EVIDENCE PAPER

Energy and environment

Clare Balboni | Tim Dobermann
Michael Greenstone | Mar Reguant
Nicholas Ryan

July 2024

DIRECTED BY

LSE | UNIVERSITY OF OXFORD

FUNDED BY

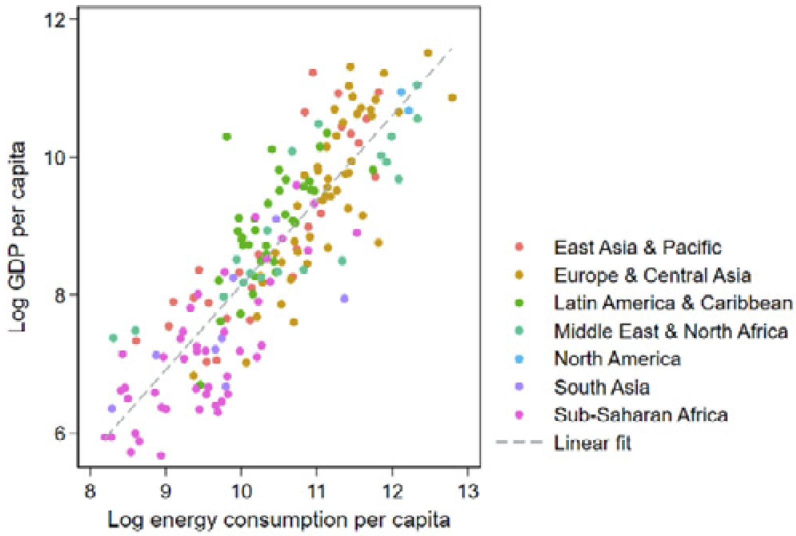
UKaid from the British people

Contents

1. Introduction[1]

Economic development requires sharp increases in the consumption of energy (**Figure 1**). The reliability and cost of energy is a critical determinant of the competitiveness and growth of small and large businesses and household wellbeing. At the same time, the energy required for firms to grow and individuals to prosper creates externalities on the local and global environment. Left unabated, these externalities can drive down future economic growth and erode development's potential to improve human welfare (Burgess, Caria, Dobermann and Saggese, 2023). The principle question is therefore how vast energy needs can be sourced to fuel growth while conserving the natural assets that underpin welfare.

Figure 1: The relationship between fossil energy consumption and income



Data Source: WDI, 2015.
Notes: Economic development requires sharp increases in the consumption of energy. Figure generated by the authors using **World Development Indicators (WDI)** and taken from IGC's Evidence Paper on Energy and Environment, 2021.

The inequality across countries in energy consumption is even wider than in income. The average American uses over 12,000 kWh of electricity per year, the average Indian less than 1,250 kWh, and the average Ethiopian a mere 90 kWh – only enough for each citizen to power a 30-watt bulb for eight hours a day. Ethiopia cannot grow out of poverty with a single bulb for each citizen. More than a billion people, largely in South Asia and sub-Saharan Africa, live without clean, reliable, and affordable energy. Improving access to electricity for households and firms is the foremost priority.

1 Special thanks to Jaspar Bechtold, Lisa Pacheco, Allegra Saggese, and Veronica Salazar-Restrepo for their excellent research assistance, and to Nikita Sharma and Aman Mishra for their meticulous copyediting.

Economic growth since the first and second industrial revolutions has been driven by industrialisation, transportation, and electrification, all powered by fossil fuel combustion. This growth path has had harmful and damaging by-products from the start (Beach and Hanlon, 2017), and these externalities are now holding back economic growth. Rapidly industrialising countries like China and India face some of the worst air pollution in recorded history (Jacobson, 2012; WHO, 2016). These externalities have direct economic impacts. For example, workers in China are, on average, 6% less productive on high pollution days (Chang et al., 2019). Most of the increase in energy consumption in the coming decades will come from low- and middle-income countries (Wolfram et al., 2012). If the majority of that growth comes from fossil fuels - though falling, they are still expected to supply 69% of primary energy demand by 2040 (IEA, 2018) - it will create damaging consequences to health, productivity, and ecosystems in those countries and around the world (IPCC, 2022).

Figure 2: The relationship between carbon emissions and income, 2022

Notes: Economic growth since the first and second industrial revolutions has been driven by industrialisation, transportation, and electrification, all powered by fossil fuel combustion. This growth path has had harmful and damaging by-products from the start and these externalities are now holding back economic growth. Figure generated by the authors using **Our World in Data**.

Environmental externalities also have important implications for energy policy. Climate change and local pollution can disrupt energy supply and increase the demand for electricity for adaptive purposes. Extreme weather such as heavy rainfall, high winds, heat waves, and tropical storms can cripple energy infrastructure assets at all stages, from generation to transmission and distribution. This can cause long and damaging outages and impose severe economic costs (Zamuda et al., 2018). For some power generation systems, such as hydropower, prolonged droughts can further reduce production. This could pose a major challenge for low- and middle-income countries, such as eastern and southern Africa, which depend heavily on hydro capacity (Conway et al., 2017). On the demand side, households in low- and middle-income countries will experience significant increases in temperature and pollution. Adapting to these new circumstances will require more electricity to power appliances such as air conditioners and air purifiers. The agriculture industry will also require more energy for irrigation in response to higher temperatures and less frequent and more unpredictable rainfall.

The tension between access and growth on one side and externalities from energy consumption on the other is the centre of IGC's research agenda on energy.

Most existing energy policies are not adequate for achieving growth nor for addressing negative externalities. A pro-development energy policy is one that maximises energy access while limiting the external costs of energy use—both locally, within low- and middle-income countries, and globally. The tension between access and growth on one side and externalities from energy consumption on the other is the centre of IGC's research agenda on energy.

More recently, however, innovations in clean energy technologies, among others, have fundamentally changed the nature of this trade-off. Our research agenda focuses on identifying and implementing these innovations which accelerate the reduction of this trade-off.

We emphasise four main questions:

1. How will the remaining unelectrified global population, over 700 million people (IEA, 2023a), gain access to electricity, and what benefits will it bring for their welfare and livelihoods?
2. How can environmental regulation check the local harms from energy consumption in countries with weak enforcement capacity?
3. What are the most effective ways for low- and middle-income countries to adopt innovations that can slow the growth of greenhouse gas emissions associated with greater energy consumption?
4. How can individuals adapt to the impacts of climate change?

We review the literature on these questions and outline the areas we think have the greatest potential for research progress in the next five years. A few cross-cutting themes emerge when considering these questions. We touch on three of these here, as they help to organise our thinking in a wide range of disparate areas.

The first recurring theme is that the progress of technology has opened a new kind of pro-development energy policy that relies on renewable energy to a much greater degree. The cost of renewable electricity generation has come down exponentially over the past several years (IRENA 2018; Way, Ives, Mealy and Farmer, 2022). Solar is generating the cheapest electricity ever known to humankind (IEA, 2020). Renewables are now assuming a larger share of investments into new electricity generation. The modularity and collapsing cost of solar has opened up new kinds of off-grid power supply substitutes for traditional grid electrification (Burgess et al., 2020). In 2021, two thirds of newly installed non-fossil energy capacity was installed at a cheaper price than coal (IRENA, 2022), with the cost of solar plummeting (Ritchie et al., 2022). Renewable energy can reduce both local and global externalities from energy use, and is therefore an essential element of any pro-development energy policy. However, the shift to renewables brings with it a greater variability in electricity supply, with associated costs (Joskow, 2011; Joskow, 2019). This could put a particular strain on less developed energy systems and markets that are smaller or only partly integrated across space. Research is needed to help guide how renewable energy should be procured and integrated into power systems in low- and middle-income countries.

A second recurring theme is that the energy sector is intertwined with politics. Energy economics gives clear, standard prescriptions for how energy policy should work: eliminate subsidies, price at a marginal cost, set prices that incorporate the external costs of energy use, regulate natural monopolies, and so forth. Such prescriptions are politically all but impossible in many countries. Instead, we see, as a rule, that energy is wildly mispriced, and many segments of the energy sector are loss-making. Energy, rather than being priced at social cost, is often priced below private cost and used as a tool for redistribution. Because energy markets are often immature in low- and middle-income countries, the governments play a much larger role in energy's distribution than in high-income countries. Analysis on these markets and on potential reforms cannot escape the political economy of energy.

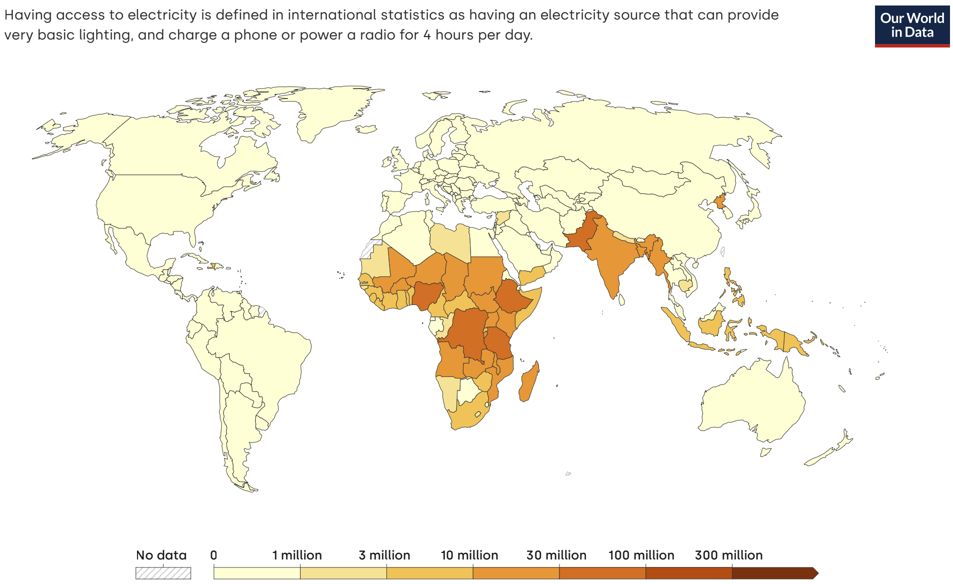
Our third cross-cutting theme is the importance of measurement and how we value natural resources, both for their extractive potential and the ecosystem services they provide. Previous conceptions of natural resources concentrated on the value derived from coal, oil, and gas for energy generation. Today's climate crisis warrants a more comprehensive valuation of nature - including natural capital, ecosystem services and biodiversity - as it provides a low-emissions alternative for energy production (i.e. hydro, biomass) and sequesters carbon. Diverse ecosystems can support agriculture production through pollination or soil nutrients, and forests and wetlands can mitigate shocks from natural disasters. Low- and middle-income countries now have the opportunity to leverage their natural capital in an evolving political landscape, where mitigation and ecosystem services continue to increase in value on a global scale. The role of natural capital is surfacing as a key tool to foster climate mitigation and adaptation globally.

We conclude by emphasising that to make progress in designing a pro-development energy policy, it is not enough for researchers to reiterate the standard prescription, or to measure and decry just how inefficient current policies are. Rather, a research agenda that aims to have influence in the real world must explore the constraints on energy policy that arise from equity, redistributive and political concerns, market failures, and governance failures. It may then use those findings to propose reforms that are not only desirable but practical.

2. Access to inexpensive, clean, and reliable energy

Energy access has many sides. Everyone, even the poorest populations, uses energy in their daily lives, be it for cooking food, staying warm, transporting themselves or their produce, lighting their home, or entertaining themselves and their families. The main difference in low- and middle-income countries is in the type and amount of energy used. In high-income countries, the energy services that meet these needs have converged to a set of convenient and relatively low-cost technologies, such as electricity and the combustion of natural gas and other fossil fuels. In low- and middle-income countries, a range of traditional energy technologies are used, each to their own purpose, and the transitions to modern technologies are often protracted.

Figure 3: Number of people without access to electricity, 2019



Data source: World Bank, OurWorldInData/energy | CC BY
Notes: Over 750 million people, mostly in sub-Saharan Africa and South Asia, do not have access to electricity. Figure generated by the authors using **Our World in Data**.

Cooking and lighting are examples of energy services in which both traditional and modern technologies serve the same needs, side by side, in the same countries or even the same communities. For cooking, 2.3 billion people use solid biomass fuel, such as charcoal, crop residue or cow dung (IEA, 2023b). As they grow richer and energy supply networks develop, many of these households switch to natural gas or electricity, which are cleaner, for households, and have a lower cost in household labour. This transition is unfolding at different rates in a range of low- and middle-income countries today. For lighting, over 750 million people, mostly in sub-Saharan Africa and South Asia, do not have access to electricity (**Figure 3**). The 'traditional' technology for these households is most often the kerosene lamp (the kerosene lamp, invented in the 1860s, itself supplanted various candle and lamp technologies (Nordhaus, 1996)). From the map, it is clear that much of the world's population without electricity is concentrated in areas of extreme poverty – in middle income countries such as India and Nigeria and in fragile states like the Democratic Republic of Congo and Sudan. Reaching universal access by 2030 will require an average annual investment around US$ 30 billion until 2030 (IEA, 2022b).

The long energy transition from traditional to modern sources of energy is inseparable from the process of economic development.

The long energy transition from traditional to modern sources of energy is inseparable from the process of economic development. We summarise the study of this transition under three broad questions:

1. **Energy demand:** what energy services and technologies do households demand, and what are the returns, both privately to households and businesses and socially to their broader economies, from increasing energy access?
2. **Energy supply:** how do market structure and government policy on energy supply affect the efficiency of energy markets? In creating efficient markets for the future, what can governments do to create a market which internalises the negative externalities from energy generation?
3. **The politics of energy:** what is the role of the state in energy markets, and how do institutional and political reforms shape the return on investments in energy access and renewable energy generation?

The first question is characterised by the most high-quality research to date—but, we will argue, there are still a number of large gaps in the evidence. The second and third questions are characterised by a long history of discussion around high-income-country markets, but relatively little evidence from low- and middle-income countries. There is substance to this gap. Historical experience may be a poor guide to creating policy today, since technological change—namely, the advent of low-cost renewable energy—has made many tenets of market design obsolete. Moreover, some policies that function well in high-income-country markets may do poorly in low- and middle-income-country markets, when state capacity is weaker or market failures are more widespread.

I. Energy demand and the benefits of access

The returns to energy access can be thought of in two parts: private returns and social returns.

Private returns are how much a household or business benefits from accessing modern energy. Benefits may take many forms, from better health and productivity to independence and security. These benefits are likely to increase in the presence of growing climate threats. For comparability, economists measure these benefits in terms of money. Private benefits can often be well-measured by demand, or willingness-to-pay (WTP), for energy. However, in the presence of market failures or household 'internalities'—benefits not accounted for by household's revealed preference choices—

measured demand may be an incomplete or inaccurate measure of private benefits. The first part of our discussion on energy demand considers under what conditions demand is a good measure of the private benefits of access, taking the example of the market for improved biomass cookstoves.

Social returns from energy access accrue to parties other than those consuming energy. Energy markets are of such policy interest precisely because social returns to energy access form an unusually large part of the gross benefits and costs of energy use. Much of this is down to environmental externalities, such as air and water pollution. Since environmental externalities are such an important object of policy, we consider them separately in Sections 3 (global externalities) and 4 (local externalities) below. In this section, we consider the social returns not due to environmental externalities. The second part of our discussion on energy demand considers why, aside from environmental harms, energy use may create external benefits or spillovers, focusing on access to electricity and the returns to electrification.

Challenges of measuring private benefits: the cookstove example

Is demand the right all-in measure of the private benefits of energy use? In principle, energy demand – a household's WTP for energy services – measures the value that they get from that service in monetary terms. In practice, demand may not capture all the benefits of using, or of saving, energy. There could be a variety of reasons why, such as informational market failures, agency problems, and credit constraints; but empirical evidence for many of these mechanisms remains thin. One example of this struggle is the literature on the energy-efficiency gap, a difference between the actual costs of energy use and the perception of those costs by households (Allcott and Greenstone, 2012). Another example, which has great policy importance for low- and middle-income countries, is the literature on household adoption of cleaner cookstoves.

The literature on improved or 'clean' cookstoves illustrates different views on whether demand is a sufficient measure of the benefits of energy access. Households cooking with biomass often use traditional cooking stove technologies, built out of local materials like mud, that are very cheap and easy to maintain but which are polluting and demand a lot of fuel. There has been significant innovation in stoves that consume much less fuel and emit less pollution than traditional versions. A large literature has asked whether household adoption of such stoves is efficient, or for some reason too slow (J-PAL, 2020).

Households appear to have very low demand for stoves that are demonstrably better on technical grounds (Mobarak et al., 2012; Berkouwer and Dean, 2020). In part, this is because manufactured stoves that are initially more efficient may be difficult to maintain, relative to traditional stoves, leading to a failure to use and maintain them (Duflo et al., 2016). In an RCT on the use of more efficient stoves that require slow cooking techniques, the users adapted their cooking and it took a year until they did not need more time (Bluffstone et al., 2022). News of stove failures spreads through social networks, suppressing demand (Miller and Mobarak, 2015).

All this sounds like the efficient functioning of a marketplace—stoves that fail on some dimension, such as durability, are weeded out by household adoption decisions.

Nonetheless, the adoption of improved cookstoves may be too low, even if a number of specific stoves have failed. One reason would be internalities, or benefits or costs within households that are not captured by stove demand. Indoor air pollution is a leading example. Biomass cooking, particularly when it takes place indoors, generates high levels of indoor air pollution (Duflo et al., 2016). Households may not know or consider the health effects of such pollution when buying a stove. Recent studies have found that real time information on indoor pollution levels (Ruiz-Tagle et al., 2021) or community-led information campaigns on the health hazards of cooking with traditional fuels (Afridi et al., 2021) can mitigate indoor pollution effectively. Further, such an intra-household failure may arise if men decide whether to spend money on an improved stove but women do the cooking. Verma and Imelda (2023) for instance, look at the impacts of replacing kerosene cook stove fuel in Indonesia with liquid petroleum gas, and find that not only did the introduction of LPG improve health outcomes for women, but also increased total hours worked for all members of the household. They argue that through different channels the improved health of the women can redistribute the intra-household division of labour, and increase both female and male labour force participation.

Credit or liquidity constraints are a second reason why adoption might be too low. Credit constraints, as a market failure and source of inefficiency, have been extensively studied. Stoves, like other energy-using goods, are durable, and buying a more expensive stove upfront may bring benefits, in terms of lower pollution or reduced energy cost, spread years into the future. Several studies have given evidence that demand for improved stoves that reduce energy consumption is significantly affected by access to credit (Levine et al., 2018; Bensch et al., 2015; Berkouwer and Dean, 2022).

Many other investments in energy access and energy-using durables are potentially affected by credit constraints in low- and middle-income countries. A study in Kenya found that demand for electricity connections was far below the fixed cost of providing such a connection, whether measured by revealed preference, experimental estimates, or by stated preference estimates (Lee et al., 2020). The authors also note that stated preference demand under a longer payment timetable, like a loan, was much higher than when the connection was to be paid upfront. Kenya has experimented with loans for the costs of new connections (Stima Loans) and with creating consumer groups to pool resources to pay fixed costs (Singh et al., 2014). Perhaps surprisingly, for poor populations credit constraints may bind not only for large, fixed investments but even for paying monthly bills. Recent research suggests that South African households with liquidity constraints may benefit from the use of pre-paid meters (Jack and Smith, 2020). These meters have also led to the emergence of mobile platforms to purchase electricity recharges (Singh et al., 2014). In Thailand, the creation of a new temporary household registration enabled poor urban households to apply for legal connections (Cook et al., 2005). In an RCT in rural Cameroon, a short-term subsidy for a lamp using a new solar technology was effective in increasing uptake and increased future WTP for the new product (Meriggi et al., 2021).

This cookstove example illustrates several reasons why household demand for an energy-using durable may not measure the entire private benefits, or costs of that durable. We would argue that many energy-using investments have a similar character, since they affect household decision-making in so many and such far reaching ways. For example, consider the channels through which electrification benefits households. Electrification releases time spent on home production and may operate as a labour-saving technology shock, increasing women's labour force participation (Dinkelman, 2011). The extension of the potential workday through lighting can impact women's fertility and labour force participation decisions (Grogan, 2016). Electrification changes where households and firms choose to locate (Dinkelman and Schulhofer-Wohl, 2015). Electrification may improve both the quantity and quality of schooling, for example by allowing for reading time in the evening, but we are not aware of any present empirical evidence on this point. Electrification may also provide health benefits by inducing households to switch away from unsafe or polluting technologies such as biomass stoves or kerosene lighting (van de Walle et al., 2013; Barron and Torero, 2017).

The private and social benefits of electrification

Thus far we have used cookstoves and electrification as examples to show the subtlety of valuing, in a comprehensive way, the private benefits of energy access. The literature on rural electrification is a good case for considering the possible external benefits of energy use due to spillovers in demand or productivity. Electrification has seen a boom of research in recent years on household valuations for electricity access and the benefits of such access. We will briefly review this work on the nature of rural demand, and argue that with the present evidence, there is still plenty of room for uncertainty about the right bundle of electrification policies.

The private benefit of energy access for the poor populations has lately been measured by several field experiments on the demand for electricity connections. The demand for grid electricity connections in Kenya is far below the cost, roughly US$ 400, of providing such a connection (Lee et al., 2020). The demand for grid electricity in India does not cover its cost among a poor rural population, and households do not value improvements in the quality of supply very much (Burgess et al., 2023). Households are extremely sensitive to price, and they have been found to rapidly take up both grid electricity when it is subsidised or off-grid electricity when it comes down in price. Households also take-up solar electricity as an alternative when the grid is too costly or not available (Burgess et al., 2020; Aklin et al., 2017; Grimm et al., 2016). If both sources are available, however, households, particularly richer households, have a strong preference for grid electricity to service higher loads (Burgess et al., 2023).

Given such estimates of low demand, should the policy recommendation be that electrification be stopped, in areas as poor as rural Kenya or rural Bihar? On this question, policy is arguably way ahead of the base of research evidence, and has answered a resounding 'no'. Policymakers in sub-Saharan Africa, South Asia and elsewhere are adopting a 'whatever it takes' strategy to electrification, investing aggressively in rural areas even where demand is low. We see at least three mechanisms that could justify such an approach, though we note this represents an area where the evidence base remains slim.

First, most evidence on the demand for electricity is for rural households. Yet electricity is used by businesses, farms, schools, hospitals, cell phone towers and for all manner of other uses. The literature on these uses is incomplete but suggests high demand for electricity from these sectors. Unreliable electricity supply is viewed by firms as a significant obstacle to doing business (Straub, 2008). Macroeconomic modelling on the general equilibrium effects of power outages across several sub-Saharan African countries finds that outages reduce output per worker by 20% on average (Fried and Lagakos, 2023). Power shortages reduce the average output of Indian manufacturers by 5%, and considerably more so among small firms that lack backup generators (Allcott et al., 2016; Alam, 2013). A similar re-optimisation of production inputs in response to outages has been documented among Chinese manufacturing firms, helping them dampen the blow to productivity (Fisher-Vanden et al., 2015). Electricity is conducive to investments in irrigation, boosting agricultural productivity in Brazil (Assuncao et al., 2015). For villages subject to an exogenous income shock around the time of electrification, there is evidence that electrification in India increased non-agricultural employment (Fetter and Usmani, 2020). In the Philippines, the cost of electrifying rural communities was recovered within a year, a result driven by large increases in agricultural income (Chakravorty et al., 2016). Electricity distribution networks have high fixed costs. If there are high returns to electrification in some rural sectors, but not necessarily for households themselves, then these high returns may justify rural electrification *en masse*.

Second, even if private demand were measured for all households, businesses, and other uses, the sum of private demands may be less than the aggregate value of electricity if there are spillovers due to electricity use. A simple example would be that if one household in a village gets a TV, many other people may stop by to watch. A more complex example would be businesses adopting technologies (like a higher capital intensity of manufacturing) that have some returns for the business itself, but also returns to the worker or other businesses, i.e. agglomeration externalities productivity (Greenstone et al., 2010). Longer-run estimates at a higher level of aggregation show large productivity benefits to electrification over the span of decades (Lipscomb et al., 2013). Historical experience also suggests there may be external returns. In both England's industrial revolution and the US' Rural Electrification Administration, energy allowed the adoption of technologies that boosted labour productivity, leading to economic growth (Jorgenson, 1984; Lucas, 2002; Crafts, 2004). These historical examples are powerful, but must be interpreted cautiously, since technology adoption and electrification are endogenous to economic growth. Contrary to the above literature, Burlig and Preonas (2021) find that village-level electrification has no medium-term impact on a number of economic outcomes, including employment, asset ownership, and education levels. Spillovers are one explanation for the difference between micro-estimates of the demand for electricity and macro-estimates of its benefits. Substantial 'external' benefits to village electrification have been found in Vietnam and India (Khandker et al., 2013; van de Walle et al., 2013).

Third, economic efficiency may not be the only or even the main aim of policymakers for rural electrification. Many governments are intent on universal electrification as a right regardless of its economic benefits, for the dignity of their citizens and as a means of redistribution, so that even poor households can be integrated into a shared, modern way of life.

Though inherently unquantifiable, this rationale alone can dominate otherwise low economic returns.

These examples, of clean cookstoves and rural electrification, show both the importance and empirical difficulty of measuring the demand for energy and the benefits of access. Energy use touches every aspect of the economy. Because of the breadth of the interactions of energy with the economy, the number of plausible reasons why demand may be an incomplete measure of the social return to investment in energy is unusually large. Policymakers, taking a farsighted view, may well be right that low demand among the poor populations today should not deter large-scale investments in growing economies.

The literature on energy access therefore suggests several areas that are high priorities for future work. These would include reconciling micro-estimates of the demand for electricity with macro-estimates of its return; understanding how market failures or inter-household spillovers affect the relationship between measured demand and the benefits of energy use; and understanding the mechanisms for any external returns of energy use. While we have focused on cooking and electricity use, many of these questions would apply equally well to energy use for heating or for transportation. We summarise some of the main research priorities in the next page.

RESEARCH PRIORITIES

- Can low-emissions innovation drive energy access?
- What is the demand for energy access and energy use for a range of users, energy sources, and end uses of energy?
- How does the advent of lower-cost renewable energy change household demand for energy services?
- How does the adoption of solar and battery systems by households and communities impact energy access and grid planning?
- What are the impacts of grid energy expansion on energy emissions?
- What are the direct gains of energy access for households, firms, and public facilities?
- Do energy demand estimates line up with direct estimates of the gains from energy access? Why or why not?
- What are the external returns to energy access? What are the sources of external returns?
- What explains the differences in micro- and macro-estimates of the returns to electrification?

II. Energy supply

Energy access needs to go hand in hand with ensuring the effective production and distribution of energy. A stream of investments is needed to ensure a growing country can match its appetite for energy. Along the way, the sources of this energy need to become cleaner. Vast innovations in renewables, among other technologies, have erased the clean energy premium. Whether, and how quickly, low- and middle-income countries can harness these innovations will depend on the institutions and regulations governing the supply of energy.

Too little attention has been given to how energy markets in low- and middle-income countries function differently. In all countries, the supply side of the energy sector is not an idealised competitive market, but a heavily regulated mix of public and private entities. This is because the energy sector typically exhibits high fixed costs, and thus increasing returns to scale, and, for some segments, tends to a natural monopoly. The state therefore must be involved in the operation or at least the regulation of these businesses to avoid market power. Examples of supply segments that fit this description include natural gas transmission pipelines and electricity transmission and distribution networks. Furthermore, energy prices are often visible to the public and, perhaps not coincidentally, become an instrument of redistribution which further complicates their efficient supply.

Several features of low- or middle-income country economies exacerbate these challenges. First, markets may be thin: the generating capacity in most East African countries is small enough that there are increasing returns to scale in generation at the level of the country, which is not true in large developed markets. Thus, additional segments of supply, which are not natural monopolies in, say, the US, are nationalised in low- and middle-income countries. Second, contracts are less likely to be enforceable. We concentrate the discussion here on barriers to efficient energy supply in low- and middle-income countries, and the emerging issues as a result of the increase in renewable energy generation.

Many investments in energy markets have a high degree of asset specificity. If a company builds a natural gas pipeline or a power plant in Ghana, that asset has a high value to Ghana but zero value serving any other country. Specificity can strain contract enforcement, since governments may be tempted to renege on investments. During Ghana's recent power crisis, the government was forced to buy, on contract, a large amount of power from private generators. These emergency generators produce at a high cost on offshore barges rather than actually investing into the country's infrastructure. This strategy may be seen as a reluctance by private companies to make any completely sunk investment in Ghana's generation sector. If they cannot come to terms with some future government, the barges will be towed away to the next crisis.

When attempts have been made to improve market functionality, success has been mixed. The standard paradigm for organising the power sector in low- and middle-income countries pulls directly from first-best economic theories: improve the operational performance of utilities, ensure a reliable supply, and attract private-sector investment through fair market mechanisms. Over the last few decades, however, only about a dozen low- and middle-income countries have been able to adopt this model successfully (World Bank, 2019b). For most low- and middle-income countries, it represented a straitjacket that clashed with political interests and difficulties in enforcing regulation. When reforms did take place, they were often partial, leading to confused systems in which elements of market activity were mixed with a strong state presence (Joskow, 2008). We discuss the political economy of market reforms in the next section.

The networked nature of grid expansion means it benefits from economies of scale—declining average costs—making electricity transmission a natural monopoly. Vertically integrated utilities spanning from generation to transmission to distribution were—and, in many countries, still are—the norm for rolling out access to unelectrified frontiers. Yet as networks expand, inefficient operations, mounting subsidies, difficulties in enforcing payments, and financing constraints begin taking their toll (Burgess et al., 2020; World Bank, 2019b). Few fundamental reforms take place during good times; in reality, problems often bubble up until there is a time of crisis and the lid blows off. Once forced to change, the energy sector gets stuck in a hybrid setup where independent power producers on attractive power purchase agreements sell alongside incumbent generators to a single buyer, introducing distortions in the dispatch of power and adding contractual rigidity across the sector.

Market rules and public investments into the sector therefore have direct impacts on how efficiently markets operate. However, rigorous evidence from low- and middle-income countries on market design is lacking, and what little there is, it is rarely used in policy design. A cross-country study on utility reforms found that the impacts of privatisation and independent regulators on access and service quality were mixed at best (Estache et al., 2006). Corruption leads to adjustments in the quantity and quality of services in line with the behaviour of a profit-maximising monopoly, stanching any potential benefits. Another study, using a panel of developing and transitional economies over two decades, finds that competition—but not privatisation—leads to gains in economic performance (Zhang et al., 2008). In Argentina, however, the privatisation of local water companies saw improvements in the quality-of-service provision, reducing child mortality in surrounding areas (Galiani et al., 2005). Overall, the evidence suggests that for privatisation to improve outcomes over the long term, it should be coupled with policies that promote competition and effective regulation (Parker and Kirkpatrick, 2005).

Low- and middle-income countries often struggle to attract enough investment in electricity to match demand. Market-distorting subsidies, non-payment, and theft need to be eliminated or reduced. Energy subsidies in these countries, which disproportionately benefit the non-poor, are often high, making them unattractive places to invest in electricity generation and distribution (McRae, 2015). Efficiency in market functionality may be improved initially by the removal of costly distortions - subsidies - to promote efficiency in pricing, which lends itself to the adoption of low marginal cost generation (i.e. solar). This can move the market towards a more socially optimal equilibrium, where externalities are accounted for. In some cases, an electricity market with renewable generators may solve existing market distortions.

Despite the benefits, there are unique barriers to the expansion of energy from renewable sources, which are crucial to understand in determining where the focus of policy should be in the low-emissions transition. Hold ups on contracts from procurement auctions for solar have led to multiple auctions and contracts being cancelled, as seen in Mexico, Turkey, and South Africa (IRENA, 2019). This hold up risk emerges in institutional settings where contract enforcement is weak. Ryan (2023) finds that in the case of India, the counterparty risk associated with high-risk states in non-intermediated auctions for solar energy led to a risk premium on prices of up to 10%, and that central intermediation eliminates this premium. Additionally, if the risk associated with the central government were equivalent to the highest risk-states, demand would fall by almost one-third.

It is clear that the involvement of national governments is crucial to secure investment, but its role also goes beyond guaranteeing contracts. Private finance is key to spurring low-carbon climate resilient growth. Public finance can be used to mobilise private sector engagement, especially in green projects. Multilateral public finance has had the largest impact in drawing in domestic private investment, making it the most significant source for renewable energy investments in low- and middle-income countries (Hascici et al., 2015). National development banks (NDB) can also play an important role in scaling climate finance. Zhang (2022) looks at the cases of Germany, India, and China, and finds that NDBs act through three main mechanisms to aid in renewable investments: providing expertise and market information to policymakers to advance market designs; mitigating policy gaps; and providing financial services that can concentrate resources behind national priorities. With a large amount of project finance coming from national and multilateral development banks, the efficacy of these procurement programmes in delivering on energy infrastructure deserve attention. Wolfram et al., (2023) investigate the variation in procurement policies between World Bank and African Development Bank sites for energy projects and find that contract bundling and ex-post auditing of infrastructure sites greatly improves the delivery and quality of energy provided. Therefore, consideration to the design of public investment programmes – from financial tools to monitoring and evaluation – is needed to ensure development of efficient, new renewable energy investments.

In a bid to boost private investment, several countries have also turned to adopting market-oriented reforms; limited evidence exists thus far on the impacts (Malik et al., 2015). Markets do not operate independently of the state but depend on public investments in infrastructure and regulation to function well. For example, congestion on the transmission grid, which is publicly built, allows firms to exercise market power, raising prices and limiting competition in the energy market (Ryan, 2021b). In economies with renewables generation, insufficient transmission capacity may also prevent renewable energy generation in one area from reducing fossil fuel generation in other areas (Fell et al., 2021). Expanding competition and supply therefore depends on the state of the entire electricity network, upstream to down. Many low- and middle-income countries may not have the scale, especially on their own, to build reasonably competitive supply sides. We therefore see high potential returns to regional integration and cooperation in the construction of supply infrastructure. At a glance this cooperation may seem to exacerbate political risk, but it may as well mitigate risk, by binding countries towards a common goal. In large advanced economies like the US or the European energy sector, integration of electricity markets can have substantial benefits (Cicala, 2022; Abrell et al., 2022). The gains from integration in low- and middle-income countries may be even more significant, increasing renewable entry and generation while simultaneously decreasing generation cost and pollution emissions (Gonzales et al., 2022).

The creation of energy generation for small-scale household adoption also deserves attention. Of the 240.6 million households who gained access to electricity in sub-Saharan Africa in 2022, 34% had a small solar home system installed. Despite offering only limited use, this is still a substantial rise from just 4% of households with new electricity access using a home solar system (IEA, 2023). However, informational asymmetries and inadequate information on solar home systems, the high costs of installation and lack of public support are some of the challenges households face (Mahadevan et al., 2023; Qureshi et al., 2017). As a result, small-scale adoption in some low- and middle-income countries tends to be restricted to highly educated and high-income households, which are mainly motivated by peer effects, energy independence, and environmental concerns (Ngonda, 2022).

Large-scale adoption of renewable sources may face an even larger set of obstacles. In Vietnam, for instance, key barriers facing PV diffusion include limited transmission capacity in existing grid systems, and complex administrative procedures (Do et al., 2020). Burke et al., (2019) look at the cases of two Asian countries that have faced rising pressure in their electrification processes, India and Indonesia, to identify the main barriers to solar and wind adoption. They find that although the entrenchment of coal and other fossil fuel producers, as well as investment lock-in into fossil generation, are important, other factors have also hindered or delayed further large-scale investments. These include hesitant support from utilities operators, transmission issues from operators, heavily subsidised fossil fuel prices and credit from foreign investors for coal projects (in the case of Indonesia), and restricted land access. While delays in land procurement and bureaucratic processes can reflect community and local governments' concerns, they are often a result of rent-seeking behaviour.

A lack of investment results inevitably in low reliability and low quality of energy supply. Governments often emphasise the extensive margin of energy access, only to neglect the intensive margin of ensuring a reliable supply. The poor state of electricity supply has both private and social costs. On the private side, businesses and households suffer from service interruptions and often rely on decentralised generation, using diesel or kerosene, that is significantly more expensive than the grid (Sudarshan, 2013). Consumers also choose to make costly compensatory investments in generators, inverters, voltage stabilisers, and the like. When electricity is unreliable or expensive, appliances such as air conditioners become harder to use, with especially severe implications for health and productivity in the hotter low- and middle-income countries (Burgess et al., 2023; Somanathan et al., 2015). And there is evidence that electricity outages lower manufacturing output at a rate of one to one (Allcott et al., 2016). The social benefits of access (Jha et al., 2021) remain unrealised when service is unreliable. Across the cities of South Asia and sub-Saharan Africa, the quality of energy services, while generally better than in rural areas, remains highly inequitable and poor in an absolute sense (Eberhard et al., 2008; Singh et al., 2014). A study on the WTP for grid stability estimates that households in Nepal would be willing to face 65% increases in monthly bills (US$ 1.11) for fewer outages (Alberini et al., 2022). Here it is important to keep track of the impact that the combination of renewable power coupled with batteries is having on ensuring reliability of supply to households and firms, and how this adoption feeds back into the grid and its revenue adequacy.

Low- and middle-income countries face two issues: few efficient generators and contracts with weak enforcement mechanisms. Both factors deter the ability of low- and middle-income countries to attract private investment, build market rules to attract energy sellers, encourage competition, and enforce the collection and delivery of contracts. Further research is needed on how markets can be designed to overcome these barriers. Looking towards the future, these policies should also reflect the growing adoption of low-cost renewable energy sources. More research is needed on evaluating the design and policies within energy markets which increase the diversity of generators and improve consumer welfare outcomes.

RESEARCH PRIORITIES

- What are the barriers to integrating renewable energy generators into existing wholesale markets?
- How can market design and regulation create better incentives for renewable energy sources in low- and middle-income countries?
- What interventions have been effective in reducing the barriers for private investment in renewable energy generation in low- and middle-income countries?
- Can electricity production markets help deliver welfare gains through the adoption of the latest and cleanest modes of production?
- What effect will increasing renewable energy penetration have on reliability, generation costs, and consumer benefits from energy access?
- How does the hybrid construction of energy markets in low- and middle-income countries, with both state and private actors, affect their efficiency in the short and long run?
- To what extent can the privatisation of different segments of the energy market, such as the distribution of electricity or natural gas, affect market efficiency? How does this depend on the political and regulatory environment?
- How can market rules and public investments in infrastructure integrate energy markets to increase efficiency?
- How does WTP for access depend on scale, reliability, and quality of supply?
- How do reforms in areas like financial contracting, procurement rules, or market formalisation and centralisation affect the efficiency of energy markets?
- What are the benefits of market integration across countries in the electricity sector?
- How do regulatory design and institutions affect energy supply and the incentives of energy supply companies?
- How can market design and regulation create better incentives for renewable energy sources in low- and middle-income countries?

III. Political economy of the energy sector

Politics lies at the heart of the dysfunction in energy sectors in low- and middle-income countries. Even simple problems, like a blown transformer, have deep roots. As discussed in Min (2015), the transformer may have blown because it was overloaded. It was overloaded because farmers drew too much power. They drew too much power because they face no price for doing so. They face no price because their votes have sustained a distorted allocation of subsidised power to rural areas.

The state is inevitably involved in the power sector as an investor, regulator, and supplier because of the scale of electricity networks, the specificity of investment to each country, and the fact that electricity transmission and distribution are monopolies by nature. No country has ever completed electrification without government support (Barnes and Floor, 1996). In most low- and middle-income countries, the power sector is largely state-owned, so the strategic choices made by utilities reflect political concerns as much as economic and technical ones. Power utilities have large employment rolls, issue immense contracting volumes, and can steer valuable electricity services to different communities— all conditions that can exacerbate patronage (World Bank, 2019b). It is not uncommon, therefore, for political factors to hinder progress toward the declared goals of infrastructure investment and electricity access.

Challenges in market reform

Many countries have looked to market reforms to restructure public companies and open them up to competition from private ones, especially when it comes to power generation. Results have been mixed. Up to half of the world's countries have pursued at least some reforms around generation: unbundling generation, transmission, and distribution; privatising components; empowering independent regulators; and creating markets to foster competition (Kessides, 2012; Brown and Mobarak, 2009).

However, many of these efforts have been half-hearted, leading to nominal changes in some parts of the sector while further entrenching state-owned utilities and political control in the most politically crucial segments, such as distribution (Murillo, 2009; Lal, 2006). Even in countries that have pursued reforms, the power sectors remain dominated by what Victor and Heller (2007) call 'dual firms' that reflect the organisational and management characteristics of private firms but retain strong political networks and interests. This includes entities like Eskom in South Africa, the National Thermal Power Corporation (NTPC) in India, and Petrobras in Brazil. In contexts where state-backed firms compete with independent power producers, such as Pakistan, public entities often benefit from subsidised inputs or kickbacks, artificially positioning themselves higher on the merit list. Politically influential independent power producers are able to extract higher rents, often with the regulator turning a blind eye. Remedying the problems of investment in and access to energy infrastructure therefore requires a political economy perspective that pays close attention to how political institutions shape the incentives and strategies of elites, different interest groups, and citizens.

Reforms alone may be inadequate to spur investment. Corruption along all stages of the chain can frustrate or delay investors. If reforms fail, a later government may take over their plans. This happened with the Dabhol facility near Mumbai (Bettauer, 2009). In other cases, governments may renege on contracts and not pay at all. Investors often seek sovereign guarantees to guard against such situations, placing the risk entirely on the government.

The presence of large firms operating on an equal plane with the government creates space for corruption and rent-seeking when institutions are weak. The biggest firms might directly influence the terms of a tender, restricting competition from potential outside entrants. Even when it appears that markets are competitive and well-functioning, allocative inefficiencies exist. Well-connected firms in India, for instance, have been found to underbid in power auctions to win contracts, only to renegotiate for better terms after being awarded the tender (Ryan, 2020). Stronger contract enforcement, therefore, can improve productive efficiency by correctly allocating contracts to lower-cost firms. It would be useful for further research to understand how politics and key actors influence the allocation and terms of generation projects.

Market reforms, or the lack thereof, also influence the speed and scale of the green transition. Under well-functioning markets, the most cost-effective technology should diffuse rapidly. The majority of power produced and sold in low- and middle-income countries is still either done by the government or through contracts bilaterally negotiated with private producers. The end product is a power purchase agreement (PPA), which typically spans 25-40 years. Recent market reforms have introduced more competition through competitive procurement and auctions, but these are only beginning to take hold. The result is that there is limited space for new technologies such as renewables to displace existing power generation technologies. Absent further government interventions, renewables are resigned to supplying the flow of future demand, rather than the existing stock. For many countries, given that existing demands are low and future demand is expected to balloon, this may be fine; for others, such as Ghana, Pakistan, or Bangladesh, over-capacity is resulting in a fiscal squeeze on the state.

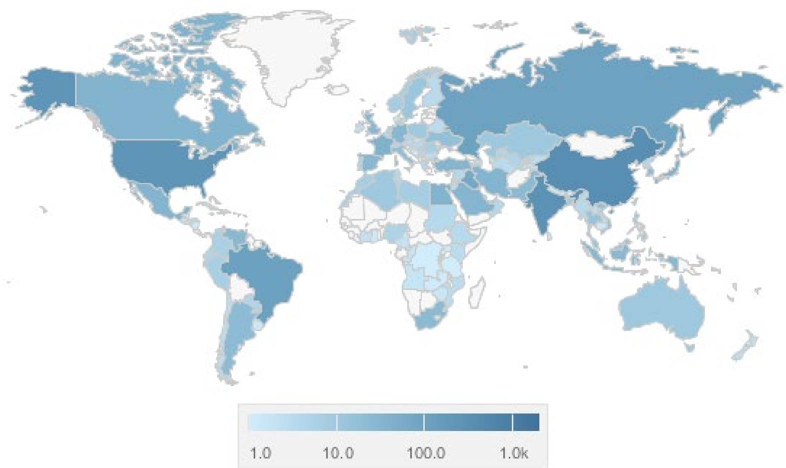
The scale of energy markets means that an efficient market may require a high degree of cooperation across borders. Consider the interconnection of transmission systems: what successful precedents exist for countries with low levels of development effectively fostering cooperation and investment to increase their power systems' scale and efficiency? Many countries are too small and poor to develop a modern power sector on their own. Many countries in sub-Saharan Africa maintain less than one gigawatt of installed generating capacity, the amount provided by a single fossil fuel or nuclear plant in the industrialised world. In Senegal, almost all power comes from small-scale, expensive, and dirty diesel generation due to the historical lack of large industrial customers to anchor more efficient baseload power plants. When the price of oil spiked in 2011, Senegal experienced widespread shortages of fuel, resulting in a disastrous power crisis. The government's inadequate response led to violent protests and the electoral defeat of President Abdoulaye Wade—another instance of energy directly influencing politics in a low- or middle-income country.

Greater regional integration and shared investment represent one possible way to overcome this problem. Significantly increasing regional integration could save more than US$ 40 billion in capital spending in the African power sector and save African consumers US$ 10 billion per year by 2040 (McKinsey, 2015). Similar benefits could be seen if the ASEAN grid in southeast Asia was connected (IEA, 2019). The difficulty of regional integration, of course, is that it involves long-term investments and trust between states, something that could be potentially feasible for ASEAN but less so for other groups of states that lack a history of common association. Governments may be reluctant to commit to one another due to lack of trust, or they may be unwilling to sacrifice control over their own power sector, which has political value. Influential firms may also baulk at the thought of opening themselves up to competition from abroad.

Political capture and subsidies

The above discussion suggests that political capture is a problem on the supply side of the energy sector; populism may represent an equally important problem on the demand side. Prices are set strategically, at levels that do not cover costs, to court politically favoured groups or secure votes (Brown and Mobarak, 2009; Di Bella et al., 2015; Coady, Flamini, and Sears, 2015; Berkouwer and Dean, 2020). High levels of line losses and billing irregularities are common, and tolerated by political leaders, who may benefit personally or politically by reducing enforcement (see **Figure 4**; Min and Golden 2014). Recent work in India using detailed billing information for millions of households and a close-election regression discontinuity design suggests that some of the subsidies might instead be politically targeted (Mahadevan, 2021). The social norm of considering electricity a right generates losses, supply rationing, and unmet demand (Burgess et al., 2020). Regular power outages or disruptions are masked by technical terms such as 'load shedding' when in reality they merely reflect the pervasive mispricing of electricity. Unlike in high-income countries, utilities are not forced to provide electricity regardless of generation cost and have a downwards-sloping demand facing the supply from power plants. Thus, weak regulation makes load shedding possible (Jha et al., 2022). Such subsidies have long-term consequences, too, sapping investments that would improve infrastructure quality (McRae, 2015).

Figure 4: Electricity distribution losses across the world



Notes: High levels of line losses and billing irregularities are common, and tolerated by political leaders, who may benefit personally or politically by reducing enforcement. Source: EIA, 2021.

In some cases, political reforms can help expand access. Min (2015) tracks night-time lights satellite imagery to show that democratic governments in low- and middle-income countries provide electricity to 10% more of their citizens than those in economically similar non-democratic states. Boräng et al., (2021) argue that only democracies with low levels of corruption are associated with increased access to electricity. Yet, this expansion may itself be short-sighted. It is driven by the pursuit of electoral majorities by democratic incumbents, who prioritise visible policy outcomes like grid extensions and new village electrification projects even as other critical activities like maintenance and new power generation are deferred. These patterns are especially pronounced in sub-Saharan Africa and South Asia. Minimal consideration goes into whether dramatic, 'grid everywhere' approaches to electrification are the most suitable strategy for a country's given context. Politicians also routinely increase the supply of electricity—for instance, by reducing load shedding—during crucial elections (Baskaran, Min, and Uppal, 2015) to enable higher levels of illegal power usage and help them win more votes (Min and Golden, 2014). While this may benefit citizens temporarily, it is clearly economically inefficient — people want power all the time, not only when they go to vote.

A root cause of many of the failures of energy markets seems to be the norm that electricity (and other forms of energy) are considered a right, rather than a private good that must be purchased (Burgess et al., 2020). For example, early evidence from households surveyed in Lahore, Pakistan, demonstrate a strong sense of entitlement to electricity (Haider and Javed, 2023). When this norm is present, politicians are committed to provide energy at low prices regardless of its external costs. Consumers, in turn, feel justified in not paying for consumption. Public suppliers lose money on every unit supplied and must eventually restrict supply to contain their losses. The result is that many consumers cannot access a reliable electricity supply, even when their WTP exceeds the cost of supplying it. How can we move from this equilibrium where electricity is a right to one where it is treated as private good? This is an area where there is an urgent need for research that identifies evidence-based and politically feasible solutions.

The literature has shown us that energy markets in low- and middle-income countries are characterised by a high degree of informality and often by heavily subsidised prices. Energy access is mediated by high levels of informality in cities in low- and middle-income countries. In India, Delhi and Ahmedabad have found some success with both regularisation schemes and the creation of small local franchises (USAID, 2004). Metering points along the perimeter walls of informal settlements, coupled with financing assistance, have been used with some success in Manila (USAID, 2004). The problems of energy access faced by the urban poor population can be exacerbated when utilities are forbidden or discouraged from supplying to unauthorised informal settlements, where households have uncertain land and tenure rights (Scott et al., 2005).

One solution to preventing non-payment is through improvements to electricity metering. When metering is incomplete or erratic, government subsidies for access can lead to perverse incentives for utilities not to invest in improving service quality, thus locking households into persistent regimes of low-quality supply (McRae, 2015). Evidence from an RCT in the Kyrgyz Republic shows that investing in smart metering rollouts can improve electricity service quality and reliability of the grid (Meeks et al., 2023). In Senegal in the 1990s, urban and rural areas were served by different agencies, leading to peri-urban households falling through the cracks in terms of access and quality (Singh et al., 2014). From the utility point of view, serving the urban poor population can represent significant additional costs due to consumption levels and low revenues because of billing difficulties. When the transaction costs involved in obtaining legal connections are high, energy theft can become commonplace (Scott et al., 2005). New technologies, such as pre-paid metering systems, have shown promise to alleviate some of these concerns (Jack and Smith, 2020).

The political space for energy subsidy and tariff reforms is narrow. Taking away or reducing the benefits for a good that everyone uses and that makes up a large part of the budgets of the poor population can spark political disaster. Energy subsidies are not as progressive as they are presented to be, often benefitting wealthier urban consumers (Coady, Flamini, and Sears ,2015; Coady, Parry, Sears, and Shang, 2015; Hahn and Metcalfe, 2021), where policies can become regressive not only by design but also due to difficulties in implementation (Berkouwer and Dean, 2022). Urban electricity subsidies can also be hard to target; for instance, South Africa's Free Basic Electricity subsidy programme has struggled to reach some of the poorest households, who may live on untitled land or share electricity connections with authorised residents.

Sound experimental evidence on behavioural responses to the removal of energy subsidies is naturally difficult to come by, but such evidence would be valuable to the design of new policies. The prevailing view is that income redistribution should not be carried out through energy policy but instead shifted to more efficient policy instruments like basic incomes or direct transfers (Barnwal 2019; Berkouwer et al., 2023).

While there has been significant work on designing effective tax systems for low- and middle-income countries that consider not only the impact of tax rate or base changes but also asymmetries in information and difficulties in compliance (Slemrod and Gillitzer, 2014; Slemrod 2016), there is far less on energy pricing.

RESEARCH PRIORITIES

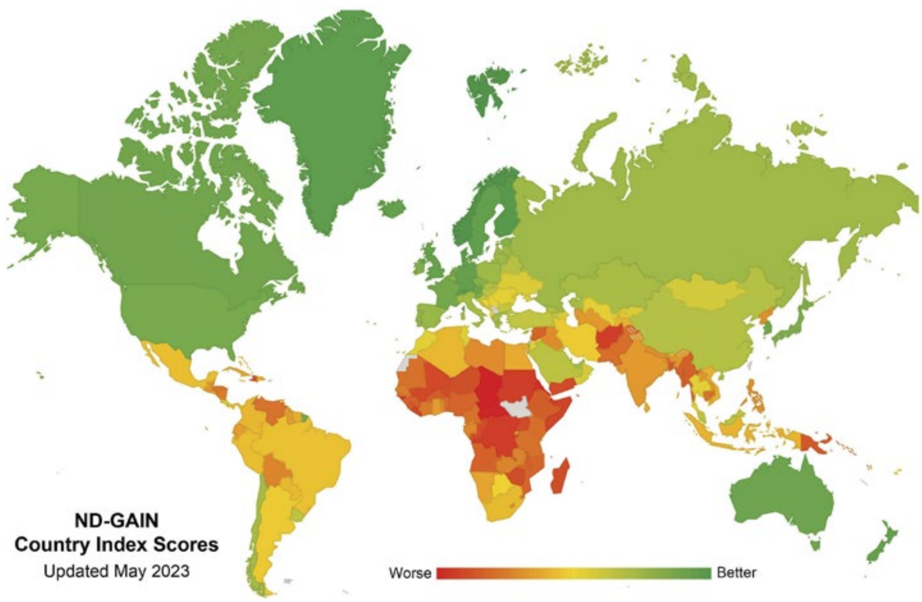
- How do supply-side politics affect investment, contracting, and the efficiency of energy markets?
- How do demand-side politics affect tariffs, reliability, and the benefits of energy access?
- How does the provision of energy affect social norms about the state?
- How can financial and institutional structures create a favourable investment environment for private suppliers?
- What kinds of institutions are most robust to political interference? How can rent-seeking and elite capture be minimised?
- How does state control over utilities impact the introduction of renewable energy sources onto the grid?

- Given political constraints, how can we develop independent and robust regulatory processes for the allocation of power and determination of tariffs?
- What reforms are necessary to move towards an equilibrium where electricity is paid for? What are the welfare consequences of such reforms?
- How can energy subsidies begin to reflect the pollution externalities associated with fossil fuel-based energy supplies?
- What distortions result from subsidies in the energy sector?
- Can unconditional transfers effectively replace energy subsidies? How can unconditional transfers be targeted to compensate the losers in energy subsidy reform?
- What are the effects of allocating energy contracts, investment, and supply on political rather than economic grounds?

3. Global externalities from energy consumption

Energy consumption supplied by fossil fuels over the last century is causing large-scale environmental changes at the global level. These changes will disproportionately harm low- and middle-income countries and poor, rural populations (**Figure 5**; IPCC, 2022; IPCC, 2018). The scale of these changes needs strategies to promote inclusive growth and eliminate extreme poverty. This must now include both mitigation and adaptation strategies.

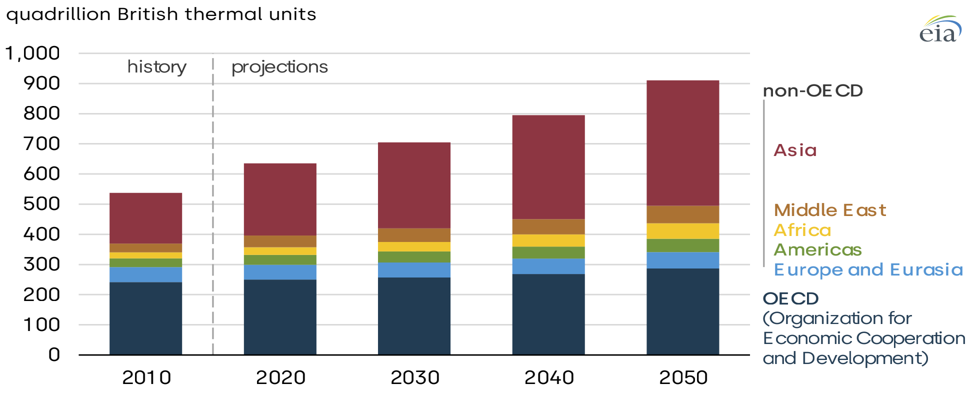
Figure 5: Vulnerability to climate change per the ND-GAIN country index



Notes: Climate change will disproportionately harm low- and middle-income countries.
Source: ND-GAIN, 2023.

Countries that are growing rapidly today, and will consequently experience a major increase in their energy use (for example, Davis and Gertler 2015; Gertler et al., 2016), now have the opportunity to build energy systems that are less emissions-intensive than what high-income countries have built in the past decades (Figure 6). For electricity, the rapid acceleration of innovation in renewable technologies and storage – and the associated declines in wholesale electricity prices – has led to optimism that significant progress in mitigation is possible, at least in the power sector. At the same time, renewable energy growth may place greater strain on power grids as they have less dispatchable energy generation in the absence of storage. Additionally, the process of adopting low-emissions technologies that aid mitigation, such as electric vehicles, will inevitably depend on readily available and reliable energy supplies (Wangsness et al., 2021). Due to their higher fixed capital costs, financing these cleaner technologies can also be problematic.

Figure 6: Global energy consumption, 2010-2050



Notes: Countries that are growing rapidly today, and will consequently experience a major increase in their energy use now have the opportunity to build energy systems that are less emissions-intensive than what high-income countries have built in the past decades.
Source: EIA, 2019.

While there is an opportunity to adopt wide-ranging innovations in clean energy, there is still an urgent need to identify the best mechanisms to support these countries in meeting their future energy demands while minimising externalities. Switching to a low emissions supply of electricity is one way to mitigate emissions; consuming more efficiently is another. Significant advancements in a large range of energy-consuming activities—from the thermal efficiency of generation plants to improved heating/cooling of structures to ultra-efficient light bulbs—present ample opportunities to get more out of each unit of energy.

Mitigating the global externality of carbon dioxide production will require conservation or re-establishment of large, carbon sinks. The balance of protection and use of natural capital generates winners and losers as those who benefit from conservation may be different from those who gain from extraction. This requires studying the coordination failures which arise when managing natural capital. In most cases, and particularly with respect to forests and other land use forms which store carbon dioxide, the benefits are not restricted to local users (or spread heterogeneously in an area). Threats to the global stock of stored carbon can come from inside as well as outside. Additionally, natural capital can offer adaptive benefits, such as protection against storm surges in coastal areas (IPCC, 2022). We therefore introduce the need for careful research to evaluate the design and functionality of markets and institutions to manage natural capital.

Research needs to be directed towards low-income countries, where a large fraction of the population works in economic activities that are heavily dependent on the weather, and face the challenge of adopting adaptation strategies to climate shocks

Research needs to be directed towards low-income countries, where a large fraction of the population works in economic activities that are heavily dependent on the weather, and face the challenge of adopting adaptation strategies to climate shocks. Low-income countries will have to help their populations adapt to the risks brought by a hotter, more variable, and disaster-prone climate. Poor countries are going to be severely harmed by climate change, with lower agricultural yields and manufacturing productivity and higher rates of premature death (Lobell and Tebaldi, 2014; Burke, Hsiang, and Miguel, 2015a; Burgess et al., 2023). Studies of climate damages continue to be important and can be extended in many ways, particularly in providing hyperlocal information on what climate change will look like on the ground.

We first review mitigation policies on the supply side, with an emphasis on renewables in the context of low- and middle-income countries. We then examine mitigation policies on the demand side, with a discussion about how demand management and energy efficiency policies might contribute to mitigating energy demand (and emissions) growth. Finally, we review the evidence so far on the global impacts of climate change and discuss the need for further research in the role of the public sector to enable adaptation.

I. Mitigation with supply-side energy policies

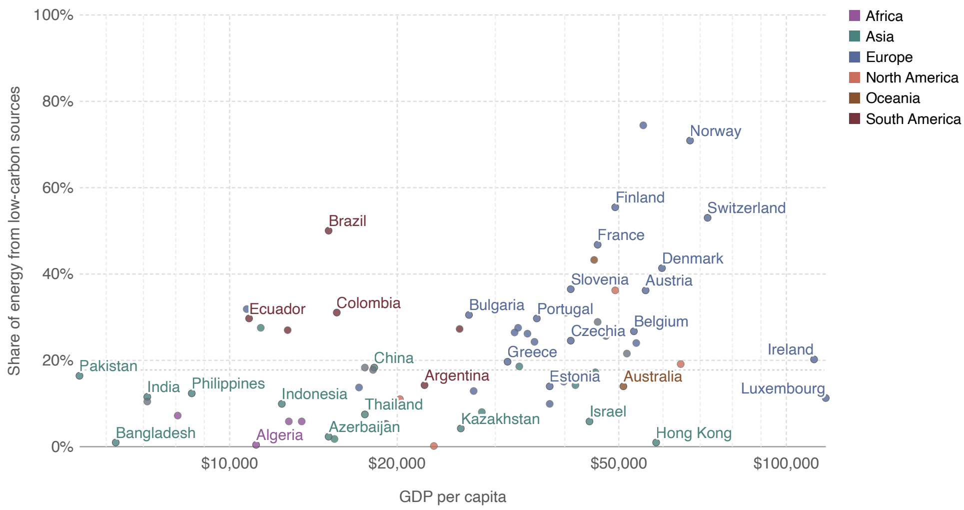
Fast-growing low- and middle-income countries will account for the bulk of the increase of energy consumption in the coming decades. This increased use of energy is essential to support the increases in growth needed to reduce poverty. There is significant variation in projections of future emissions from low- and middle-income countries. For example, Shoibal and Tavoni (2013) estimate that to reach global energy poverty alleviation by 2030, final energy demand will need to grow by 7% globally, while the IEA estimates that electricity demand will increase by 2.5% and fossil fuel demand by 0.8%. Scenario modelling is dependent on future policies which impact the price of renewable and fossil fuel-based energy sources. There is consensus, however, that if countries were to rely on fossil fuels to meet this increased consumption, it will lead to shorter and sicker lives for their people and increase the likelihood of disruptive climate change for the planet as a whole. To play their part in meeting global climate targets, these countries need to find a cleaner road to energy consumption, often in the form of low-emission electricity generation. This is becoming more realistic in the short and medium term given the plummeting costs of renewable energy (Banares-Sanchez et al., 2023). In 2021, two-thirds of newly installed non-fossil energy capacity was less expensive per kilowatt hour than coal (IRENA, 2023). Innovation in technologies on the generation side, as well as the demand side, offer a clearer path to a transition away from the dependency on fossil fuels.

Many low- and middle-income countries, such as Brazil or Zambia, have been fortunate enough to benefit from abundant hydropower, creating a clean electricity mix. However, hydropower, like other renewables, can come with a degree of variability (in this case, seasonally), so governments need to look into thermal base loads or other means of storage. The question remains how future demand will be met, especially if hydro capacities—or willingness for large dam construction projects—reach their limits. Strip out hydro and low- and middle-income countries do, on average, lag behind on installation of renewables—though it must be said that this applies almost as readily to high-income countries as well (**Figure 7**).

Figure 7: Share of low-carbon sources in energy generation across GDP per capita, 2022

Low-carbon energy is the sum of nuclear and renewable sources, and is measured as a percentage of primary energy[1] consumption using the substitution method[2]. Gross domestic product (GDP) is adjusted for inflation and differences in the cost of living between countries.

Our World in Data



Data source: Energy Institute - Statistical Review of World Energy (2024); World Bank (2023) OurWorldInData.org/energy I CC BY
Note: GDP data is expressed in international-$[3] at 2017 prices.

1. Primary energy: Primary energy is the energy available as resources – such as the fuels burnt in power plants – before it has been transformed. This relates to the coal before it has been burned, the uranium, or the barrels of oil. Primary energy includes energy that the end user needs, in the form of electricity, transport and heating, plus inefficiencies and energy that is lost when raw resources are transformed into a usable form. You can read more on the different ways of measuring energy in our article.

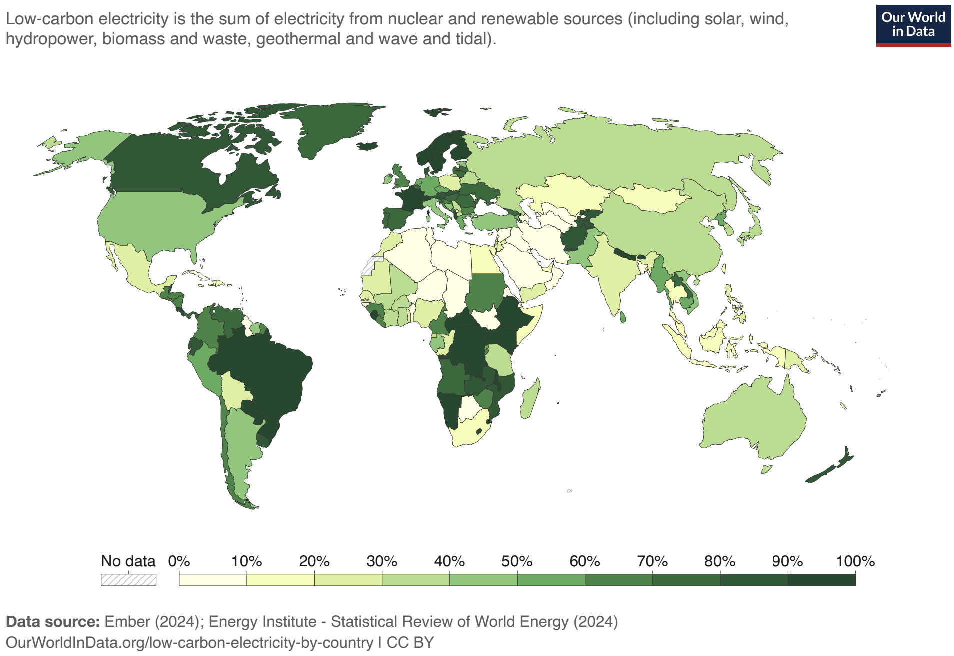
2. Substitution method: The 'substitution method' is used by researchers to correct primary energy consumption for efficiency losses experienced by fossil fuels. It tries to adjust non-fossil energy sources to the inputs that would be needed if it was generated from fossil fuels. It assumes that wind and solar electricity is as inefficient as coal or gas. To do this, energy generation from non-fossil sources are divided by a standard 'thermal efficiency factor' – typically around 0.4 Nuclear power is also adjusted despite it also experiencing thermal losses in a power plant. Since it's reported in terms of electricity output, we need to do this adjustment to calculate its equivalent input value. You can read more about this adjustment in our article.

3. International dollars: International dollars are a hypothetical currency that is used to make meaningful comparisons of monetary indicators of living standards. Figures expressed in international dollars are adjusted for inflation within countries over time, and for differences in the cost of living between countries. The goal of such adjustments is to provide a unit whose purchasing power is held fixed over time and across countries, such that one international dollar can buy the same quantity and quality of goods and services no matter where or when it is spent. Read more in our article: What are Purchasing Power Parity adjustments and why do we need them?

Notes: Low- and middle-income countries, including some high income countries, lag behind in the installation of renewables. Figure generated by the authors using **Our World in Data**.

Large-scale renewable energy sources have the potential to support energy demand growth while cutting local and global air pollution. There are several reasons to be optimistic about the growth of renewable energy in the years to come (**Figure 8**). The cost of large-scale renewables, especially solar, has fallen dramatically in the last decade (IEA, 2022a). Innovation has flourished. Moreover, in many low-income countries, such as those in East Africa, petroleum fuels are currently essential sources of power generation. The expense of the existing supply makes renewable generation cost-competitive in a growing number of settings today. In a cross-country comparative study from 1985 to 2017 higher oil prices but not higher coal or gas prices were found to increase renewables generation (Nguyen et al., 2021). The renewable potential in South Asian and sub-Saharan Africa is enormous. For example, sub-Saharan Africa is estimated to have 474 gigawatts of potential hydropower, wind, and geothermal capacity and an immense 11 terawatts of potential solar capacity (McKinsey, 2015). Finally, some emerging economies – most notably China—have recognised that unfettered use of fossil fuels has large negative health impacts and that regulations that make these fuels more expensive are an important next step. Recent policies in China have included an emissions trading system for coal power plants as well as direct government regulation of quantities generated (Cao et al., 2021).

Figure 8: Share of electricity generated from low-carbon sources, 2023



Notes: Renewable energy will grow in the years to come. Figure generated by the authors using Our World in Data.

Despite this favourable environment, increasing renewable supply in low- and middle-income countries from the current low base will not be a straightforward process. In the first instance, renewables do not compete on a level playing field with fossil fuels. The absence of taxes or regulatory systems to price the externalities associated with fossil fuels means that such fuels are effectively subsidised since their external cost is not reflected in energy prices. Untargeted subsidies on energy consumption can further distort the energy mix and hinder renewables expansion compared to efficient tariffs combined with targeted transfers (Hancevic et al., 2022). In the context of high-income countries, a recent study on electricity prices in the US provides evidence that prices are well below social marginal cost (Borenstein and Bushnell, 2022). This places renewables at a substantial competitive disadvantage. Indeed, fossil fuels are often subsidised below even their private cost through mandated prices and inconsistent enforcement of payments (Davis, 2017). This can also affect the expansion of decentralised energy systems as the grid is also typically subsidised. A final layer is the availability of local fossil fuel resources. Countries that have domestic coal, oil, or gas may be able to extract these at low costs. Furthermore, they often also represent important sources of government revenue and frequently form a powerful interest group. These factors impede the adoption of renewables.

Additionally, other political, technical, and economic obstacles prevent renewables from generating a substantial share of electricity supply in low- and middle-income countries. Politically, renewable energy generation is placed at a disadvantage when energy prices do not reflect the social costs of pollution, even more today as innovations like hydraulic fracturing have brought down the private prices of oil and gas. Technically, the integration of intermittent renewables will strain power grids, given the high costs of energy storage and the weak grid management infrastructure in low- and middle-income countries. Even in high-income countries with established electricity grids, integrating many distributed small-scale renewables requires large-scale investment to avoid peak net withdrawals (Astier et al., 2023). With increased renewables, the system requires a more flexible generation mix, abundant transmission capability, and more efficient system operation. Low- and middle-income countries that already have unreliable supply and frequent load-shedding may struggle to manage substantial renewable capacity in the existing grid. Economically, the finance of renewable generation, with its high capital and low marginal costs, will require clear regulatory and policy support in the short run. As the share of renewables increases, it will also require policy that ensures that the costs of intermittency imposed by renewables are covered.

A key focus for this theme therefore is to understand how energy policy needs to be changed to allow renewables to be an important part of the energy supply in low- and middle-income countries. The externalities from increased energy consumption require a profound shift in energy policy. These changes need to take place globally, but the political economy of countries with fragile institutions and low state capacity makes these challenges more considerable for low- and middle-income countries. We discuss potential ways to address the problems caused by intermittency, in particular market integration and pricing. We then turn to the financial constraints that low- and middle-income countries are likely to experience when making the large-scale investments necessary to adopt cleaner sources of energy and the effectiveness of potential solutions to reduce them.

Intermittency, market integration, and pricing

A constraint for renewables like solar and wind that lack accompanying storage is that their intermittent nature makes them non-dispatchable. This means the grid operator effectively must run these plants when they produce, and that this production cannot be scheduled or fully controlled. There is substantial literature documenting the potential issues of renewable energy and intermittency (Borenstein, 2012). Empirical estimations of the costs of intermittency, however, suggests that these costs have been smaller than initially thought in markets with substantial presence of renewables (Petersen, Reguant, and Segura, 2024; Weber and Woerman, 2024). It remains to be seen if these encouraging results remain for low- and middle-income countries, which have small or regional power grids, with no backup capacity and weak monitoring and control of transmission and distribution constraints.

There are both economic and technical ways to address this problem of intermittency. We focus on the economic side. Regional integration of electricity markets can increase the value of energy produced from renewable sources (Kambanda, 2013), by mutualising the risk of lower and unexpected supply. For example, the US state of Iowa and Denmark have been able to greatly expand the production of wind power through their participation in regional electricity markets that allow them to sell wind generated electricity to places where the demand is not perfectly correlated with local demand (IWEA, 2015; Mauritzen, 2012). While there has been substantial integration in many high-income countries, low- and middle-income countries and regions still lag behind; for example, within Africa, imports account for only 4.5% of total electricity supplied (IEA, 2020). In China, the lack of integration between provincial electricity grids is a barrier to entry for new wind and solar PV projects (Auffhammer et al., 2021). Another study on the country's energy sector finds that market segmentation negatively affects energy efficiency through distorted price signals, government protection of firms with rent-seeking links to local officials, and restraints on cross-regional agglomeration (Zhang, 2022).

Increasing the energy market integration and trade in energy across national borders therefore offers significant benefits. Besides opening-up opportunities for renewables (Gonzales et al., 2022), the integration of electricity markets also offers other economic benefits by equalising prices across regions, as well as introducing some potential costs by increasing the opportunities for the exercise of market power (Cicala, 2022). Further evidence on the opportunities, challenges, and potential impacts on renewable electricity generation associated with regional power market integration in sub-Saharan Africa and South Asia is needed.

Additionally, one could consider pricing schemes, such as real-time pricing, as an avenue to facilitate the integration of renewable power. There exists an extensive theoretical literature on the weak incentives renewables face due to the lack of residential response to electricity price (Joskow and Tirole, 2007; Ambec and Crampes, 2021). This lack of response leads to historic pricing mechanisms which favour capacity of generators that 'ramp up' electricity in response to swings in demand. However, new evidence in high-income countries suggest that consumers are willing to adjust their consumption when given notice, although to a limited extent (Jessoe and Rapson, 2014), even more in the presence of automation. Given the more elastic nature of electricity consumption in low- and middle-income countries, and the fact that new technologies are making consumers more aware of prices (Jack and Smith, 2020), it is possible that effective pricing coupled with good information designs could facilitate the integration of renewables and minimise the costs of intermittency, although the particular metering technologies of each country might limit the specific incentives that can be provided.

Lastly, there has been significant innovation in energy storage. Batteries, much like solar or wind, follow Wright's Law: an exponential decline in cost as cumulative capacity increases (Way et al., 2022). There is little indication that these cost declines are slowly down, raising possibilities that renewables plus large-scale storage can be cost competitive in the coming years or decade. For countries with existing hydropower generation, pumped storage may also be a feasible avenue to store power. At smaller levels, as electrification trends increase, especially in transportation, the use of battery swaps in cities can also become a potential source of great demand flexibility.

Financing renewables

Though this has been on the decline, much of the costs of renewables come in the form of upfront capital costs (EIA, 2020). When capital markets function poorly, this becomes a real constraint for the uptake of renewables. Credit and capital constraints are particularly important in low-income countries, which could act as a significant barrier for mitigation strategies. For instance, Choudhary and Limodio (2022) argue that banks in low-income countries face liquidity risk which leads to deterring long-term investment. This bias towards short-term investment is especially relevant for renewables integration and poses an additional barrier for grid investments with long-term benefits. There is a large basket of candidate renewable-financing mechanisms, including renewable purchase obligations, feed-in tariffs, feed-in price premia, auction procurement, capital subsidies, accelerated depreciation or exemption from import duties.

An important area of investigation is which of these, or other, mechanisms can be effective in low- and middle-income countries. For example, more than 30 states in the US have implemented renewable portfolio standards that introduce minimum requirements for renewables' share and allow for trading to achieve this flexibly (EIA, 2012). Depending on states' endowments of renewable sources, these portfolio standards had different impacts on emissions and renewables generation: those with large intermittent renewable sources saw larger reductions in carbon dioxide emissions but smaller increases in renewables generation relative to states with larger endowments of dispatchable renewables sources such as hydropower (Fullerton and Ta, 2022; Zhou and Solomon, 2020). Nevertheless, these standards were found to have reduced carbon emissions at a cost roughly consistent with estimates of the social cost of carbon (Lyon, 2016), with most of their impact on wind generation and little to no effect on solar generation (Deschenes et al., 2023). In India, low targets and incomplete compliance have made such standards a weak spur to renewable capacity addition—states, which set their own Renewable Purchase Obligations, are reluctant to increase generation costs in any way. Similarly, renewable portfolio targets in China have been found to be largely inefficient and have had a limited effect on the share of renewables in regional energy production (Wang et al., 2022).

Historically, the most common policy for attracting renewable energy independent power projects in Africa has been feed-in tariffs, which pay the owners of energy systems per unit of electricity produced. However, feed-in tariffs have resulted in fewer projects than anticipated. In contrast, the competitive tenders run in South Africa and Uganda in recent years have had much greater success. South Africa shifted from a feed-in tariff regime in 2011 and since then has run four renewable energy bid rounds, resulting in 92 solar and wind projects totalling 6,237 milliwatts. Prices are now far below the original feed-in tariffs and have fallen 48% for wind and 71% for solar photovoltaics. Wind energy prices are now as low as US$c 4.7/kWh. Uganda's GETFiT competitive tenders, although on a much smaller scale, have also been successful in generating a pipeline of projects at prices cheaper than those obtained from unsolicited or directly negotiated deals.

Other low- and middle-income countries are also leading the way: Brazil's descending price clock auctions have been successful in attracting significant investment at low prices. In India, a recent auction for 1.2 gigawatts of solar capacity delivered bids of US$c 3.6/kWh. There is huge potential to adopt competitive tenders or auctions for grid-connected renewable energy in other low- and middle-income countries. The challenge is ensuring auction designs fit country contexts and that transaction costs are appropriate to local markets. It remains to be seen to what extent some of the very low prices observed can be delivered in practice, and some countries, such as Peru, have successfully implemented auction rules in place to encourage deployment (IRENA, 2015; IEA, 2017). Policies that reduce regulatory and market-related risks can reduce financing cost of renewables: a study on wind power in the EU finds that such policies reduced the costs of renewable energy deployment by 29% (May and Neuhoff, 2021).

Another regulatory approach to expanding and financing renewable energy generation is the deployment of emissions markets or trading schemes, to incentivise generators with low emissions to enter the market. This policy has traditionally been overlooked in the context of low- and middle-income countries, where institutional and informational requirements were perceived to be excessive (Stavins, 2003). Evidence on the efficacy of these policies remains mixed. Cao et al., (2021) find that an emissions trading scheme (ETS) in China led to emissions reductions due to lower production of electricity rather than entry of new low-emissions generators or improved production efficiency. This still represents the market (successfully) at work, but may raise concerns about leakage (the displacement of emissions elsewhere). In contrast, pollution markets for industrial plants in India were found to substantially reduce emissions (Greenstone et al., 2023). Further research on the efficacy of pollution markets, their design and the institutional barriers to improving information and credibility are needed for low- and middle-income countries.

An important area for future research is understanding how electricity markets can be designed in tandem with other price setting policies for carbon to support well-functioning and efficient electricity markets which are attractive for new renewable energy generators. This may draw on the growing evidence base from high-income country settings. This includes evidence on the interaction of targets and policies, market failures and policy instruments, and optimal pricing policies. Villavicenci and Finon (2022) evaluate the interaction of emission reduction targets, target share of renewables and new flexibility technologies (such as storage techniques) in the EU, and argue that a first-best policy mix should adjust over time to account for trade-offs between economic efficiency and environmental performance. They find that emissions constraints alone do not lead to higher optimal shares of renewable generation, while high renewables share targets have a lower environmental performance in the absence of emission caps.

Technological advances that increase supply flexibility may also increase arbitration capabilities which improve the economics of fossil fuels, and therefore should be countered with tighter carbon constraints. Fischer et al., (2021) attempt to identify second-best policies that are able to target key market failures in the European electricity market, namely carbon emissions, learning-by-doing and R&D externalities, and limited efficiency-improving measures. They find that under a fixed emissions target, an electricity tax is a good second-best substitute for efficiency subsidies, but that there is limited leeway to substitute innovation policies. These findings can be useful to identify key policies that should be prioritised, especially given the limited policy options in low- and middle-income countries that face jurisdictional constraints.

When it comes to grid financing, Feger et al., (2022) assesses how policymakers should design tariffs that address the challenges of network financing and vertical equity, while also achieving renewable energy targets. By looking at solar adoption by households in Switzerland, they show that regulators' preferences between solar diffusion and household welfare equity lead to different optimal policies. Achieving solar adoption targets while still maximising welfare would require high installation cost subsidies, reductions to marginal prices, and high fixed fees. Future research into how these policy mixes can be combined in a low- or middle-income country setting can shed light into how policymakers can achieve renewable goals under institutional constraints.

RESEARCH PRIORITIES

- How can low- and middle-income countries best manage the intermittency issues associated with low carbon energy sources?
- What policies are effective in encouraging the adoption of storage technologies that aid grid management?
- Can pricing designs, such as real-time pricing, help manage intermittency challenges?
- How large is the role of credit constraints and capital market imperfections in slowing the adoption of renewables? How can these constraints be overcome?
- How can the performance of renewable auctions be enhanced through auction theory and past experiences?
- What are the most effective financial instruments for increasing low-carbon energy supply?
- What type of market designs and pricing policies are optimal to achieve low-carbon energy targets in low- and middle-income countries?

II. Mitigation with demand-side energy policies

The range of interventions that will create a lower carbon content in the expected increase in energy consumption in low- and middle-income countries have focused so far on the supply-side and the constraints that may limit the adoption of renewable energy. However, a number of interventions on the demand-side could be considered. One of them is improving energy-efficiency or designing policies that incentivise energy-efficient investments from firms and households.

Energy-efficiency is a large component of many climate change abatement plans. However, efficiency policies have not often been rigorously evaluated, particularly in low- and middle-income countries where the scope for implementing them may be greatest. The expected rise in global energy consumption from low- and middle-income countries will come with grid connected energy availability, and an increasing number of purchases of energy-using appliances at a certain level of development (Wolfram et al., 2012). More evidence is therefore needed on understanding demand-side management as countries progress along the development arc.

Differentiating between the private and social returns of efficiency in such programmes will be important in low- and middle-income countries. For example, when tariffs are below private costs for political reasons, there may be much stronger rationales for utility-led demand-side management and energy-efficiency programmes, as the incentives to reduce consumption on the part of households might be limited. Note that the issue of limited incentives for energy efficiency is also true for countries with fossil fuel subsidies (Davis, 2017). As another rationale for public intervention, recent work in the Kyrgyz Republic suggests that the social returns to energy efficiency can also include benefits in the form of increased reliability

(Carranza and Meeks, 2021), which consumers might not internalise. Recent experimental evidence from installing pre-paid metres in Cape Town, South Africa, found that these new technologies reduced consumption while directly removing the challenges associated with bill payments (Jack and Smith, 2020).

Such policies can not only reduce consumption – in turn aiding mitigation efforts – but also address some of the costs of poor urban energy services. Cities, which consume about 75% of the world's primary energy (United Nations, 2014), are at the heart of any demand-side and energy-efficiency policies as they represent the richest consumers and largest markets. In cities, the role of passive building design deserves more investigation, especially as Africa and Asia are home to some of the fastest growing cities. A large number of new buildings will need to be built in the coming years. Recent work in Mexico suggests that energy-efficient housing might not always have the intended energy savings (Davis et al., 2020), and therefore careful planning given the existing evidence should help improve the outcomes of such programmes. Note that the specific issues around building more compact and more efficient urban areas are further discussed in the IGC Cities evidence paper.

Evidence on the returns to energy efficiency

Engineering estimates suggest that some investments may have particularly high returns—for instance, efficient air conditioners and cool-roof technology (McNeil et al., 2011; Phadke et al., 2013; Akbari et al., 2011). Yet for many technologies touted for their high returns, actual adoption and use remains low. The wedge between high projected returns and low adoption is commonly referred to as the 'energy-efficiency gap'. Jaffe and Stavins (1994) and Allcott and Greenstone (2012) survey the field two decades apart; unfortunately, despite the time lapse, the latter survey highlights a lack of credible empirical evidence on the question of why no one is making these investments. If market or information failures prevent investment (for instance if energy efficiency investments have credence good properties that makes their qualities difficult to identify even after they have been purchased (Lanz and Reins, 2021)), then policy intervention could promote both energy efficiency and economic efficiency. Alternatively, it may be that efficiency measures have unobserved costs of adoption or less-than-ideal real-world performance, neither of which would justify policy intervention. In the context of low- and middle-income countries, significant credit constraints can also prevent consumers from availing themselves of profitable investment opportunities. If credit constraints are binding, informational campaigns alone might not solve the problem. Limited warranties or quality could also shorten the expected life of an appliance and limit the net present value of more energy efficient goods, making them less desirable investments.

A recent literature has begun to sort out these issues, although primarily in high-income countries. For example, recent research in the US underscores how engineering estimates of energy savings may overestimate real-world performance, a divergence that may explain a good portion of the observed 'energy-efficiency gap' (Fowlie, Greenstone, and Wolfram, 2018; Allcott and Greenstone, 2017). Rebound effects of energy efficiency programmes in the US have also been studied (Kahouli and Pautrel, 2023; Shojaeddini and Gilbert, 2023). Davis et al., (2014) find lower-than-expected returns to energy efficiency from appliance replacements in Mexico, arising in part due to rebound effects and also due to potential monitoring issues with the replacement of appliances that were not functioning. An RCT of industrial energy audits in Indian manufacturing plants saw that plants responded to increases in energy productivity by using more, not less, energy (Ryan, 2018). Christensen et al., (2023) find that labour skills can drive a substantial share of the energy-efficiency gap in weatherisation interventions in the US, suggesting a role for training and incentive programmes that can deliver improved energy savings, which could also play a role in low- and middle-income countries.

The literature on consumer and firm responses to energy standards and labels is largely focused on high-income countries like the US (Houde, 2018; Houde and Spurlock, 2015) or EU countries (Brutscher et al., 2021, Stergiou and Kounetas, 2021). Countries such as India and China have had both voluntary and/or mandatory certification programmes for a wide range of energy-intensive appliances and products for over twenty years, with labelling similar to that used in European countries and the EnergyStar programme in the US, yet evidence in such contexts remains much more limited. A choice experiment in India that investigated consumer responses to energy labels found that including energy cost information on efficiency labels increased WTP for more efficient refrigerators (Jain et al., 2021). While global evidence in Montalbano et al., (2022) suggests that energy efficiency is associated with higher firm productivity, firms targeted by a command-and-control energy savings policy in China experienced reduced profitability and production growth (Xiao et al., 2023). Much more research is required to understand the impact of energy standards and labels in low- and middle-income countries.

The use of behavioural economics to encourage the adoption of more efficient technologies could be a promising avenue of research here. A study on energy demand in Brazil finds hysteresis - long lasting effects of past policies - which could bias welfare estimates of energy efficiency policies (Costa and Gerard, 2021). There is a growing base of evidence on the use of 'nudges' as a means to change consumer energy behaviour, including evidence from India (Allcott and Mullainathan, 2010; Sudarshan, 2013).

RESEARCH PRIORITIES

- What are the private and social rates of return to energy efficiency investments and policies in low- and middle-income countries?
- How do energy efficiency strategies compare in terms of greenhouse gas reductions on a cost per ton abated to supply-side interventions? How does the comparison differ in low- and middle-income countries?
- Are there informational or other barriers to individuals and firms making energy efficiency investments in low- and middle-income countries?
- Is there a larger 'energy efficiency gap' in low- and middle-income countries? What roles are played by existing distortions such as low electricity prices, credit constraints, and limited warranties? If so, what policy tools are available to remove these barriers to making efficient energy efficiency investments?
- Do energy users in low- and middle-income countries shift their consumption under nudges, and if so, by how much?

III. Climate adaptation

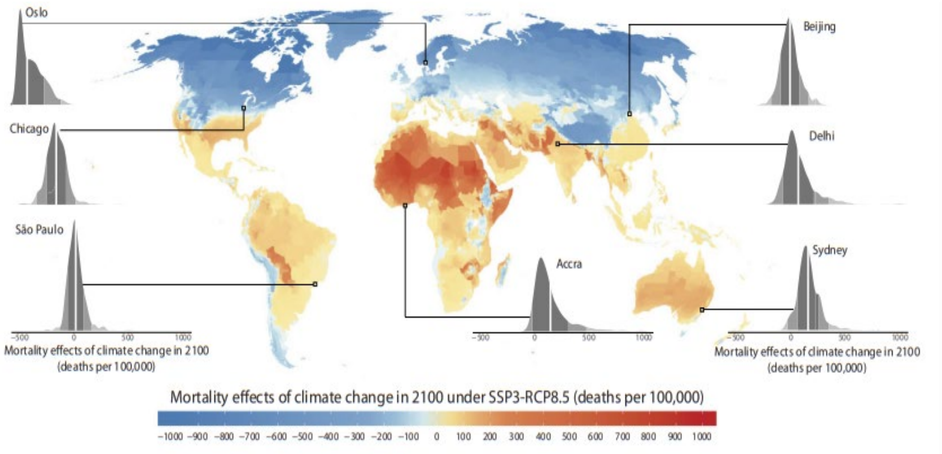
Households and firms will require assistance in adapting to the global externalities generated by increased use of energy across low- and middle-income countries. A warmer world saps the productivity of agriculture, lowers the efficacy and supply of labour (Lobell and Tebaldi, 2014; Burke et al., 2015; Baker et al., 2020; Heyes and Saberian, 2022), and affects the provision of public goods such as water and sewer treatment (Danelon et al., 2021). Hot days and nights inhibit the body's physiological processes, especially among the elderly, leading to premature death (Karl et al., 1993; Sherwood and Huber, 2010; Carleton et al., 2022). Floods destroy capital and end lives, discouraging economic activity (Kocornik-Mina et al., 2020). Changes in climate alter the conditions under which social interactions occur, potentially increasing the likelihood of conflict (Burke, Hsiang, and Miguel, 2015b). The list of impacts certainly also includes fundamental changes in the use of energy (Rode et al., 2020) among others. Emerging research also suggests that higher temperatures substantially reduce the growth prospects of low- and middle-income countries (Dell, Jones, and Olken, 2012; Burgess et al., 2023; Cruz and Rossi-Hansberg, 2021).

Poor countries in particular are going to be severely harmed by climate change, with lower agricultural yields and manufacturing productivity and higher rates of premature death (Lobell and Tebaldi, 2014; Burke, Hsiang, and Miguel 2015a; Burgess, Deschenes, Donaldson, and Greenstone, 2023). Studies to predict the potential economic damages from climate change, in particular at the hyperlocal level, will remain an important avenue of research, as they will help inform what type of public services and private forms of defensive expenditures are critically needed in response and where these needs are the strongest. Below we review the evidence on what impacts are well understood, and how research can address the gaps in knowledge related to the spatial and temporal distribution of damages.

The benefits and costs of adaptation in response to climate change is an emerging area of research where more work is a high priority. The frontier of understanding perhaps comes from a recent study that examines the full mortality costs of climate change, accounting for adaptation costs and benefits (Carleton et al., 2022). This study argues that income growth will naturally provide some protection against climate change but that examination of societies today also reveals that there are adaptation opportunities in response to differences in temperatures. Specifically, it finds that without any income growth or adaptation in response to temperature changes that the mortality cost of climate change would be approximately 125 per 100,000 people. However, income growth and adaptation (inclusive of its costs) are projected to be enormously beneficial; specifically, they are projected to reduce the projected impact by almost 80% to 28 additional deaths per 100,000 poeple, with income growth accounting for the majority of the decline. The precise roles of income and climate-induced adaptation will vary from sector to sector but they must be kept as north stars in any climate strategy.

First, research must consider how the potential lack of information on the local impacts of climate change affects the decisions of governments and individuals. A key first step is producing hyperlocal estimates of climate's impacts, ideally down to the community level. **Figure 9** provides local estimates around the planet for mortality risk but, of course, there will be risks in a wide range of other sectors, including labour productivity, exposure to inundation and damages from sea level rise and storms, agricultural productivity, and on. For this information to lead to public and private changes in workplaces, construction of structures and/or sea walls, land use, among others, it needs to be available at the community level with information on the time scale that these changes will arrive. But how this information is provided to firms and households will affect their decision-making process (Hsiao, 2023). A focus on extending the climate impacts literature to provide information at the local level is critical because information on the global average impact is not helpful to people or governments in any individual community or jurisdiction. Similarly, there is an important need for research on how to effectively communicate projected climate impacts so that they are influential with local governments and communities, and overcome potential cognitive biases and other barriers to information acquisition.

Figure 9: The mortality cost of climate change in 2099 across the world



Notes: A warmer world saps the productivity of agriculture, lowers the efficacy and supply of labour. Hot days and nights inhibit the body's physiological processes, especially among the elderly, leading to premature death. Source: [Carleton et al., 2020](#).

Second, there is an immense opportunity to uncover socially beneficial private and public adaptations to climate change. Existing research has documented that the benefits of people working in sectors that are less exposed to climatic change or by enabling them to purchase technologies that protect them from the deleterious effects of higher temperature such as air conditioners (Barreca et al., 2016; Graff Zivin, Hsiang, and Neidell 2018; He and Tanaka, 2023). While some studies highlight the importance of migration as an adaptation mechanism in low- and middle-income countries (Cruz and Rossi-Hansberg, 2021; Cassin et al., 2022), other researchers project that under current migration laws only a small fraction of the people affected the most will migrate internationally, sharply increasing global inequality and poverty compared to a scenario with permissive migration policies (Burzynski et al., 2022).

In the case of governments, there is a need to understand how to best consider the implications of climate change when making policy and investment decisions. Infrastructure investments will play a role in supporting the income growth that aids adaptation; at the same time, however, these assets are uniquely exposed to natural disasters, and especially if they are on the coast, to sea-level rise. Coastal areas have long been a boon for commerce but their susceptibility might make infrastructure investments here risky. This is due to the outright damage from disasters but also the long-term re-allocation of economic activity away from these areas. An analysis of Vietnam's infrastructure construction shows clear short-term benefits from coastal road construction, but these benefits vanish and become sub-optimal to roads built further in-land once future sea-level rise is factored in (Balboni, 2019). Bridges can help in adapting to floods by ameliorating lost access to local labour markets (Brooks and Donovan, 2020). The Chinese government's investment into high-speed rail infrastructure has been shown to be an effective strategy for both adaptation to and mitigation of local air pollution (Barwick et al., 2022). Similar considerations will come into play in the design of cities and of the infrastructure systems that support them.

Private responses at the firm and sectoral levels are also likely to be critical. Spatial reallocation is likely to be a key response to climate change, but we understand little about how flows of workers into cities and from agriculture into services and manufacturing can be encouraged in anticipation of future changes. As discussed in the **IGC Cities evidence paper**, if migration is the result of climate change damage as opposed to the result of a welfare-improving choice, the benefits of proximity that cities give rise to may not be captured. Forced displacement into cities in response to floods may also be associated with increased urban disorder (Castells-Quintana et al., 2022). Individual firms also need to adapt to the risks imposed by climate change. Investing in more technology-intensive manufacturing production processes may be a useful adaptation tool, as these processes lead to higher energy efficiency at the industrial level, while also reducing carbon emissions (Avenyo and Tregenna, 2022). Despite evidence that firms are aware of climate change, conscious efforts to adapt appear minimal (Agrawala et al., 2011). Inertia to respond to risks is well-documented among both individuals and firms. Cognitive barriers affect our abilities to judge and act on complex, probabilistic decisions over adaptation (Grothmann and Patt, 2005). Information and other behavioural nudges may therefore help induce optimal decisions into adaptation. In this area public information campaigns and the promotion of climate resilient technologies are likely to play a central role. Gao et al., (2023) find that information on pollution data in China increased the responsiveness of migration decisions to pollution. Silva et al., (2023) find that in response to disaster alerts in Brazil, labour markets concentrate in less industrialised sectors, local consumption declines, financial development decreases and there are spillovers to neighbouring villages.

Burgess et al., (2023) is instructive and is an example of the type of research that can help. It documents that an increase in hot days raises mortality among rural, but not urban, poor. When heat strikes during the growing season, the poor who are engaged in agriculture suffer from reduced productivity and wages, which drives the witnessed increase in mortality. Importantly, the availability of local bank branches – a potentially life-saving source of credit – alleviates these impacts. For instance, financing can support private investments into more resilient crops or crop varieties that better resist changes in climate. There is an urgent need to think about how transfer schemes and financial and insurance instruments can be designed to help the most vulnerable households adapt to climate change.

Understanding how new technologies and crop choices can protect farmers is also critical here. Farmers adjust to fluctuations in the weather by moving into non-farm activities or changing the size of cultivation (Banerjee 2007; Kazianga and Udry, 2006). Fortunate farmers may have access to weather insurance, helping them ride out the vagaries of the climate (Barnett and Mahul, 2007). Similarly, agricultural extension efforts can help with land use decisions, including crops switching. Evidence from an RCT on rural Nicaraguan households who are exposed to weather variability shows that one year of conditional cash transfers with either vocational training or a productive investment grant both provided protection against weather shocks and households showed higher consumption levels, income smoothing as well as a diversification of economic activities post intervention (Macours et al., 2022).

What matters, however, is whether households are constrained in accessing these adaptive measures. Given the general equilibrium effects present in climate shocks, there is a clear argument for the provision of public goods to aid adaptation. How these should be designed, targeted, and implemented, in particular for the most vulnerable, is an active area for research that we plan to deepen and encourage.

The evidence on the impacts of climate change so far underscores the urgency of identifying research and policy options to facilitate growth which is the centrepiece of the IGC's mission. Pointedly, Africa and South Asia's success in reducing vulnerability to climate change likely lies in their ability to generate sustained growth and development. There is thus an urgent need to understand how policies that affect trade, structural change, and growth can aid adaptation to climate change. A recent review by Balboni, Kala, and Bhogale (2023) emphasises the need for research in both measuring the efficacy of adaptation measures undertaken by households and governments as well as the spatial and general equilibrium impacts of adaptation. Increasingly economic and social policy will need to be designed to help individuals adapt while accounting for the spatial implications of these decisions.

IV. Natural capital

Natural capital influences economic development in myriad ways that we are only beginning to understand. Allowing the stock of natural capital to collapse, as it has been doing in recent decades (IPCC, 2022), is exposing us to additional risks. Therefore, research is also needed to better quantify the monetary benefits derived from natural capital under the stresses and shocks from climate change. For example, the collapse of keystone species such as vultures in India has been found to have led to an increase in water-borne diseases, producing mortality impacts on the same order of magnitude as those expected from excess heat by the end of the century (Frank and Sudarshan, 2023).

Biodiversity is one form of natural capital with a plethora of positive economic consequences. Biodiversity loss therefore threatens agricultural production (Worm et al., 2006; Dainese et al., 2019), worsening income shocks from natural disasters (Noack et al., 2022), drug discovery (Simpson et al., 1996; Rausser and Small, 2000; Costello and Ward, 2006), and has been linked to the emergence and transmission of infectious diseases

(Keesing et al., 2010). Evidence on the value derived from natural assets or biodiversity is currently limited. An improved understanding of the value of natural capital can allow us to reach a conservation equilibrium which protects non-substitutable forms of nature and biodiversity. From what we do know, value is highly dependent on the ecosystem and the current integration into economic processes. We discuss further below how natural capital valuation and preservation plans an essential role in the mitigation of carbon emissions and the facilitation of adaptation response mechanisms. In low- and middle-income countries, where there is a high stock of natural endowments, protection of natural capital becomes increasingly important for policymakers internationally.

A key investment choice governments may have is the preservation, restoration, and conservation of natural capital. There is a significant literature on the substitutability of natural capital for other forms of capital (Cohen et al., 2019). Given limited state capacity, some natural resources will have to be given priority over others. Therefore, the first step is to understand which assets are the most valuable, and for whom. Services can be derived from a number of environmental assets including biodiversity, forests, and water, which all have high economic value with low substitutability. Trees absorb and store carbon dioxide (Bellassen and Luyssaert, 2014); bees support pollination (Gallai et al., 2009); and water is essential for agriculture and for hydropower generation (Chong and Sunding, 2006). Still, more research is needed on valuing natural resources using methods that are well-suited for low- and middle-income countries. Valuation methods based on revealed preferences may be severely downward biassed, especially for poorer people in environments with more market failures and less access to abatement technologies (Greenstone and Jack, 2015).

In order to provide the global benefit of carbon sequestration, institutions, and markets must create the right conditions and incentives for conservation. We need more research to shed light on the main market failures and political tensions that block sustainable outcomes. For example, consider the central tension between government, firms, and citizens to exploit forests and convert land for other uses (Burgess et al., 2012). A global imperative (climate change) may compel the national government to preserve the forest; local firms may be driven by a desire for rent extraction; and individuals may lack attractive economic alternatives that disincentivise deforestation. For countries like Indonesia, Brazil, and the Democratic Republic of Congo (DRC), the exploitation of forest land is central to national development. Thus, there is an urgent need to devise effective policies that balance local development and global conservation objectives in a way that is feasible. Since the benefits of conservation accrue at different geographic scales relative to the benefits of resource exploitation, there will be winners and losers. Effective policies must therefore think about the ideal conservation finance schemes that will make them politically feasible at all relevant scales.

One popular policy is payment-for-ecosystem-services (PES). While some PES interventions have showed clear benefits, for example in the case of deforestation (Jayachandran et al., 2017), the evidence on their performance remains mixed (Pattanayak et al., 2010; Jayachandran, 2023). More evidence on when and why these programmes can be effective is needed (Jack and Jayachandran, 2019). Another potential intervention focuses on strengthening property rights (for example, through land titling). These interventions have also had mixed results (BenYishay et al., 2017; Wren-Lewis et al., 2020; Tseng et al., 2021; Jayachandran, 2022). Conservation interventions (for example, the reintroduction of a near extinct species; rewilding) also hold promise to protect biodiversity, but rigorous evidence on their impact is largely missing. Explicit command and control regulation to avoid deforestation or habitat degradation in the Amazon was found to be far more costly than incentive-based mechanisms (Souza-Rodrigues, 2019), encouraging further research into different incentive schemes to ensure cost-effective natural capital protection.

The costs of economic growth are closely linked to environmental impacts, and biodiversity is also a large component in these costs. Through channels such as air pollution and urbanisation, economic activity has large effects on biodiversity loss (Liang et al., 2023), while electrification itself can also have direct consequences for biodiversity and species survival (Brei et al., 2016). As low- and middle-income countries across the world intensify their electrification processes and urbanise rapidly, understanding the importance of maintaining biodiversity together with how these processes affect the environment becomes a crucial part in developing policy that can achieve a green transition without further disrupting biodiverse ecosystems. Fossil fuel production for instance can be in itself a major threat to conservation goals, as oil platforms expand into more remote areas in search of undiscovered reserves. However, leaving corporations to their own devices can lead to over-deforestation and loss of biodiversity in regions where there are large gains from extractive activities but also where there is considerable biodiversity wealth, highlighting the reliance on public regulation (Cust et al., 2023).

RESEARCH PRIORITIES

- How can trade, growth, and structural change help households and firms in low- and middle-income countries adapt to the effects of climate change?
- How effective are natural capital investments in stimulating local economic growth?
- What are the necessary public goods to aid adaptation to climate change for households and firms?
- How should insurance markets, financial markets and transfer schemes be designed to help vulnerable households, particularly in agriculture, adapt to the effects of climate change?
- What is the role of information provision about the impacts of climate in inducing socially optimal policies and behaviour to adapt to these effects? How can governments effectively deliver the local information on climate impacts necessary to help the public and private sectors adapt effectively?
- How can behavioural nudges be used to incentivise optimal decisions in adaptation?
- How can increased energy service access benefit adaptation to climate change?
- How does higher energy efficiency relate to climate change adaptation? What policies can help in making less carbon intensive technology adaptive?

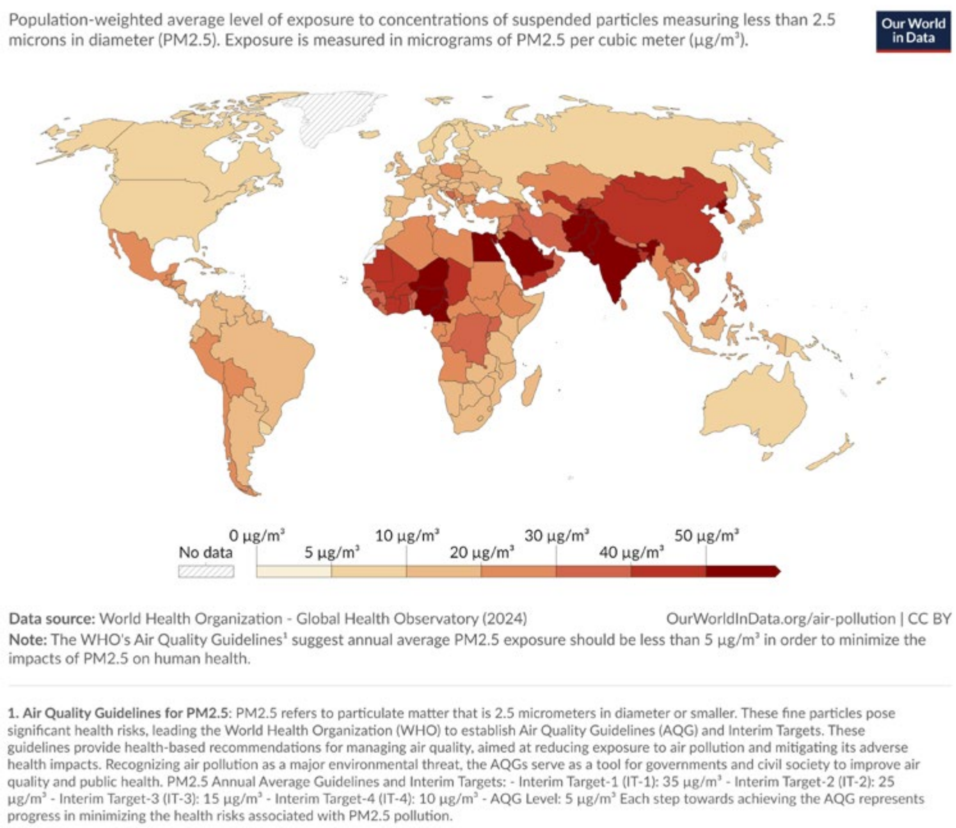
4. Local externalities from energy consumption

Massive expansions in energy access during industrialisation and urbanisation—when people move from bicycles to cars, for example, or from darkness to electricity—have always massively increased pollution, congestion, and other external costs. Only a handful of countries in the world have air that is safe to breathe per the standards of the World Health Organization (**Figure 10**). Today's low- and middle-income countries have the most acute air-pollution problem ever experienced in world history.

Today's low- and middle-income countries have the most acute air-pollution problem ever experienced in world history.

Growth in output may mismeasure or overstate welfare gains if growth degrades environmental quality and natural resources. For the billions of people growing up under a cloud of haze, such long-term exposure is sure to impact health and human capital, imposing unknown costs on the growth potential of a country. Additionally, the air is not the only medium through which people are exposed to pollution: contaminated water, either due to poor waste and sewage treatment or other reasons, can also undermine health and wellbeing. However, our focus will be on the pollution associated with energy consumption.

Figure 10: Annual PM2.5 exposure around the world, 2019



Notes: Today's low- and middle-income countries have the most acute air-pollution problem ever experienced in world history. Figure generated by the authors using Our World in Data.

More thought needs to be put into mechanisms for improving environmental quality. However, there remains little rigorous work on the efficacy and costs of environmental regulations in low- and middle-income countries (Greenstone and Hanna, 2014 and Duflo et al., 2013 are exceptions). Households value clean air, but we know little about the heterogeneity in valuation across space and income and even less about the costs of different kinds of abatement investments. Information on sources of pollution and abatement strategies are severely lacking at local levels. Translating information about the problem into behavioural change is another tall order. Regulators in low- and middle-income countries do not have good information on the sources of emissions or the costs of abatement through different strategies. The pure technological costs of abatement—like a factory running a machine or the retirement of a polluting vehicle—may be much lower than the social costs of that abatement, such as the regulatory systems needed to ensure the machine runs or the vehicle is scrapped properly. Even when sound environmental regulations are put into place, they often go unenforced. Progress in reducing externalities from energy use can only be made if enough attention is paid to both the design and implementation of policies.

I. Consequences of pollution for health and productivity

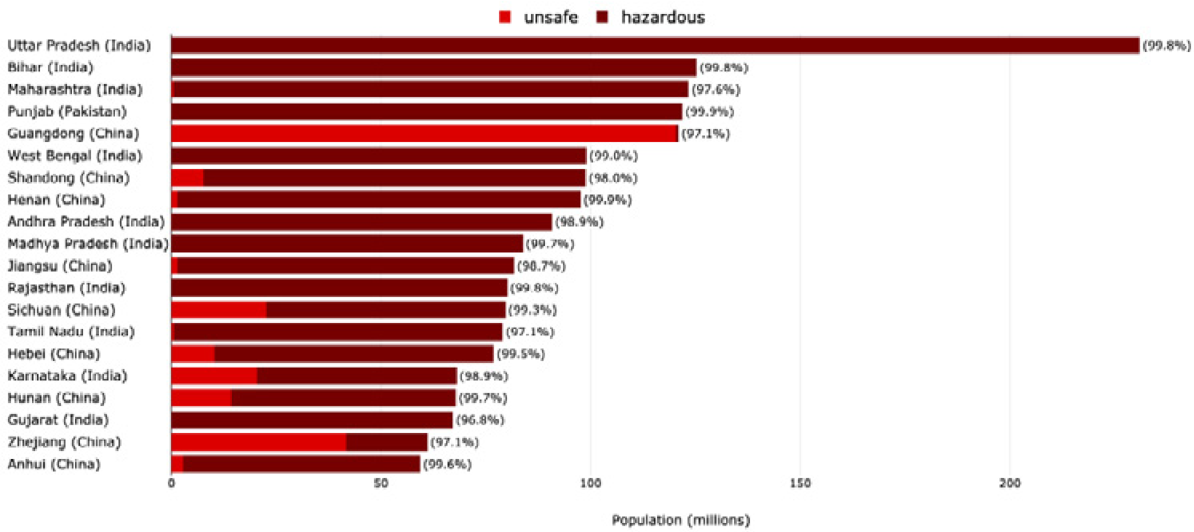
Table 1: Health impacts of pollution on environmental quality

Country	Pollutant	Health impact: magnitude	Methodology	Author (year)
Indonesia	PM	Infant mortality: 1.2 percent	Quasi-experiment	Jayachandran (2008)
Mexico	CO and PM	Infant mortality: elasticities of 0.227 (CO) and 0.415 (PM)	IV	Arceo et al. (2012)
China	TSP	Life expectancy: 2.5 years	Spatial discontinuity	Chen et al. (2013)
China	Water quality (index)	Stomach cancer deaths: 9.7 percent	Quasi-experiment	Ebenstein (2012)
Bangladesh	Fecal coliform	Infant mortality: 27 percent	Quasi-experiment	Field et al. (2011)
Kenya	E. Coli	Child diarrhea: 25 percent	RCT	Kremer et al. (2011)
Mexico	SO_2	Labor supply: 0.61 hours/week	Quasi-experiment	Hanna and Oliva (forthcoming)
India	Agrochemical	Multiple, child, and infant health	Quasi-experiment	Brainerd and Menon (2014)

Notes: Summary of empirical findings on the impact of pollution on environmental quality. Pollutants are abbreviated as follows: particulate matter (PM), carbon monoxide (CO), total suspended particulate (TSP), sulfur dioxide (SO_2). RCT refers to a randomized controlled trial. Findings are as reported in the paper citied in the rightmost column. A lack of relevant information for a number of the studies precludes the translation of the heath impacts into elasticities.
Source: **Greenstone and Jack, 2015**

As illustrated in **Figure 11**, there are only a fortunate few who are not exposed to harmful levels of air pollution. For the remaining six billion people, air pollution is either silently deteriorating their health or overtly draining years off their lives. Particulate matter air pollution cuts global life expectancy short by nearly two years (Greenstone and Fan, 2018) and may represent the greatest 'external' threat to public health in the world. Dirty water also allows for the rampant spread of disease: diarrhoea kills 2,195 children everyday, more than AIDS, malaria, and measles combined (Liu et al., 2012). The health consequences of polluted air are just now beginning to be understood, but the early conclusions have been clear - pollution damages health and human capital. Not only do exposed humans get sick, their cognitive functions decline (Gibbens, 2018). While pollution was rampant at the time of industrialisation in Europe, it is likely that today's low- and middle-income countries are faced with an even more acute crisis. Identifying the precise and heterogenous impacts of pollution is an essential start for planning how to combat this growing crisis.

Figure 11: Population, in millions, of those exposed to certain PM2.5 levels



Notes: For almost six billion people, air pollution is either silently deteriorating their health or overtly draining years off their lives. Source: Rentschler et. al., 2022.

Exposure to pollutants such as airborne particulate matter (PM), ozone, and nitrogen dioxide is directly associated with increased mortality and the onset of cardiovascular and respiratory disease (Brunekreef and Holgate, 2002; Adhvaryu et al., 2023; Heo et al., 2023) while also increasing mortality rates of diseases that affect the respiratory system, such as influenza (Graff Zivin et al., 2023). London's great smog event of 1952, triggered by stagnant weather conditions that dramatically increased the concentration of air pollutants, is a perfect case study. Over the course of a few days, several thousand more people died than expected, establishing a direct link between pollution and mortality. Importantly, the death rate remained higher for months following the episode (UK Ministry of Health, 1954). Damaging effects have been found even at low levels of exposure. From the mid-19th to mid-20th centuries, acute pollution exposure accounted for at least one out of every 200 deaths in London (Hanlon, 2022).

The production of energy through combustion is the leading culprit for human-made particulate pollution (Philip et al., 2014). Large coal-fired power plants spew toxic pollutants into the air. The advent of mechanised transit and the proliferation of backup electricity generation have brought people much closer to the harmful by-products of combustion. Farmers looking to clear their fields of residual crops opt for the cheapest and quickest way: they burn the crop-stubble in their fields. Pastoralists eyeing more land for their animals choose to cut—or, again, burn—the forests to clear space. Winds carry these carcinogenic clouds into nearby areas and cities, exposing large numbers of people to pollution. An estimated 12.5% of all deaths in India in 2017 were directly attributable to air pollution, with over half due to exposure to ambient particulate matter (Balakrishnan et al., 2019). Poor air quality in India is estimated to have reduced average life expectancies by three years (Greenstone et al., 2015).

The failures of energy distribution described in the first section increase the pollution intensity of energy production and use in cities in low- and middle-income countries. Unreliable electricity spurs the combustion of kerosene, diesel, coal, and fuel oil, which are large sources of urban air pollution (Goel and Guttikunda, 2015; Guttikunda and Calori, 2013; Guttikunda et al., 2013). This pollution lowers productivity, makes people sick, shortens their lives (Hanna and Oliva, 2015; Graff Zivin and Neidell, 2012; Guttikunda and Goel, 2013; Chen et al., 2015; Greenstone et al., 2015; Datt et al., 2023; Lavy et al., 2022), and undermines the economic and health benefits of moving to a city in the first place. Pushed into building up captive power to combat unreliable supply, demand for electricity could be unnaturally suppressed, leading to ineffective policy.

Pollution is also generated in or near the home. Indoor air pollution is the third highest risk factor in the global disease burden (Lim et al., 2012). In low- and middle-income countries, the burning of charcoal for cooking and heating is a dangerous source of black carbon, a component of PM2.5. After subsidies were granted on coal to be used in boilers for winter heating in northern China (areas above the Huai River), average life expectancies were reduced by about three years (Ebenstein et al., 2017) for the intended beneficiaries of the policy. Long term exposure has devastating effects: Aggregated up, the 500 million residents of northern China are expected to lose 2.5 billion years of life expectancy. The social and economic costs of this are staggering. In Bangladesh, an estimated 57 million people were exposed to arsenic-contaminated water in wells, resulting in higher levels of morbidity and negatively affecting schooling attainment, the likelihood of being in a skilled occupation, entrepreneurship levels, and income (Pitt, Rosenzweig, and Hassan, 2015). Another study in Bangladesh found that households that switched from deep wells to surface wells contaminated with faecal bacteria saw infant and child mortality increase by 27% (Field, Glennerster, and Hussam, 2011).

While there is an extensive body of research linking pollution to adverse outcomes, more work is needed to uncover the causal impact of sustained pollution exposure in low- and middle-income countries. Data is more readily available in high-income country contexts, but it is unclear how generalisable findings are to countries like India or China. Much of the literature examines exposure in the short term or at certain points in time (such as in infancy or in utero) to analyse impacts. A broader quantification of the impacts of pollution exposure of many years is only beginning to be built up (for example, Zhang et al., 2018 and Ebenstein et al., 2017).

An especially intriguing and emerging area of research examines the impacts of air pollution exposure on cognitive development and cognition. Recent work in the US and China suggests that early life exposure can affect long-run cognitive development and cognition (Isen, Rossin-Slater, and Walker, 2017; Bishop, Ketcham, and Kuminoff, 2019; Ebenstein and Greenstone, 2020).

In high-income countries, higher exposure to air pollution has been found to decrease academic achievement while increasing educational inequality (Duque and Gilraine, 2022). Comparing siblings who were born before or after the opening of industrial installations responsible for emitting toxic air pollutants, Persico (2022) finds that prenatal exposure decreases expected future wages and increases the likelihood of being in poverty in adulthood. Yao et al., (2023) find similar effects of short-term pollution on cognitive performance of college students in China.

Further impacts have been documented on short-run behaviour, such as increasing the occurrence of violence and crime (Herrnstadt et al., 2021). Building the evidence base on such impacts in low- and middle-income countries could greatly increase the known costs of air pollution associated with energy consumption. In these cases, where non-renewable sources of energy are associated with high externalities, such as fuelwood and deforestation, electrification can have even more significant aggregate benefits (Bošković et al., 2023).

Finally, the distributional and heterogeneous impacts of pollution across a wide range of outcomes are even less well understood. Recent evidence from Colombia suggests that exposure to pollution is even more unequal than social and economic inequalities in an urban setting, and that economic, social, and air quality disparities intersect, with the poorest populations also being the most exposed to air pollution (Bonilla et al., 2023). There is an active need for research in this area.

Pollution is not the only local externality that is caused by energy use. Energy use in the transportation sector, for example the growth in the use of private vehicles, causes massive externalities due to congestion. Many cities in low- and middle-income countries, from Lagos to Karachi, are notoriously gridlocked. An experiment in India, at a partial equilibrium level, found that a hypothetical congestion pricing regime would nonetheless have little benefit, since commuters value travelling at peak times very highly (Kreindler, 2020). Is congestion pricing feasible, given nearly complete smartphone adoption in many cities, and what would be its benefits on a large scale? What is the right policy mix for transportation in low- and middle-income country cities? We leave questions of urban economics to the IGC Cities theme. However, there is often not a clean demarcation between these topics, since public investments, infrastructure, and policy with respect to urban growth feedback upon energy demand and the externalities due to energy use.

RESEARCH PRIORITIES

- Measure the effects of long-term exposure to air pollution, water pollution, and other externalities from energy use.
- Assess the distributional and heterogeneous impacts of pollution exposure by gender, socioeconomic status, caste, or other categories.
- Measure congestion externalities and their effect on energy demand, as well as the reverse relationship from energy demand growth to congestion.
- How can public perception of air pollution mobilise or encourage changes in air pollution regulation?
- What low-cost interventions can best mitigate point-source emissions in industry?
- How effective is a payment for ecosystem services (PES) programme in mitigating seasonal crop burning in the agriculture sector?

II. Guarding against pollution and the willingness to pay for environmental quality

Given that pollution is the greatest external risk to human health, we might expect that both governments and individuals have a high willingness to pay (WTP) for preventing it. Yet poor environmental quality throughout low- and middle-income countries could imply that this WTP is low. An experiment generating exogenous variation in the quality of water supply in Kenya found that households were only willing to pay US$ 11 per year for clean water (Kremer et al., 2011). For a long time, policy concerns over matters like pollution were displaced by the conquest of growth. Simply put, the marginal utility of consumption outranked the marginal utility of environmental quality.

This could in part be a function of a historical lack of information on impacts. China was, until recently, the embodiment of the growth-at-all-costs approach: tremendous economic success with disastrous implications for environmental quality and pollution. However, in 2013, China declared war on air pollution, setting aside US$ 270 billion for its National Air Quality Action Plan, with the Beijing city government topping up with an additional US$ 120 billion (Greenstone and Fan, 2018). In the three years between 2013 and 2016, China succeeded in reducing particulate pollution exposure by 12% on average, an improvement on par with the progress made in the US between 1998 and 2016 (Greenstone et al., 2021). Few countries, if any, have made such substantial progress in improving air quality in such a short span of time.

Not all countries have the resources, determination, or institutions to wage a war on pollution at the scale China did. Residents who are stuck in highly polluted areas might therefore seek mechanisms to reduce their own exposure or carry on despite the risks. How can—and how do—households or individuals defend themselves against the ruinous effects of pollution? Any protective measure is sure to be costly. How much are individuals willing to pay to defend themselves from local pollution and improve overall environmental quality? Does this willingness extend beyond only the private gains from such behaviour? These are important questions that we need more evidence on in order to determine what optimal environmental regulation should look like.

One methodological challenge has been measuring revealed WTP. One difficulty for estimation is that market failures (such as capital constraints) may cause the measured WTP to differ from its 'true' value (Greenstone and Jack, 2015). Defensive responses to pollution are likely to be diverse, with a range of costs. Quantifying how much households are willing to pay for their own self-protection requires us to first obtain a better understanding of the choices households make in the face of pollution, such as fertility decisions or adjustments to migration (Greenstone and Jack, 2015). Chen et al., (2022) for instance find that migration has been a significant channel of adaptation to increased levels of pollution in Chinese counties. While these are long-run adjustments to pollution exposure, there are also short-term changes in behaviour, particularly spending, to adjust to pollution exposure. For example, individuals buy an increased number of air purifiers and face masks on the days where the AQI exceeds certain thresholds (Sun et al., 2017; Zhang and Mu, 2018). Individuals also are likely to increase their spending on healthcare in areas of elevated pollution levels (Barwick et al., 2018) while they decrease spending in other consumer categories, such as restaurants (Barwick et al., 2019). From these methods, WTP for less polluted air is revealed, as well as the true cost of air pollution mitigation by individuals found from their spending on health, protective gear, and technology.

Obtaining exogenous variation has, naturally, proven difficult thus far. Research in China closely tracked the sales of air purifiers and, using quasi-experimental variation from the north versus south China divide created by the Huai River policy, determined the marginal WTP for clean air (Ito and Zhang, 2020). The estimated marginal WTP is increasing in incomes, but with substantial heterogeneity. Ito and Zhang (2020) also examine how widespread media coverage on pollution starting in 2013 affected the WTP. As the issue has been given more serious attention, WTP for clean air has increased considerably. Applying these results, a cost-benefit analysis showed clear benefits from a heating-system reform programme around the Huai River, with households willing to pay US$ 32.7 per year to eliminate the pollution stemming from this policy. Globally, Besley and Hussain (2023) look at coal-fired power stations across 51 countries and find large WTP from households for clean air, with a lower bound of aggregate WTP of almost US$ 600 billion.

While we are aware of many of the negative impacts of air pollution on mortality, mental health, and productivity, there still remains a lack of evidence on the impacts of long-term pollution exposure. Future research into pollution should work to quantify both the WTP for avoidance of air pollution, but also should prioritise estimates for long-run variation in first order outcomes under high exposure to air pollution (Greenstone et al., 2021). Significant research is needed to improve the quantification of pollution damages and understand the mechanisms which prevent damages from accruing generally, and to those who are most vulnerable. Expanding information access, evaluating the spatial distribution of pollutants, and identifying effective enforcement mechanisms for abatement are all areas of further research.

RESEARCH PRIORITIES

- Can we measure WTP for environmental quality through household defensive responses to local pollution?
- What interventions are households or employers willing to adopt to mitigate the impacts of pollution?
- Does spatial sorting occur in response to local pollution?
- How do social norms and market failures (for example, imperfect information, capital constraints) affect WTP for environmental quality through defensive expenditures?
- What causes WTP for environmental quality to change? Do public information campaigns alter WTP?

III. Enforcing regulation in settings with weak institutions

Table 2: Evidence for high marginal costs of environmental policies in low- and middle-income countries

Country	Finding	Methodology	Author (year)
Brazil	Decentralization increases water pollution	Fixed effects	Lipscomb and Mobarak (2011)
Mexico	Policy loopholes undermine effectiveness	Temporal discontinuity	Davis (2008)
Mexico	Voluntary certification lowers regulatory costs	Structural identification	Foster and Guiterrez (2012)
Mexico	Large inframarginal payments lower policy impacts	Fixed effects, RD	Davis et al. (forthcoming) Boomhower and Davis (2014)
Bangladesh	Policy has large unintended consequences	Quasi-experiment	Field et al. (2011)
Philippines	Public and private provision are substitutes	Fixed effects, IV	Bennett (2012)
India	Public support improves the effectiveness of environmental policies	Fixed effects	Greenstone and Hanna (2014)

Notes: Summary of empirical findings on the marginal costs of environmental policies in developing countries.

Source: Greenstone and Jack, 2015.

Regulation is necessary to make energy bear its full social cost, guiding consumers and firms to internalise these costs in their behaviours. Poor environmental quality, therefore, might be the product of poorly designed regulation. We have discussed one potential reason for the current poor state of environmental quality: the utility from further consumption exceeds that of an improved environment—beating poverty trumps all else. Another view is that high marginal costs slow improvements in environmental quality. A key factor determining this is the local capacity for policy design and implementation of abatement policies. When institutions are weak, the cost of enforcing regulation can become prohibitive to the point where further investments into abatement are no longer socially efficient. Acquiring information about pollution and compliance with regulations can also be costly. Although advances in technologies and monitoring are greatly reducing the costs of detecting violators, the costs of monitoring and enforcement alone may make investments in new policy unpalatable. Tough environmental regulations on the books are not enough (Greenstone and Hanna, 2014). In the case of oil drilling in forest areas for example, better corporate governance is not enough to improve forest protection, and the importance of public regulation highlights the relevant role institutions must play to implement environmental standards (Cust et al., 2023).

India is an excellent case study in strong environmental regulations leading to weak outcomes. A command-and-control system regulates industrial pollution, yet a large RCT found generally weak monitoring of air and water pollution and widespread non-compliance (Duflo et al., 2013). A system of mandated third-party pollution audits among industrial firms seemed, at first, to be a reasonable way to ensure compliance. However, firms were free to choose their auditors and paid them directly, allowing them to collude in fudging the numbers: many firms came in just under the threshold for penalisation. The experiment randomly allocated firms to auditors and made payments through a common pool, breaking the direct links between them. As a result, auditors reported more truthfully and plants lowered emissions (Duflo et al., 2013). This highlights the importance of political economy in determining the effectiveness of regulations when enforcement is weak.

Imperfect information is an overarching challenge. Regulators in India receive unreliable and infrequent emissions data. Breaking policy incurs a heavy penalty, but information flows to the regulator are weak. While plants are required to purchase costly abatement equipment, the regulator does not have the monitoring capacity to ensure that the equipment is used and that emissions are being reduced. The result is that emissions remain high. To compensate for this weak information, proxies like energy consumption or capital investment can be penalised with measures that are costly (for example, plant closure) but unpredictable and thus ineffective overall (Duflo et al., 2018).

In the presence of imperfect information, a degree of flexibility may be necessary to allow regulators to collect and use local information. The potential challenge with flexibility is that it comes with discretion, a power which can be abused. A field experiment in Gujarat, India found significant discretion in regulators' decisions about which plants to inspect and what penalties to impose (Duflo et al., 2018). By upping the frequency of inspections and removing the element of discretion, they successfully increased regulatory scrutiny—plants were more routinely visited by inspectors, as required. However, they found that regulators were no more likely to identify the most extreme polluters, and so compliance increased only marginally. Technology offers a solution to the information problem. Ongoing follow-up work in Gujarat seeks to understand the effect of more reliable information through the installation of Continuous Emissions Monitoring Systems (CEMS) for industrial air pollution. Real-time emissions data not only helps in monitoring; it also acts as the first step toward creating a market for emissions. Transparency around pollution levels can also allow environmental regulation to have a further reach. Rating industries on pollution emission levels acts as a strong public signal to show which firms are adhering to pollution standards. In Maharashtra, India, the government released information on 20,000 industrial stack samples over several years under the Maharashtra Star Rating Programme. Residents were informed about industry emissions in their area, allowing citizens to call for action and encouraging competition between firms to reduce emissions. Similar evidence has also been found in China: Greenstone et al., (2022) studied the implementation of automated monitoring of pollution at the municipal level and identified large underreporting by public officials, whereas the use of new measurement technology was able to increase private adaptation. He et al., (2020) finds that coordination of central planning incentives and local regulation towards public monitoring of water quality also lowered pollution levels.

Policies at the individual level also indicate that increasing access to information and credit can be key mechanisms for households' adoption of cleaner technologies. In a cookstove example from India, Afridi et al., (2021) show that educating households on the adverse health effects of cooking with solid fuels increases take-up of liquid petroleum gas. In an RCT experiment in rural India, Jack et al., (2022) evaluate the effectiveness of conditional cash transfers for farmers to opt out of burning crops and find that while most already knew of the negative effects of clearing fires, the policy is able to increase compliance after partial upfront payments.

RESEARCH PRIORITIES

- How can regulations meant to reduce local pollution emissions and improve environmental quality work when monitoring and enforcement are weak?
- Political economy of regulation: why do governments adopt, or fail to adopt, environmental regulations, and how does this depend on benefits and costs?
- As new technologies reduce the marginal costs of detecting violators to near zero, what are the implications for efficient and politically feasible regulation in low- and middle-income countries?
- What role does rent seeking or even bribery play in determining local environmental quality, and can such behaviour be reduced?
- Exploring the efficacy of information disclosure, emissions markets, and other advanced regulatory instruments in low- and middle-income countries.

5. Conclusion

Many low- and middle-income countries today—from Rwanda to Ethiopia to India to the Philippines—are undertaking an enormous and urgent push to bring modern energy to all of their citizens. This effort is justified by the necessity of modern, reliable energy for inclusive economic growth and, increasingly, for participation in an interconnected society. We also understand that having plentiful natural resources, such as water, clean air, and other environmental services, are necessary to raise the living standards of today's poor populations. Expansion of energy and innovative management of natural capital are needed to enable this growth.

The enormous growth in energy services needed for this higher level of access will result in enormous damage to the local and global environment if powered by fossil fuels. This tension between expansion and externalities is softening, due to innovations in renewable generation, energy efficient technologies and the declining cost of clean fuels. Hence, there is both a need and a justification to adopt a new pro-development energy policy that achieves modern levels of energy access and service while limiting the growth of environmental damages from energy use at a more competitive price. This is not possible without creating well-functioning markets, expanding supply, and regulating emissions.

In this evidence paper, we have argued that the problem is not only—or even mainly—one of technology, but also one of politics and policy. In the short term, the research we cite has shown that the features of energy markets everywhere— complex links between energy consumption and external costs resulting in distorted price mechanisms; a large share of public ownership, poor information, and high capital costs; political interference; difficulties in contracting and market design due to natural monopoly and asset specificity—result in a series of market and governance failures in low- and middle-income countries. Even taking technology as given, there appear to be large possible efficiency gains and welfare gains from policy reforms that cut through these distortions. We do not mean to say that any of these constraints are easily solved, or even that many of them could be wholly removed, but only that at the margin they appear to leave space for beneficial policy reforms.

The next five years—and the next fifty—will be tumultuous for the energy sector and the global environment.

To repeat a few examples: could politicians remove energy subsidies if they buy out citizens with targeted unconditional transfers? How can compensation policy reduce barriers to diffusion of renewable energy at the grid level? What institutional weaknesses lead to price fluctuations from the intermittency of renewable energy generation? How can natural capital be integrated into economic policy? Which incentive scheme design can ensure cost effective natural capital protection in low- and middle-income countries? How can public investments lower the costs of adaptation to extreme heat and other environmental harms?

In the longer run, technology is changing rapidly, and the trade-off between choosing low cost or low emissions is waning. Innovation is even accelerating this process in some cases, such as China. Renewable energy, particularly solar and wind, is a case in point. Low- and middle-income countries will adopt renewable energy if it is cost competitive. Whether renewable energy is cost competitive will depend on whether energy prices include social costs, on public investments to physically integrate markets, on institutions to contract and procure energy and establish energy markets, and on international policy toward technology transfer and trade. The next five years—and the next fifty— will be tumultuous for the energy sector and the global environment. Research on the design of energy policies is likely to be of enormous social value, even when it remains some way behind the pace of change on the ground.

6. References

Abdul Latif Jameel Poverty Action Lab (J-PAL). (2020). Cookstoves to reduce indoor air pollution. ***J-PAL Policy Insights.*** Last modified February 2020.

Abrell, J., Rausch, S., and Streitberger, C. (2022). The Economic and Climate Value of Flexibility in Green Energy Markets. ***Environmental and Resource Economics***, 83(2), 289–312.

Adhvaryu, A., Molina, T., Nyshadham, A., Tamayo, J., and Torres, N. (2023). The health costs of dirty energy: Evidence from the capacity market in Colombia. ***Journal of Development Economics***, 164, 103116.

Afridi, F., Debnath, S. and Somanathan, E. (2021). A Breath of Fresh Air: Raising Awareness for Clean Fuel Adoption. ***Journal of Development Economics***, 151(102674).

Agrawala, S., Carraro, M., Kingsmill, N., Lanzi, E., Mullan, M., and Prudent-Richard, G. (2011). Private sector engagement in adaptation to climate change: approaches to managing climate risks. ***OECD Environment*** Working Paper No. 39.

Akbari, H., Xu, T., Taha, H., Wray, C., Sathaye, J., Garg, V., Reddy, K. N. (2011). Using cool roofs to reduce energy use, greenhouse gas emissions, and urban heat-island effects: Findings from an India experiment (Working Paper No. LBNL-4746E). ***Retrieved from Lawrence Berkeley National Lab*** (LBNL), Berkeley, CA.

Aklin, M., Bayer, P., Harish, S. P., and Urpelainen, J. (2017). Does basic energy access generate socioeconomic benefits? A field experiment with off-grid solar power in India. ***Science Advances***, 3(5), e1602153.

Alam, M. (2013). Coping with blackouts: Power outages and firm choices. ***Retrieved from Department of Economics, Yale University***.

Alberini, A., Steinbuks, J., and Timilsina, G. (2022). How Valuable is the Reliability of Residential Electricity Supply in Low-Income Countries? ***Evidence from Nepal. The Energy Journal***, 43(4).

Allcott, H., and Mullainathan, S. (2010). Behavior and energy policy. ***Science***, 327(5970), 1204-1205.

Allcott, H., and Greenstone, M. (2012). Is there an energy efficiency gap? ***Journal of Economic Perspectives***, 26(1), 3-28.

Allcott, H., and Greenstone, M. (2017). Measuring the welfare effects of residential energy efficiency programmes. ***National Bureau of Economic Research*** Working Paper 23386.

Ambec, S., and Crampes, C. (2021). Real-time electricity pricing to balance green energy intermittency, ***Energy Economics***, Volume 94, 105074.

Assunção, J., Lipscomb, M., Mobarak, A. M., and Szerman, D. (2015). Infrastructure development can benefit the environment: electrification, agricultural productivity and deforestation in Brazil. ***LACEA 2015 Papers***.

Allcott, H., Collard-Wexler, A., and O'Connell, S. D. (2016). How do electricity shortages affect industry? Evidence from India. American Economic Review, 106(3), 587-624.deforestation in Brazil. ***LACEA 2015 Papers***.

Astier, N., Rajagopal, R., and Wolak, F. A. (2023). Can Distributed Intermittent Renewable Generation Reduce Future Grid Investments? Evidence from France. ***Journal of the European Economic Association***, 21(1), 367–412.

Auffhammer, M., Wang, M., Xie, L., and Xu, J. (2021). Renewable Electricity Development in China: Policies, Performance, and Challenges. ***Review of Environmental Economics and Policy***, 15(2): 323-339.

Avenyo, E. K. and Tregenna, F. (2022). Greening manufacturing: Technology intensity and carbon dioxide emissions in developing countries. ***Applied Energy***, 324 (C).

Baker, R., T. Carleton, A. D'Agostino, M. Delgado, T. Foreman, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, A. Jina, R. Kopp, K. McCusker, I. Nath, M. Pecenco, J. Rising, A. Rode, J. Simcock, J. Yuan. (2020). Labor Supply in a Warmer World: The Impact of Climate Change on the Global Workforce. ***Mimeograph***.

Balboni, C. A. (2019). In harm's way? Infrastructure investments and the persistence of coastal cities (Working Paper). ***Retrieved from The London School of Economics and Political Science (LSE)***.

Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R. S., Brauer, M., Cohen, A. J., Sabde, Y. (2019). The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: The Global Burden of Disease Study 2017. ***The Lancet Planetary Health***, 3(1), e26-e39.

Banares-Sanchez, I., Burgess, R., László, D., Simpson, P., Van Reenen, J., and Wang, Y. (2023). Ray of Hope? China and the Rise of Solar Energy. Working Paper.

Banerjee, L. (2007). Effect of flood on agricultural wages in Bangladesh: An empirical analysis. World Development, 35(11), 1989-2009.

Barnes, D. F., and Floor, W. M. (1996). Rural energy in developing countries: a challenge for economic development. ***Annual Review of Energy and the Environment***, 21.

Barnett, B. J., and Mahul, O. (2007). Weather index insurance for agriculture and rural areas in lower-income countries. ***American Journal of Agricultural Economics***, 89(5), 1241-1247.

Barnwal, P. (2019). Curbing leakage in public programs with direct benefit transfers. ***Mimeograph***.

Barreca, A., Clay, K., Deschenes, O., Greenstone, M., and Shapiro, J. S. (2016). Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. ***Journal of Political Economy***, 124(1), 105- 159.

Barron, M., and Torero, M. (2017). Household electrification and indoor air pollution. ***Journal of Environmental Economics and Management***, 86, 81-92.

Barwick, P. J., Li, S., Rao, D., and Zahur, N. B. (2018). The Healthcare Cost of Air Pollution: Evidence from the World's Largest Payment Network. ***National Bureau of Economic Research*** Working Paper No. 24688.

Barwick, P. J., Li, S., Lin, L., and Zou, E. (2019). From Fog to Smog: the Value of Pollution Information. ***National Bureau of Economic Research*** Working Paper No. 26541.

Barwick, P. J., Donaldson, D., Li, S., Lin, Y., and Rao, D. (2022). Improved Transportation Networks Facilitate Adaptation to Pollution and Temperature Extremes. ***National Bureau of Economic Research*** Working Paper No. 30462.

Baskaran, T., Min, B., and Uppal, Y. (2015). Election cycles and electricity provision: Evidence from a quasi-experiment with Indian special elections. ***Journal of Public Economics***, 126, 64-73.

Beach, B., and Hanlon, W. W. (2017). Coal smoke and mortality in an early industrial economy. The Economic Journal, 128(615), 2652-2675.

Bellassen, V. and Luyssaert, S. (2014). Carbon sequestration: Managing forests in uncertain times. ***Nature***, 506(7487), 153-155.

Bensch, G., Grimm, M., and Peters, J. (2015). Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso. ***Journal of Economic Behavior and Organization***, 116, 187-205.

BenYishay, A., Heuser, S., Runfola, D., and Trichler, R. (2017). Indigenous land rights and deforestation: Evidence from the Brazilian Amazon. ***Journal of Environmental Economics and Management***, 86(C), 29-47.

Berkouwer, Susanna B. and Joshua T. Dean (2022). Credit, Attention, and Externalities in the Adoption of Energy Efficient Technologies by Low-Income Households. ***American Economic Review***, 10 112, 3291–3330

Berkower, S., Biscaye, P., Hsu, E. Kim, O. Lee, K., Miguel, E. and Wolfram, C. (2023). Money or Power? Choosing Covid-19 Aid in Kenya, ***Forthcoming***, ***Energy Economics***.

Besley, T. and Hussain, A. (2023). Global Gains From a Green Energy Transition: Evidence on Coal-Fired Power and Air Quality Dissatisfaction. ***CEPR*** Discussion Paper No. 18046.

Bettauer, R. J. (2009). India and International Arbitration: The Dabhol Experience. ***Geo. Wash. Int'l L. Rev.***, 41, 381.

Bishop, K., Kecham, J., and Kuminoff, N. (2019). Hazed and Confused: The Effect of Air Pollution on Dementia. ***National Bureau of Economic Research*** Working Paper No. 24970.

Bluffstone, R., Beyene, A. D., Gebreegziabher, Z., Martinsson, P., Mekonnen, A., and Toman, M. (2022). Experience and Learning with Improved Technologies: Evidence from Improved Biomass Cookstoves in Ethiopia. ***Environmental and Resource Economics***, 81(2), 271–285.

Bonilla, J. A., Aravena, C., and Morales-Betancourt, R. (2023). Assessing Multiple Inequalities and Air Pollution Abatement Policies. ***Environmental and Resource Economics***, 84(3), 695–727.

Borăng, F., Jagers, S. C., and Povitkina, M. (2021). In Light of Democracy and Corruption: Institutional Determinants of Electricity Provision. ***The Energy Journal***, 42(2), 165-181.

Borenstein, S. (2012). The Private and Public Economics of Renewable Electricity Generation. ***Journal of Economic Perspectives***, 26(1). pp. 62-92.

Borenstein, S., and Bushnell, J. B. (2022). Do Two Electricity Pricing Wrongs Make a Right? Cost Recovery, Externalities, and Efficiency. ***American Economic Journal: Economic Policy***, 14(4), 80–110.

Bošković, B., Chakravorty, U., Pelli, M., and Risch, A. (2023). The effect of forest access on the market for fuelwood in India. ***Journal of Development Economics***, 160, 102956.

Brei, M., Pérez-Barahona, A., and Strobl, E. (2016). Environmental pollution and biodiversity: Light pollution and sea turtles in the Caribbean. ***Journal of Environmental Economics and Management***, 77, 95-116.

Brooks, W., and Donovan, K. (2020). Eliminating Uncertainty in Market Access: The Impact of New Bridges in Rural Nicaragua. ***Econometrica***, 88(5), 1965–1997.

Brown, D. S., and Mobarak, A. M. (2009). The transforming power of democracy: regime type and the distribution of electricity. ***American Political Science Review***, 103(2), 193-213.

Brunekreef, B., and Holgate, S. T. (2002). Air pollution and health. ***The Lancet***, 360(9341), 1233- 1242.

Brutscher, P.-B., Ravillard, P., and Semieniuk, G. (2021). Do Energy Efficient Firms Have Better Access to Finance? ***The Energy Journal***, 42(01), 171-198.

Burgess, R., Caria, S., Dobermann, T., and Saggese, A. (2023). Innovation, growth, and the environment. ***IGC White Paper on Sustainable Growth***.

Burgess, R., Deschenes, O., Donaldson, D., and Greenstone, M. (2023). Weather, climate change, and death in India. ***(Working Paper)***.

Burgess, R., Greenstone, M., Ryan, N., and Sudarshan, A. (2020). The Consequences of Treating Electricity as a Right. ***Journal of Economic Perspectives***, 34 (1): 145-69.

Burgess, R., Greenstone, M., Ryan, N., and Sudarshan, A. (2023). Demand for Electricity on the Global Electrification Frontier. ***American Economic Review*** (Revise and Resubmit).

Burgess, R., Hansen, M., Olken, B. A., Potapov, P., and Sieber, S. (2012). The political economy of deforestation in the tropics. ***The Quarterly Journal of Economics***, 127 (4): 1707–1754.

Burke, M., Hsiang, S. M., and Miguel, E. (2015a). Global non-linear effect of temperature on economic production. ***Nature***, 527(7577), 235.

Burke, M., Hsiang, S. M., and Miguel, E. (2015b). Climate and conflict. ***Annual Review of Economics***, 7(1), 577-617.

Burke, P. J., Widnyana, J., Anjum, Z., Aisbett, E., Resosudarmo, B., and Baldwin, K. G. H. (2019). Overcoming barriers to solar and wind energy adoption in two Asian giants: India and Indonesia. ***Energy Policy***, 132(C), 1216-1228.

Burlig, F., and Preonas, L. (2021). Out of the darkness and into the light? Development effects of rural electrification. ***Retrieved from University of California Berkeley*** Working Paper No. 268.

Burzyński, M., Deuster, C., Docquier, F., and de Melo, J. (2022). Climate Change, Inequality, and Human Migration. ***Journal of the European Economic Association***, 20(3), 1145–1197.

Cao, J., Ho, M. S., Ma, R., and Teng, F. (2021). When carbon emission trading meets a regulated industry: Evidence from the electricity sector of China. ***Journal of Public Economics***, 200(C), 104470.

Carleton, T., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Jina, A., Kopp, R. E., McCusker, K. E., Nath, I., Rising, J, Rode, A., Seo, H. K., Viaene, A., Yuan, J., and Zhang, A. T. (2022). Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. ***The Quarterly Journal of Economics***, 137(4), 2037–2105.

Carranza, E., and Meeks, R. (2021). Energy Efficiency and Electricity Reliability. ***The Review of Economics and Statistics***, 103(3), 461-475.

Cassin, L., Melindi-Ghidi, P., and Prieur, F. (2022). Confronting climate change: Adaptation vs. Migration in Small Island Developing States. ***Resource and Energy Economics***, 69, 101301.

Castells-Quintana, D., Lopez-Uribe, M. del P., and McDermott, T. K. J. (2022). Population displacement and urban conflict: Global evidence from more than 3300 flood events. ***Journal of Development Economic***s, 158, 102922.

Chakravarty, S. and Tavoni, M. (2013). Energy poverty alleviation and climate change mitigation: Is there a trade off? ***Energy Economics***, 40, S67–S73

Chakravorty, U., Emerick, K., and Ravago, M. L. (2016). Lighting up the last mile: The benefits and costs of extending electricity to the rural poor. ***Resources for the Future Discussion Paper***, 16- 22.

Chang, T. Y., Graff Zivin, J., Gross, T., and Neidell, M. (2019). The effect of pollution on worker productivity: evidence from call center workers in China. ***American Economic Journal: Applied Economics***, 11(1), 151-72.

Chen, Y., Ebenstein, A., Greenstone, M., and Li, H. (2015). Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. ***Proceedings of the National Academy of Sciences***, 110(32), 12936- 12941.

Chen, S., Oliva, P., and Zhang, P. (2022). The effect of air pollution on migration: Evidence from China. ***Journal of Development Economics***, 156, 102833.

Chong, H. G. and Sunding, D. L. (2006). Water Markets and Trading. ***Annual Review of Environment and Resources***, 31.

Choudhary, M. A., and Limodio, N. (2022). Liquidity Risk and Long-Term Finance: Evidence from a Natural Experiment. ***The Review of Economic Studie***s, 89(3), 1278–1313.

Christensen, P.,Francisco, P., Myers, E. and Souza, M. (2023). Decomposing the Wedge between Projected and Realized Returns in Energy Efficiency Programs. ***The Review of Economics and Statistics 2023***, 105 (4): 798–817.

Cicala, S. (2022). Imperfect markets versus imperfect regulation in US electricity generation. ***American Economic Review***, 112 (2): 409-41.

Coady, D. P., Flamini, V., and Sears, L. (2015). The unequal benefits of fuel subsidies revisited: Evidence for developing countries. ***Retrieved from the International Monetary Fund.***

Coady, D., Parry, I. W., Sears, L., and Shang, B. (2015). How large are global energy subsidies? ***Retrieved from the International Monetary Fund Working Paper No. 15-105***.

Cohen, F., Hepburn, C.J., and Teytelboym, T. (2019). Is Natural Capital Really Substitutable? ***Annual Review of Environment and Resources***, 2019, 44(1), 425–448.

Conway, D., Dalin, C., Landman, W. A., and Osborn T. J. (2017). Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. ***Nature Energy*** 2: 946– 953.

Cook, C. C. (2005). Assessing the impact of transport and energy infrastructure on poverty reduction. ***Asian Development Bank.***

Costa, F., and Gerard, F. (2021). Hysteresis and the Welfare Effect of Corrective Policies: Theory and Evidence from an Energy-Saving Program. ***Journal of Political Economy***, 129(6), 1705–1743.

Crafts, N. (2004). Productivity growth in the industrial revolution: A new growth accounting perspective. ***The Journal of Economic History***, 64(2), 521-535.

Cruz, J.-L., and Rossi-Hansberg, E. (2021). The Economic Geography of Global Warming. ***National Bureau of Economic Research*** Working Paper No. 28466.

Cust, J., Harding, T., Krings, H., and Rivera-Ballesteros, A. (2023). Public governance versus corporate governance: Evidence from oil drilling in forests. J***ournal of Development Economics***, 163, 103070.

Danelon, A. F., Spolador, H. F. S., and Kumbhakar, S. C. (2021). Weather and population size effects on water and sewer treatment costs: Evidence from Brazil. ***Journal of Development Economics***, 153, 102743.

Datt, G., Maitra, P., Menon, N., and Ray, R. (2023). Coal Plants, Air Pollution and Anaemia: Evidence from India. ***The Journal of Development Studie***s, 59(4), 533–551.

Davis, L. W., Fuchs, A., and Gertler, P. (2014). Cash for coolers: evaluating a large-scale appliance replacement programme in Mexico. ***American Economic Journal: Economic Policy***, 6(4), 207-38.

Davis, L. W. and Gertler, P. J. (2015). Contribution of air conditioning adoption to future energy use under global warming. ***Proceedings of the National Academy of Sciences*** 112.19:5962-5967.

Davis, L.W. (2017). The Environmental Cost of Global Fuel Subsidies. ***The Energy Journal***, 38(1), 10.5547/01956574.38.SI1.ldav.

Davis, L. W., Martinez, S., and Taboada, B. (2020). How Effective is Energy-Efficient Housing? Evidence from a Field Experiment in Mexico. ***Journal of Development Economics***, 143(3), 102390.

Deschenes, O., Malloy, C., and MacDonald, G. G. (2023). Causal Effects of Renewable Portfolio Standards on Renewable Investments and Generation: The Role of Heterogeneity and Dynamics. ***National Bureau of Economic Research*** Working Papers No. 31568.

Dell, M., Jones, B. F., and Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. ***American Economic Journal: Macroeconomics***, 4(3), 66-95.

Di Bella, M. G., Norton, M. L., Ntamatungiro, M. J., Ogawa, M. S., Samake, I., and Santoro, M. (2015). Energy subsidies in Latin America and the Caribbean: stocktaking and policy challenges. ***Retrieved from the International Monetary Fund*** Working Paper No. 15-30.

Dinkelman, T. (2011). The effects of rural electrification on employment: New evidence from South Africa. ***American Economic Review***, 101(7), 3078-3108.

Dinkelman, T. and Schulhofer-Wohl, S. (2015). Migration, congestion externalities, and the evaluation of spatial investments. ***Journal of Development Economics***, 114, 189-202.

Do, T. N., Burke, P. J., Baldwin, K. G. H., and Nguyen, C. T. (2020). Underlying drivers and barriers for solar photovoltaics diffusion: The case of Vietnam. ***Energy Policy***, 144(C).

Duflo, E., Greenstone, M., Pande, R., and Ryan, N. (2013). Truth-telling by third-party auditors and the response of polluting firms: Experimental evidence from India. ***The Quarterly Journal of Economics***, 128(4), 1499-1545.

Duflo, E., Greenstone, M., and R. Hanna (2016). Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves. ***American Economic Journal: Economic Policy***, 8(1), 80-114.

Duflo, E., Greenstone, M., Pande, R., and Ryan, N. (2018). The value of regulatory discretion: Estimates from environmental inspections in India. ***Econometrica***, 86(6), 2123-2160.

Duque, V., and Gilraine, M. (2022). Coal use, air pollution, and student performance. ***Journal of Public Economic***s, 213(C), 104712.

Ebenstein, A., Fan, M., Greenstone, M., He, G., and Zhou, M. (2017). New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. ***Proceedings of the National Academy of Sciences***, 114(39), 10384-10389.

Ebenstein, A. and M., Greenstone, M. (2020). Childhood Exposure to Particulate Air Pollution, Human Capital Accumulation, and Income: Evidence from China. ***Mimeograph***.

Eberhard, A., Foster, V., Briceño-Garmendia, C., Ouedraogo, F., Camos, D., and Shkaratan, M. (2008). Underpowered: the state of the power sector in Sub-Saharan Africa. ***Retrieved from World Bank Group***: https://www.openknowledge. worldbank.com/handle/10986/7833

EIA. (2012). Most states have renewable portfolio standards. Available from: http://www.eia.gov/ todayinenergy/detail.cfm?id=4850

EIA. (2019). International Energy Outlook 2019. Available from: https://www.eia.gov/todayinenergy/detail.php?id=41433

EIA. (2020). Cost and Performance Characteristics of New Generating Technologies, ***Annual Energy Outlook 2020***. Available from: https://www.eia.gov/ outlooks/aeo/assumptions/pdf/table_8.2.pdf

EIA. (2021). Electricity: Total Distribution Losses Annual. Available from: https://www.eia.gov/international/data/world/electricity/more-electricity-data?pd=2&p=000000000000000000000000004&u=1&f=A&v=heatmap&a=-&i=none&vo=value&t=C&g=00000000000000000000000000000000000000000000000001&l=249-ruvvvvvfvtvnvv1vrvvvvfvvvvvvfvvvou20evvvvvvvvvvnvvvs0008&s=1609459200000&e=1609459200000&vb=132&ev=truenternational - U.S. Energy Information Administration (EIA)

Estache, A., Goicoechea, A., and Trujillo, L. (2006). Utilities reforms and corruption in developing countries. ***Retrieved from The World Bank***: http://dx.doi.org/10.1016/j.jup.2008.07.002.

Feger, F., Pavanini, N., and Radulescu, D. (2022). Welfare and Redistribution in Residential Electricity Markets with Solar Power. ***The Review of Economic Studies***, 89(6), 3267–3302.

Fell, H., Kaffine, D. T., and Novan, K. (2021). Emissions, Transmission, and the Environmental Value of Renewable Energy. ***American Economic Journal: Economic Policy***, 13(2), 241–272.

Fetter, T. and Usmani, F. (2020). Fracking, Farmers, and Rural Electrification in India. Working Paper.

Field, E., Glennerster, R., and Hussam, R. (2011). Throwing the baby out with the drinking water: Unintended consequences of arsenic mitigation efforts in Bangladesh (Working Paper). ***Retrieved from Harvard University, Department of Economics***.

Fischer, C., Hübler, M., and Schenker, O. (2021). More birds than stones – A framework for second-best energy and climate policy adjustments. ***Journal of Public Economics***, 203(C), 104515.

Fisher-Vanden, K., Mansur, E. T., and Wang, Q. J. (2015). Electricity shortages and firm productivity: evidence from China's industrial firms. ***Journal of Development Economics***, 114, 172-188.

Fowlie, M., Greenstone, M., and Wolfram, C. (2018). Do energy efficiency investments deliver? Evidence from the weatherization assistance program. ***The Quarterly Journal of Economics***, 133(3), 1597-1644.

Fried, S. and Lagakos, D. (2023). Electricity and Firm Productivity: A General-Equilibrium Approach. ***American Economic Journal: Macroeconomics***, forthcoming.

Fullerton, D., and Ta, C. (2022). What Determines Effectiveness of Renewable Energy Standards? General Equilibrium Analytical Model and Empirical Analysis. ***National Bureau of Economic Research*** Working Paper No. 29783.

Galiani, S., Gertler, P., and Schargrodsky, E. (2005). Water for life: The impact of the privatization of water services on child mortality. ***Journal of Political Economy***, 113(1), 83-120.

Gallai, N., Salles, J. M., Settele, J., and Vaissière, B. E. (2009). Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. ***Ecological economics***, 68(3), 810-821.

Gao, X., Song, R., and Timmins, C. (2023). Information, migration, and the value of clean air. ***Journal of Development Economics***, 163, 103079.

Gertler, P. J., Shelef, O., Wolfram, C. D. and Fuchs, A. (2016). The Demand for Energy-Using Assets among the World's Rising Middle Classes. ***American Economic Review***, 106 (6): 1366-1401.

Gibbens, S. (2018). Air pollution robs us of our smarts and our lungs. ***Retrieved from National Geographic***: https://www.nationalgeographic.com/environment/2018/09/news-airquality-brain- cognitivefunction

Goel, R., and Guttikunda, S. K. (2015). Evolution of on-road vehicle exhaust emissions in Delhi. ***Atmospheric Environment***, 105, 78-90.

Graff Zivin, J., Hsiang, S. M., and Neidell, M. (2018). Temperature and human capital in the short and long run. ***Journal of the Association of Environmental and Resource Economists***, 5(1), 77-105.

Graff Zivin, J., Neidell, M., Sanders, N. J., and Singer, G. (2023). When Externalities Collide: Influenza and Pollution. ***American Economic Journal: Applied Economics***, 15(2), 320–351.

Gonzales, L., Ito, K., and Reguant, M. (2022). The Dynamic Impact of Market Integration: Evidence from Renewable Energy Expansion in Chile. ***National Bureau of Economic Researc***h Working Paper No. 30016.

Graff Zivin, J., and Neidell, M. (2012). The impact of pollution on worker productivity. ***American Economic Review***, 102(7), 3652-73.

Greenstone, M., Hornbeck, R., and Moretti, E. (2010). Identifying agglomeration spillovers: Evidence from winners and losers of large plant openings. ***Journal of Political Economy***, 118(3), 536-598.

Greenstone, M., and Hanna, R. (2014). Environmental regulations, air and water pollution, and infant mortality in India. ***American Economic Review***, 104(10), 3038-72.

Greenstone, M., and Jack, B. K. (2015). Envirodevonomics: A research agenda for an emerging field. ***Journal of Economic Literature***, 53(1), 5-42.

Greenstone, M., Nilekani, J., Pande, R., Ryan, N., Sudarshan, A., and Sugathan, A. (2015). Lower pollution, longer lives: life expectancy gains if India reduced particulate matter pollution. ***Economic and Political Weekly***, 50(8).

Greenstone, M., and Fan, C. Q. (2018). Introducing the Air Quality Life Index. ***AQLI Annual Report***.

Greenstone, M., He, G., Jia, R., and Liu, T. (2022). Can Technology Solve the Principal-Agent Problem? Evidence from China's War on Air Pollution. ***American Economic Review: Insights***, 4(1), 54–70.,

Greenstone, M., He, G., Li, S., and Yongchen Zou, E. (2021). China's War on Pollution: Evidence from the First 5 Years. ***Review of Environmental Economics and Policy***, 15(22): 281–299.

Greenstone, M., Pande, R., Sudarshan, A. and Ryan, N. (2023). Can Pollution Markets Work in Developing Countries? Experimental Evidence from India. ***The Warwick Economics Research Paper Series*** Working Paper No. 1453.

Grimm, M., Lenz, L., Peters, J., and Sievert, M. (2016). Demand for off-grid solar electricity: Experimental evidence from Rwanda. ***IZA Discussion Paper Serie***s (10427).

Grogan, L. (2016). Household electrification, fertility and employment: Evidence from the Colombian censuses. ***Journal of Human Capital***, 10(1), 109-158.

Grothmann, T., and Patt, A. (2005). Adaptive capacity and human cognition: the process of individual adaptation to climate change. ***Global Environmental Change***, 15(3), 199-213.

Guttikunda, S. K., and Calori, G. (2013). A GIS based emissions inventory at 1 km× 1 km spatial resolution for air pollution analysis in Delhi, India. ***Atmospheric Environment***, 67, 101-111.

Guttikunda, S. K., and Goel, R. (2013). Health impacts of particulate pollution in a megacity— Delhi, India. ***Environmental Development***, 6, 8-20.

Guttikunda, S. K., Kopakka, R. V., Dasari, P., and Gertler, A. W. (2013). Receptor model-based source apportionment of particulate pollution in Hyderabad, India. ***Environmental Monitoring and Assessmen***t, 185(7), 5585-5593.

Haščiči, I., Rodríguezi, M. C., Jachniki, R., Silvai, J., and Johnstone, N. (2015). Public Interventions and Private Climate Finance Flows: Empirical Evidence from Renewable Energy Financing. ***OECD*** Working Paper No. 80.

Hahn, R. W., and Metcalfe, R. D. (2021). Efficiency and equity impacts of energy subsidies. ***American Economic Review***, 111(5), 1658-1688.

Haider, E. and Javed, U. (2023) Constructing electricity as entitlement: Energy politics in Lahore, Pakistan. IGC Project report. ***International Growth Centre***. London.

Hancevic, P. I., Nuñez, H. M., and Rosellón, J. (2022). Electricity Tariff Rebalancing in Emerging Countries: The Efficiency-equity Tradeoff and Its Impact on Photovoltaic Distributed Generation. ***The Energy Journal***, 43(4), 69-93

Hanlon, W. W. (2020). Coal smoke, city growth, and the costs of the industrial revolution. ***The Economic Journal***, 130(626), 462-488.

Hanlon, W. W. (2022). London fog: A century of pollution and mortality, 1866-1965. ***The Review of Economics and Statistics***, 1-49.

Hanna, R., and Oliva, P. (2015). The effect of pollution on labor supply: Evidence from a natural experiment in Mexico City. ***Journal of Public Economics***, 122, 68-79.

He, G., Wang, S., and Zhang, B. (2020). Watering Down Environmental Regulation in China. ***The Quarterly Journal of Economics***, 135(4), 2135–2185.

He, G., and Tanaka, T. (2023). Energy Saving May Kill: Evidence from the Fukushima Nuclear Accident. ***American Economic Journal: Applied Economics***, 15(2), 377–414.

Heo, S. W., Ito, K., and Kotamarthi, R. (2023). International Spillover Effects of Air Pollution: Evidence from Mortality and Health Data. ***National Bureau of* Economic Research Working Paper No. 30830.**

Herrnstadt, E., Heyes, A., Muehlegger, E., and Saberian, S. (2021). Air Pollution and Criminal Activity: Microgeographic Evidence from Chicago. ***American Economic Journal: Applied Economics***, 13(4), 70–100.

Heyes, A., and Saberian, S. (2022). Hot Days, the ability to Work and climate resilience: Evidence from a representative sample of 42,152 Indian households. J***ournal of Development Economics***, 155, 102786.

Houde, S., and Spurlock, C. A. (2015). Do energy efficiency standards improve quality? Evidence from a revealed preference approach. ***Retrieved from Lawrence Berkeley National Lab*** Working Paper No. LBNL-182701.

Houde, S. (2018). How consumers respond to product certification and the value of energy information. ***The RAND Journal of Economics***, 49(2), 453-477.

Hsiao, A. (2023). Sea level rise and urban adaptation in Jakarta. ***Technical Report***.

Intergovernmental Panel on Climate Change. (2018). Global Warming of 1.5ºC.

Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

International Energy Agency (IEA). (2017). Peru Renewable Energy Auctions. ***Joint Policy and Measures Database IEA/IRENA***.

International Energy Agency. (2018). World Energy Outlook 2018.

International Energy Agency. (2019). Establishing multilateral power trade in ASEAN.

International Energy Agency. (2020). Electricity Market Report - December 2020.

International Energy Agency. (2022a). Solar PV Analysis. September 2022.

International Energy Agency. (2022b). For the first time in decades, the number of people without access to electricity is set to increase in 2022, IEA, Paris. November 2022.

International Energy Agency. (2023a). Annual increase in population with electricity, access by technology in sub-Saharan Africa, 2015-2022. September 2023.

International Energy Agency. (2023b). A Vision for Clean Cooking Access for All. World Energy Outlook Special Report. IEA, African Development Bank Group. July 2023.

International Renewable Energy Agency. (2015). Renewable energy auctions: A guide to design.

International Renewable Energy Agency. (2018). Renewable power generation costs in 2018.

International Renewable Energy Agency. (2019). Renewable Energy Auctions: Status and Trends Beyond Price.

International Renewable Energy Agency. (2023). Renewable Energy Statistics - 2023. Abu Dhabi, 2023. IRENA.

Iowa Wind Energy Association. (2015). Iowa's Wind Potential for Addressing 111(d) Goals: The Potential for Tapping Iowa's Wind Resources to Reduce CO2 Emissions.

Isen, A. Rossin-Slater, M., and Walker, R. (2017). Every Breath You Take- Every Dollar You'll Make: The Long-Term Consequences of the Clean Air Act of 1970. ***Journal of Political Economy***, 125(3), 849-909.

Ito, K., and Zhang, S. (2020). Willingness to pay for clean air: Evidence from air purifier markets in China. ***Journal of Political Economy***, 128(5), 1627-1672.

Jack, B. K., and Smith, G. (2020). Prepaid Metering, Electricity Use and Utility Revenue. ***American Economic Journal: Applied Economics***, 12 (2): 134-68.

Jack, B. K. and Jayachandran, S. (2019). Self-selection into payments for ecosystem services programs. ***Proceedings of the National Academy of Sciences***, 116(12), 5326-5333.

Jack, B. K., Jayachandran, S., Kala, N., Pande, R. (2022). Money (Not) to Burn: Payments for Ecosystem Services to Reduce Crop Residue Burning. Princeton University, Department of Economics, Center for Economic Policy Studies Working Paper 307.

Jacobson, M. Z. (2012). Air pollution and global warming: history, science, and solutions. ***Cambridge University Press***.

Jaffe, A. B., and Stavins, R. N. (1994). The energy- efficiency gap What does it mean? ***Energy Policy***, 22(10), 804-810.

Jain, M., Rao, A. B., and Patwardhan, A. (2021). Energy Cost Information and Consumer Decisions: Results from a Choice Experiment on Refrigerator Purchases in India. The Energy Journal, 42(2), 253-272.

Jayachandran, S. (2023). The inherent trade-off between the environmental and anti-poverty goals of payments for ecosystem services. Environmental Research Letters, 18(2), 025003.

Jayachandran, S., De Laat, J., Lambin, E. F., Stanton, C. Y., Audy, R. and Thomas, N. E. (2017). Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. Science, 357,267-273.

Jessoe, K., and Rapson, D. (2014). Knowledge is (less) power: Experimental evidence from residential energy use. ***American Economic Review***, 104(4), 1417-38.

Jha, A., Preonas, L., and Burlig, F. (2022). Blackouts: The Role of India's Wholesale Electricity Market. ***National Bureau of Economic Research*** Working Paper No. 29610.

Jorgenson, D. W. (1984). The role of energy in productivity growth. ***The Energy Journal***, 5(3), 11-26.

Joskow, P. and Tirole, J. (2007). Reliability and Competitive Electricity Markets. ***The RAND Journal of Economics*** , 38 (1), 60-84.

Joskow, P. L. (2008). Lessons learned from the electricity market liberalization. ***Energy Journal***, 29(2): 9 –42.

Joskow, P. L. (2011). Comparing the costs of intermittent and dispatchable electricity generating technologies. ***American Economic Review***, 101(3), 238-41.

Joskow, P. L. (2019). Challenges for wholesale electricity markets with intermittent renewable generation at scale: the US experience. ***Oxford Review of Economic Policy***, Volume 35, 2, 291–331.

Kahouli, S., and Pautrel, X. (2023). Residential and Industrial Energy Efficiency Improvements: A Dynamic General Equilibrium Analysis of the Rebound Effect. ***The Energy Journal***, 44(3), 23-63.

Kala, N., Balboni, C., and Bhogale, S. (2023). ***Climate Adaptatio***n. VoxDevLit, June, 7(1).

Kambanda, C. (2013). Power trade in Africa and the role of power pools. Retrieved from the African Development Bank: http://www.afdb.org/en/blogs/integrating-africa/post/power-trade-in-africa- and-the-role-of-power-pools012101/

Karl, T. R., Jones, P. D., Knight, R. W., Kukla, G., Plummer, N., Razuvayev, V., and Peterson, T. C. (1993). A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. ***Bulletin of*** **the American Meteorological Society, 74(6), 1007-1024.**

Kazianga, H., and Udry, C. (2006). Consumption smoothing? Livestock, insurance and drought in rural Burkina Faso. ***Journal of Development Economics***, 79(2), 413-446.

Kessides, I. N. (2012). The impacts of electricity sector reforms in developing countries. ***The Electricity Journal***, 25(6), 79-88.

Khandker, S., Barnes, D., and Samad, H. (2013). Welfare impacts of rural electrification: A panel data analysis in Vietnam. ***Economic Development and Cultural Change***, 61(3).

Kocornik-Mina, A., McDermott, T., Michaels, G., and Rauch, F. (2020). Flooded cities. ***American Economic Journal: Applied Economics***, 12 (2): 35-66.

Kreindler, G. (2020). Peak-Hour Road Congestion Pricing: Experimental Evidence and Equilibrium Implications. ***Mimeo***, Harvard University.

Kremer, M., Leino, J., Miguel, E., and Zwane, A. P. (2011). Spring cleaning: Rural water impacts, valuation, and property rights institutions. ***The Quarterly Journal of Economics***, 126(1), 145-205.

Lal, S. (2006). Can good economics ever be good politics? A case study of India's power sector. ***Retrieved from the World Bank Group*** Working Paper No. 83.

Lanz, B., and Reins, E. (2021). Asymmetric Information on the Market for Energy Efficiency: Insights from the Credence Goods Literature. ***The Energy Journal***, 42(4), 91-109.

Lavy, V., Rachkovski, G., and Yoresh, O. (2022). Heads Up: Does Air Pollution Cause Workplace Accidents? ***National Bureau of Economic Research*** Working Paper No. 30715.

Lee, K., Miguel, E., and Wolfram, C. (2020). Experimental evidence on the economics of rural electrification. ***Journal of Political Economy***, 128(4), 1523-1565.

Lee, K., Miguel, E., and Wolfram, C. (2020). Does Household Electrification Supercharge Economic Development? ***Journal of Economic Perspectives***, 34 (1): 122-44.

Levine, D. I., Beltramo, T., Blalock, G., Cotterman, C., and Simons, A. M. (2018). What Impedes Efficient Adoption of Products? Evidence from Randomized Sales Offers for Fuel-Efficient Cookstoves in Uganda. ***Journal of the European Economic Association***, 16(6), 1850-1880.

Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., ... and Aryee, M. (2012). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. ***The Lancet***, 380(9859), 2224-2260.

Lipscomb, M., Mobarak, A. M., and Barham, T. (2013). Development effects of electrification: Evidence from the topographic placement of hydropower plants in Brazil. ***American Economic Journal: Applied Economics***, 5(2), 200-231.

Liu, L., Johnson, H. L., Cousens, S., Perin, J., Scott, S., Lawn, J. E., ... and Mathers, C. (2012). Global, regional, and national causes of child mortality: an updated systematic analysis for 2010 with time trends since 2000. ***The Lancet***, 379(9832), 2151-2161.

Lobell, D. B., and Tebaldi, C. (2014). Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades. ***Environmental Research Letters***, 9(7), 074003.

Lucas, R. (2002). The Industrial Revolution: Past and Future. **Harvard *University Press***, Cambridge.

Lyon, T. P. (2016). Drivers and Impacts of Renewable Portfolio Standards. ***Annual Review of Resource Economics***, 8:1, 141-155.

Macours, K., Premand, P., and Vakis, R. (2022). Transfers, Diversification and Household Risk Strategies: Can Productive Safety Nets Help Households Manage Climatic Variability? ***The Economic Journal***, 132(647), 2438–2470.

Mahadevan, Meera. (2021). The price of power: Costs of political corruption in Indian electricity. Working Paper.

Mahadevan, M., Meeks, R., and Yamano, T. (2023). Reducing information barriers to solar adoption: Experimental evidence from India. E***nergy Economics***, 120: 106600.

Malik, K., Cropper, M., Limonov, A., and Singh, A. (2015). The impact of electricity sector restructuring on coal-fired power plants in India. ***The Energy Journal***, 287-312.

Mauritzen, J. (2012). Dead battery? Wind power, the spot market, and hydro power interaction in the Nordic electricity market. ***Mimeograph***.

May, N., and Neuhoff, K. (2021). Financing Power: Impacts of Energy Policies in Changing Regulatory Environments. ***The Energy Journal***, 42(4), 131-151.

McKinsey and Co. (2015). Brighter Africa: The growth potential of the sub-Saharan electricity sector. Available from: http://www.mckinsey.com/~/media/mckinsey/dotcom/insights/energy%20resources%20materials/powering%20africa/brighter_africa_the_growth_potential_of_the_sub-saharan_electricity_sector.ashx

McNeil, M.A, Ke, J., Rue de Can, S., Letschert, V., and McMaho, J. (2011). Business case for energy efficiency in support of climate change mitigation, economic and societal benefits in India. ***Lawrence Berkeley National Laboratory*** Technical Report No. LBNL-5344E.

McRae, S. (2015). Infrastructure quality and the subsidy trap. ***American Economic Review***, 105(1):35–66.

Meeks, R. C., Omuraliev, A., Isaev, R., and Wang, Z. (2023). Impacts of electricity quality improvements: Experimental evidence on infrastructure investments. ***Journal of Environmental Economics and Management***, 120(7), 102838.

Meriggi, N. F., Bulte, E., and Mobarak, A. M. (2021). Subsidies for technology adoption: Experimental evidence from rural Cameroon. ***Journal of Development Economics***, 153, 102710.

Miller, G., and Mobarak, A. M. (2015). Learning about new technologies through social networks: experimental evidence on nontraditional stoves in Bangladesh. ***Marketing Science***, 34(4), 480-499.

Min, B., and Golden, M. (2014). Electoral cycles in electricity losses in India. ***Energy Policy***, 65: 619–625.

Min, B. (2015). Power and the vote: Elections and electricity in the developing world. New York: Cambridge University Press.

Mobarak, A. M., Dwivedi, P., Bailis, R., Hildemann, L., and Miller, G. (2012). Low demand for nontraditional cookstove technologies. ***Proceedings of the National Academy of Sciences***, 109(27), 10815-10820.

Montalbano, P., Nenci, S., and Vurchio, D. (2022). Energy Efficiency and Productivity: A Worldwide Firm-level Analysis. ***The Energy Journal***, 43(01), 93-115.

Murillo, M.V. (2009). Political competition, partisanship, and policy making in Latin American public utilities. New York: Cambridge University Press.

ND-GAIN. (2023). Country Index. Available from: https://gain.nd.edu/our-work/country-index

Ngonda, T. (2022). A scoping review of adopter attributes, motivations, and barriers of solar home systems adoption: Lessons for sub-Saharan Africa. ***Renewable Energy and Sustainable Development***.

Nguyen, J., Valadkhani, A., and Hajargasht, G. (2021). The Choice between Renewables and Non-renewables: Evidence from Electricity Generation in 29 Countries. ***The Energy Journal***, 42(01), 49-68.

Nordhaus, W. (1996). Do real-output and real-wage measures capture reality? The history of lighting suggests not. ***The economics of new goods.*** Chicago: University of Chicago Press, 27-70.

Parker, D., and Kirkpatrick, C. (2005). Privatisation in developing countries: A review of the evidence and the policy lessons. ***Journal of Development Studies***, 41(4):513– 541.

Pattanayak, S. K., Wunder, S., and Ferraro, P. J. (2010). Show Me the Money: Do Payments Supply Environmental Services in Developing Countries? ***Review of Environmental Economics and Policy***, 4(2), 254-274.

Persico, C. (2022). Can Pollution Cause Poverty? The Effects of Pollution on Educational, Health and Economic Outcomes. ***National Bureau of Economic Research*** Working Paper No. 30559.

Petersen, C., Reguant, M., and Segura, L. (2024) Measuring the impact of wind power and intermittency, ***Energy Economics***, Volume 129.

Phadke, A., Abhyankar, N., and Shah, N. (2013). Avoiding 100 new power plants by increasing efficiency of room air conditioners in India: Opportunities and challenges. ***Retrieved from Lawrence Berkeley National Laboratory***.

Philip, S., Martin, R.V., van Donkelaar, A., Lo, J.W., Wang, Y., Chen, D., and Macdonald, D.J. (2014). Global chemical composition of ambient fine particulate matter for exposure assessment. ***Environmental Science and Technology***, 48(22), 13060-13068.

Pitt, M., Rosenzweig, M., and Hassan, N. (2015). Identifying the cost of a public health success: Arsenic well water contamination and productivity in Bangladesh. ***National Bureau of Economic Research*** Working Paper No. 21741.

Qureshi, T. M., Ullah, K., and Arentsen, M. (2017). Factors responsible for solar PV adoption at household level: A case of Lahore, Pakistan. ***Renewable and Sustainable Energy Review***s, 78: 754-763.

Rentschler, M., Jun, E., and Leonova, N. (2022). Air Pollution and Poverty: PM2.5 Exposure in 211 Countries and Territories. ***The World Bank Policy Research*** Working Paper No. 10005.

Ritchie, M. J., Avenant, J., Engelbrecht, J. A. A., Rix, A. J., and Booysen, M. J. (2023). Optimal sizing of battery-less domestic rooftop PV systems in South Africa using a probabilistic electricity synthesiser. ***Energy for Sustainable Development***, 76, 101268.

Rode, A., Carleton, T., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., … and Yuan, J. (2021). Estimating a social cost of carbon for global energy consumption. ***Nature***, 598(7880), 308-314.

Ruiz-Tagle, J. C., and Schueftan, A. (2021). Nudging for Cleaner Air: Experimental Evidence from an RCT on Wood Stove Usage. Environmental and Resource Economics, 79(4), 713–743.

Ryan, N. (2018). Energy productivity and energy demand: Experimental evidence from Indian manufacturing plants. ***National Bureau of Economic Research*** Working Paper No. 24619.

Ryan, N. (2020). Contract enforcement and productive efficiency: Evidence from the bidding and renegotiation of power procurement contracts in India. ***Econometrica***, 88 (2): 383-424.

Ryan, N. (2023). Holding Up Green Energy: Counterparty Risk in the Indian Solar Power Market. ***Econometrica*** (Revise and Resubmit)

Ryan, N. (2021b). The competitive effects of transmission infrastructure in the Indian electricity market. ***American Economic Journal: Microeconomics***, 13 (2): 202-42.

Scott, N., McKemey, K., and Batchelor, S. (2005). Energy in low-income urban communities (Technical Report Contract Number R8146). ***Department for International Development***.

Sherwood, S., and Huber, M. (2010). An adaptability limit to climate change due to heat stress. ***Proceedings of the National Academy of Scienc***e, 107(21), 9552-9555.

Shojaeddini, E., and Gilbert, B. (2023). Heterogeneity in the Rebound Effect: Evidence from Efficient Lighting Subsidies. ***Environmental and Resource Economics***, 84(1), 173–217.

Silva, T. C., Muniz, F. J., and Tabak, B. M. (2023). The Impact of Government Disaster Surveillance and Alerts on Local Economic and Financial Conditions. ***Environmental and Resource Economics***, 84(2), 559–591.

Singh, R. et al., (2014). Energy access realities in urban poor communities of developing countries: assessments and recommendations. ***GNESD- UNEP***.

Slemrod, J., and Gillitzer, C. (2014). Tax Systems. Cambridge: MIT Press.

Slemrod, J. (2016). Tax compliance and enforcement: New research and its policy implications. ***Retrieved from the Ross School of Business*** Working Paper No. 1302.

Somanathan, E. et al., (2015). The impact of temperature on productivity and labor supply: Evidence from Indian manufacturing. **Retrieved from Delhi School of Economics** Working Paper No. 244.

Souza-Rodrigues, E. (2019). Deforestation in the Amazon: A Unified Framework for Estimation and Policy Analysis. ***The Review of Economic Studie***s, 86(6), 2713–2744.

Stavins, R. N. (2003). Experience with market-based environmental policy instruments. ***Handbook of environmental economics*** (Volume 1, 355-435). Elsevier.

Stergiou, E., and Kounetas, K. (2021). European Industries' Energy Efficiency under Different Technological Regimes: The Role of CO2 Emissions, Climate, Path Dependence and Energy Mix. ***The Energy Journal***, 42(1), 93-128.

Straub, S. (2008). Infrastructure and development: A critical appraisal of the macro level literature. ***Retrieved from the World Bank*** Working Paper No. 4590.

Sudarshan, A. (2013). The behavioural effects of monetary contracts: Using peer comparisons and financial incentives to reduce electricity demand in urban Indian households. ***Stanford Institute for Theoretical Economics: Psychology and Economics Summer Workshop*** (Sep 23-25).

Sun, C., Kahn, M., and Zheng, S. (2017). Self-protection investment exacerbates air pollution exposure inequality in urban China. ***Ecological Economics***, 131(5).

Tseng, T.-W. J., Robinson, B. E., Bellemare, M. F., BenYishay, A., Blackman, A., Boucher, T., et al., (2021). Influence of land tenure interventions on human well-being and environmental outcomes. ***Nature Sustainability***, 4(3), 242–251.

UK Ministry of Health. (1954). Mortality and morbidity during the London fog of December 1952. Reports on Public Health and Medical Subjects No 95. ***Retrieved from the Highline Medical Services Organisation, London***.

United Nations. (2014). World urbanization prospects: The 2014 revision. ***Retrieved from the United Nations:*** **http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf**

USAID. (2004). Innovative approaches to slum electrification. United States Agency for International Development.

Van de Walle, D., Ravallion, M., Mendiratta, V., and Koolwal, G. (2013). Long-term impacts of household electrification in rural India. ***Retrieved from The World Bank***.

Verma, A. P., and Imelda. (2023). Clean Energy Access: Gender Disparity, Health and Labour Supply. ***The Economic Journa***l, 133(650), 845–871.

Victor, D. G., and Heller, T. C. (Eds.). (2007). The political economy of power sector reform: the experiences of five major developing countries. Cambridge University Press.

Villavicencio, M., and Finon, D. (2022). The Social Efficiency of Electricity Transition Policies Based on Renewables. Which Ways of Improvement? ***The Energy Journa***l, 43(6). 195-216.

Wang S., Zhao, W., Fan, S., Xue, L., Huang Z., Liu, Z. (2022). Is the Renewable Portfolio Standard in China Effective? Research on RPS Allocation Efficiency in Chinese Provinces Based on the Zero-Sum DEA Model. ***Energies***, 15(11): 3949.

Wangsness, P. B., and Halse, A. H. (2021). The Impact of Electric Vehicle Density on Local Grid Costs: Empirical Evidence from Norway. ***Energy Journal***, 42(5), 49-167.

Way, R., Ives, M. C., Mealy, P., and Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. ***Joule***, 6(9), 2057–2082.

Weber, P., and Woerman, M. (2024) Intermittency or Uncertainty? Impacts of Renewable Energy in Electricity Markets, ***Journal of the Association of Environmental and Resource Economists***, forthcoming.

Wolfram, C., Miguel E., Hsu, E., and Berkouwer, S. B. (2023) Donor Contracting Conditions and Public Procurement: Causal Evidence from Kenyan Electrification. ***National Bureau of Economic Research*** Working Paper No. 30948.

Wolfram, C., Shelef, O., and Gertler, P. (2012). How will energy demand develop in the developing world? ***Journal of Economic Perspectives***, 26(1), 119-38.

World Bank. (2019a). Beyond the gap: How countries can afford the infrastructure they need while protecting the planet.

World Bank. (2019b). Rethinking Power Sector Reform in the Developing World.

World Development Indicators. (2015). World Bank Open Data. Available from: https://data.worldbank.org/

World Health Organization. (2016). Ambient air pollution: A global assessment of exposure and burden of disease.

Wren-Lewis, L., Becerra-Valbuena, L., and Houngbedji, K. (2020). Formalizing land rights can reduce forest loss: Experimental evidence from Benin. ***Science Advances***, 6(26).

Xiao, Y., Huang, H., Qian, X. M., and Chen, L. (2023). Can carbon emission trading pilot facilitate green development performance? Evidence from a quasi-natural experiment in China. ***Journal of Cleaner Production***, 400, 136755.

Yao, Z., Zhang, W., Ji, X., and Weng, W. (2023). Short-Term Exposure to Air Pollution and Cognitive Performance: New Evidence from China's College English Test. ***Environmental and Resource Economics***, 85(1), 211–237.

Zamuda, C. D., Bilello, D., Conzelmann, G., Mecray, E., Satsangi, A. Tidwell, and V., Walker, B. (2018). Energy Supply, Delivery, and Demand. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. ***US Global Change Research Program,*** Washington, DC, USA, pp. 174–201

Zhang, F. (2022). The policy coordinator role of national development banks in scaling climate finance: Evidence from the renewable energy sector. ***Climate Polic***y, 22(6), 754-769.

Zhang, J., and Q. Mu. (2018). Air pollution and defensive expenditures: Evidence from particulate-filtering facemasks. ***Journal of Environmental Economics and Management*** 92: 517–36.

Zhang, X., Chen, X., and Zhang, X. (2018). The impact of exposure to air pollution on cognitive performance. ***Proceedings of the National Academy of Sciences***, 115(37), 9193-9197.

Zhang, Y. F., Parker, D., and Kirkpatrick, C. (2008). Electricity sector reform in developing countries: an econometric assessment of the effects of privatization, competition and regulation. ***Journal of Regulatory Economics***, 33(2), 159-178.

Zhou, S. and Solomon, B. D. (2020). Do renewable portfolio standards in the United States stunt renewable electricity development beyond mandatory targets? ***Energy Policy***, 140(C).

www.theigc.org