren C, Bothe P, Semieniuk G. Climate change and the global distribution of wealth. *Nat Clim Chang* 2025; **15**: 364–74.
- 128 Zhang AT, Patnaik S, Jha S, Agrawal S, Gould CF, Urpelainen J. Evidence of multidimensional gender inequality in energy services from a large-scale household survey in India. *Nat Energy* 2022; **7**: 698–707.
- 129 Health Effects Institute. State of Global Air Report 2024. Health Effects Institute, Institute for Health and Metrics Evaluation. 2024.
- 130 Jenkins KEH, Sovacool BK, Mouter N, Hacking N, Burns MK, McCauley D. The methodologies, geographies, and technologies of energy justice: a systematic and comprehensive review. *Environ Res Lett* 2021; **16**: 043009.
- 131 Goforth T, Levin T, Nock D. Incorporating energy justice and equity objectives in power system models. *Renew Sustain Energy Rev* 2025; **210**: 115155.
- 132 Gill-Wiehl A, Ferrall I, Kammen DM. Equal goods, but inequitable capabilities? A gender-differentiated study of off-grid solar energy in rural Tanzania. *Energy Res Soc Sci* 2022; **91**: 102726.
- 133 Osumuyiwa O, Odero M, Wall A, et al. Mobilizing power quality and reliability measurements for electricity equity and justice in Africa. *Nat Energy* 2025; **10**: 395–403.
- 134 Stock R, Birkenholtz T. Photons vs firewood: female (dis) empowerment by solar power in India. *Gend Place Cult* 2020; **27**: 1628–51.
- 135 Velasco-Herrejon P, Bauwens T. Energy justice from the bottom up: a capability approach to community acceptance of wind energy in Mexico. *Energy Res Soc Sci* 2020; **70**: 101711.
- 136 Garces E, Tomei J, Franco CJ, Dynner I. Lessons from last mile electrification in Colombia: examining the policy framework and outcomes for sustainability. *Energy Res Soc Sci* 2021; **79**: 102156.
- 137 Mensah JK. Electricity and informal settlements: towards achieving SDG 7 in developing countries. *Energy Res Soc Sci* 2022; **93**: 102844.
- 138 Haselip J, Chen K, Marwah H, Puzzolo E. Cooking in the margins: exploring the role of liquefied petroleum gas for refugees in low-income countries. *Energy Res Soc Sci* 2022; **83**: 102346.
- 139 Parikh P, Fu K, Parikh H, McRobie A, George G. Infrastructure provision, gender, and poverty in Indian slums. *World Dev* 2015; **66**: 468–86.
- 140 Baker E, Nock D, Levin T, et al. Who is marginalized in energy justice? Amplifying community leader perspectives of energy transitions in Ghana. *Energy Res Soc Sci* 2021; **73**: 101933.
- 141 Dupas P. Health behavior in developing countries. *Annu Rev Econ* 2011; **3**: 425–49.
- 142 Sovacool BK. Reviewing, reforming, and rethinking global energy subsidies: towards a political economy research agenda. *Ecol Econ* 2017; **135**: 150–63.
- 143 Harring N, Jönsson E, Matti S, Mundaca G, Jagers SC. Cross-national analysis of attitudes towards fossil fuel subsidy removal. *Nat Clim Chang* 2023; **13**: 244–49.
- 144 Gould CF, Schlesinger S, Toasa AO, et al. Government policy, clean fuel access, and persistent fuel stacking in Ecuador. *Energy Sustain Dev* 2018; **46**: 111–22.
- 145 Greve H, Lay J. “Stepping down the ladder”: the impacts of fossil fuel subsidy removal in a developing country. *J Assoc Environ Resour Econ* 2023; **10**: 121–58.
- 146 Rose J, Ankel-Peters J, Hodel H, Sall M, Bensch G. The interrupted modern energy transition to LPG and the charcoal renaissance in urban Senegal. *NPJ Clim Action* 2024; **3**: 96.
- 147 Arze del Granado FJ, Coady D, Gillingham R. The unequal benefits of fuel subsidies: a review of evidence for developing countries. *World Dev* 2012; **40**: 2234–48.

- 148 Patnaik S, Jha S. Caste, class and gender in determining access to energy: a critical review of LPG adoption in India. *Energy Res Soc Sci* 2020; **67**: 101530.
- 149 Pollard SL, Williams KN, O'Brien CJ, et al. An evaluation of the Fondo de Inclusión Social Energético program to promote access to liquefied petroleum gas in Peru. *Energy Sustain Dev* 2018; **46**: 82–93.
- 150 Gould CF, Schlesinger SB, Molina E, Bejarano ML, Valarezo A, Jack DW. Household fuel mixes in peri-urban and rural Ecuador: explaining the context of LPG, patterns of continued firewood use, and the challenges of induction cooking. *Energy Policy* 2020; **136**: 111053.
- 151 Aiken E, Bellue S, Karlan D, Udry C, Blumenstock JE. Machine learning and phone data can improve targeting of humanitarian aid. *Nature* 2022; **603**: 864–70.
- 152 Mani S, Jain A, Tripathi S, Gould CF. The drivers of sustained use of liquified petroleum gas in India. *Nat Energy* 2020; **5**: 450–57.
- 153 Arnold C. Can AI help beat poverty? Researchers test ways to aid the poorest people. *Nature* 2025; **638**: 878–80.
- 154 Pu CJ, Lambin EF, Kusimawe I, et al. How poverty is measured impacts who gets classified as impoverished. *Proc Natl Acad Sci USA* 2024; **121**: e2316730121.
- 155 Gill-Wiehl A, Ray I. Affording a clean stack: evidence from cookstoves in urban Kenya. *Energy Res Soc Sci* 2023; **105**: 103275.
- 156 Hahn RW, Metcalfe RD. Efficiency and equity impacts of energy subsidies. *Am Econ Rev* 2021; **111**: 1658–88.
- 157 Jewell J, McCollum D, Emmerling J, et al. Limited emission reductions from fuel subsidy removal except in energy-exporting regions. *Nature* 2018; **554**: 229–33.
- 158 Gould CF, Bailis R, Balakrishnan K, et al. In praise of cooking gas subsidies: transitional fuels to advance health and equity. *Environ Res Lett* 2024; **19**: 081002.
- 159 Ridley M, Rao G, Schilbach F, Patel V. Poverty, depression, and anxiety: causal evidence and mechanisms. *Science* 2020; **370**: eaay0214.
- 160 Swinburn BA, Kraak VI, Allender S, et al. The global syndemic of obesity, undernutrition, and climate change: the *Lancet* Commission report. *Lancet* 2019; **393**: 791–846.
- 161 Haakenstad A, Yearwood JA, Fullman N, et al, and the GBD 2019 Healthcare Access and Quality Collaborators. Assessing performance of the Healthcare Access and Quality Index, overall and by select age groups, for 204 countries and territories, 1990–2019: a systematic analysis from the Global Burden of Disease Study 2019. *Lancet Glob Health* 2022; **10**: e1715–43.
- 162 Currie J, Vogl T. Early-life health and adult circumstance in developing countries. *Annu Rev Econ* 2013; **5**: 1–36.
- 163 Lee JT, Callaway DS. The cost of reliability in decentralized solar power systems in sub-Saharan Africa. *Nat Energy* 2018; **3**: 960–68.
- 164 Lemanski C, Haque AN, de Groot J, McAskill N. The false optimism of electrification: why universal electricity access has not delivered urban energy transformation in South Africa. *Energy Policy* 2025; **198**: 114506.
- 165 Nock D, Levin T, Baker E. Changing the policy paradigm: a benefit maximization approach to electricity planning in developing countries. *Appl Energy* 2020; **264**: 114583.
- 166 Ibrahim H, Liu X, Zariffa N, Morris AD, Denniston AK. Health data poverty: an assailable barrier to equitable digital health care. *Lancet Digit Health* 2021; **3**: e260–65.
- 167 Diaz-Bonilla C, Radyakin S. Botswana confronts data challenges head-on in transition to digital data collection and management. World Bank Blogs. Jan 28, 2025. <https://blogs.worldbank.org/en/opendata/botswana-confronts-data-challenges-head-on-in-transition-to-digi> (accessed March 3, 2025).

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