Rethinking Energy Efficiency in the Developing World

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> "Energy efficiency has enormous potential to increase global productivity and prosperity while cutting waste and limiting emissions. We must move quickly, decisively and in concert to enact and expand these bold measures."
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> – *Achim Steiner, Executive Director of the UN Environment Programme*

1 Introduction

Over the past decade, technological advances have significantly reduced the energy inputs required to provide fundamental energy services such as cooking, lighting, space heating, and cooling. The International Energy Agency (IEA) estimates that energy efficiency improvements could deliver more than a third of the cumulative reductions of greenhouse gas (GHG) emissions necessary to stabilize climate change (IEA, 2018). International aid agencies have also emphasized the development-oriented benefits that energy efficiency can deliver, including reduced pressure on household and national budgets, poverty alleviation, and improved power-system reliability.[1] [2] A coalition of governments and international organizations has pledged to double the global rate of improvements in energy efficiency by 2030 (United Nations General Assembly, 2015).[3]

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[1] See, for example, https://www.undp.org/content/undp/en/home/2030-agenda-for-sustainable-development/planet/sustainable-energy/energy-efficiency.html

[2] Also see: https://efficiencyforaccess.org/why-efficiency-for-access

[3] This is Sustainable Development Goal 7.3.

In developing and emerging economies, energy efficiency improvements have the *potential* to mitigate tensions between economic growth objectives and sustainable development commitments. But the empirical evidence on the social returns to these investments is limited. Rapidly increasing demand for energy services raises pressing questions about what impacts enhanced energy efficiency could have on future energy consumption trajectories; which efficiency investments can deliver the largest social returns; what kinds of policy interventions will be required to spur these investments; and who the beneficiaries will be. This paper surveys the empirical microeconomic evidence and begins to chart a course for future research to address key gaps in understanding.[4]

A large literature has investigated the economics of efficiency investments and the policies that support them (Allcott and Greenstone, 2012; Gillingham et al., 2009; Jaffe and Stavins, 1994). Over the past several decades, economists have assessed private returns on energy efficiency investments (Metcalf and Hassett, 1999; Fowlie et al., 2018), investigated the market barriers and failures that can result in under-investment (Gerarden et al., 2015; Hausman, 1979; Sallee, 2014), and evaluated the impacts of a broad range of policies that aim to accelerate the adoption of cost-effective efficiency improvements (Burlig et al., 2019; Geller, 2006; Levinson, 2016; Houde and Aldy, 2017). This literature has generated critical insights and policy guidance. But it has historically emphasized applications in high income, highly industrialized countries.

Researchers' attention is increasingly focused on energy efficiency potential in developing and emerging economy contexts. One reason is that almost all of the world's energy demand growth is forecast to occur in non-OECD counties. Figure 1 summarizes projections from the IEA World Energy Outlook (2018) which estimates that low and middle income countries (LMICs) will increase their combined energy demand by 45% over the next two decades.[5]

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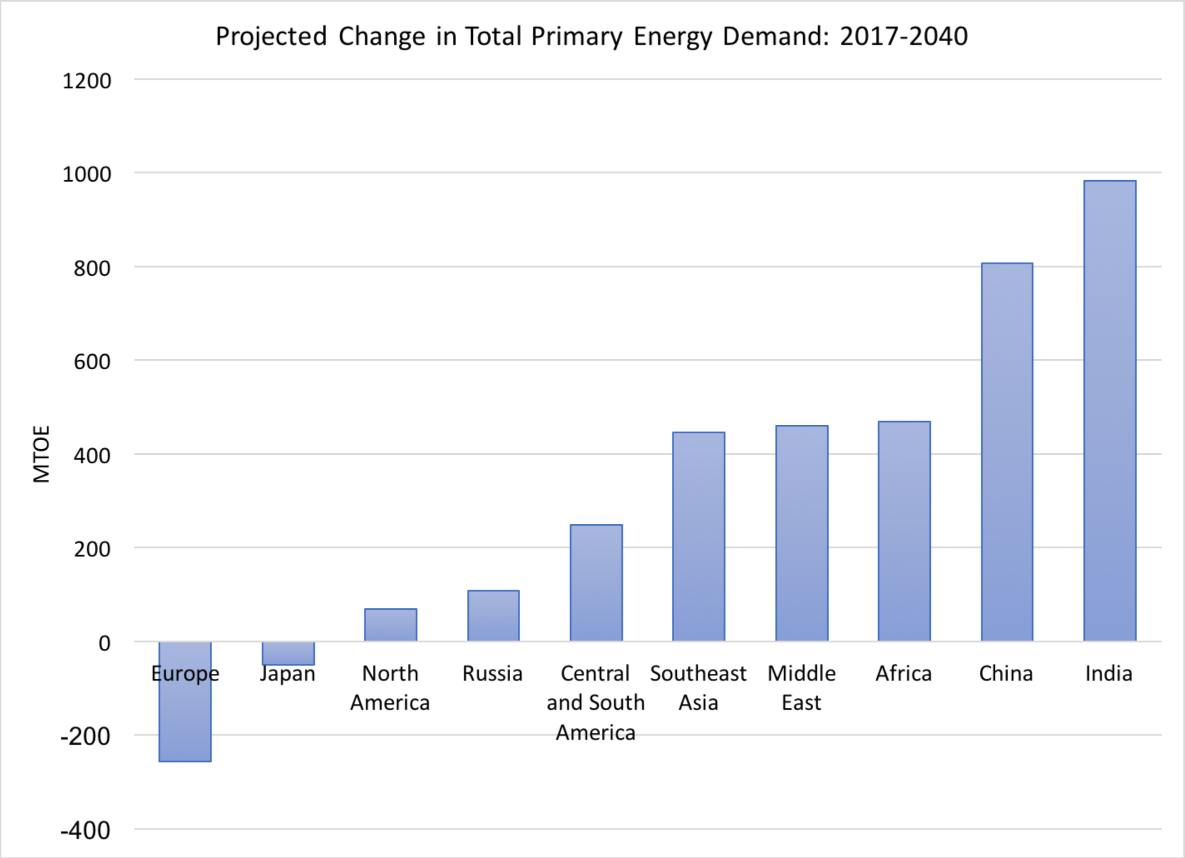
[4] This paper emphasizes the microeconomic aspects of these questions. Macroeconomic lines of inquiry are also important, but beyond our scope.

[5] Some economists have argued that these projections likely under-estimate future demand growth given increasing penetration of air conditioners and other energy-using assets (Wolfram et al., 2012; Davis and Gertler, 2015).



Source: IEA/OECD World Energy Outlook (2018)

There are also stark differences in energy intensity metrics across low, middle, and high income countries. Figure 2 tracks one measure of energy intensity – energy inputs per dollar of GDP – using data from the World Bank.[6] This measure is an imperfect proxy for energy *efficiency*; differences across countries and across time could be driven by differences in industrial composition.[7] That said, the limited evidence we do have indicates that levels of investment in energy efficiency in LMICs are low relative to high income countries (HICs) (see, for example, Van Buskirk et al. (2007)).

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[6] This energy intensity metric is constructed as the ratio between energy supply and gross domestic product measured at purchasing power parity. Country classifications are based on the World Bank country income classifications, which are determined using GNP per capita. Data source: https://data.worldbank.org/indicator/EG.EGY.PRIM.PP.KD?end=2015start=1990

[7] More direct measures of energy efficiency are difficult to construct for all countries given data limitations.

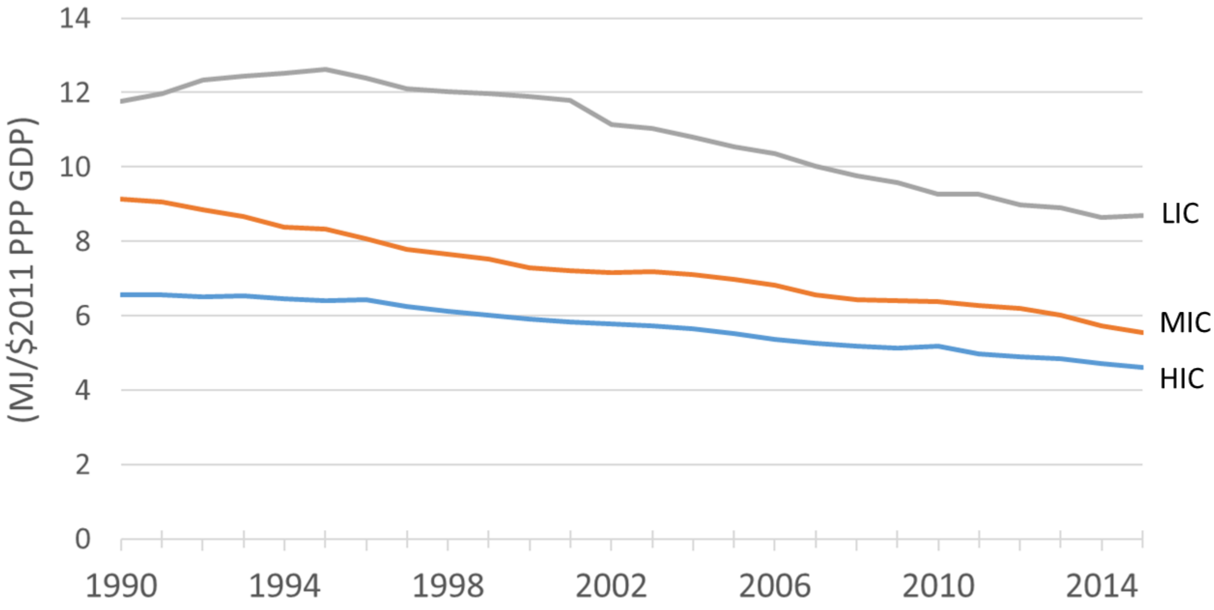

Figure 2: Energy Intensity Level of Primary Energy, By Country Income Group (1990 - 2015)

Another development attracting the attention of empirical researchers is the increasing scale of energy efficiency investments in LMICs. For example, the Global Environment Fund reports investing more than US$1.25 billion in energy efficiency projects across 115 developing and transition countries (GEF, 2014).[8] Programs designed to accelerate adoption of energy efficient lighting initiatives are spreading through Sub-Saharan Africa (UNEP, 2012), Central and South America (ESMAP, 2013), and South Asia (World Bank, 2010). Energy service companies[9] and energy efficiency revolving funds are being deployed to accelerate private energy efficiency investments in LMICs (ESMAP, 2016).

These investments in energy efficiency notwithstanding, energy intensity in LMICs remains much higher than in HICs. There is a palpable sense that accelerating the deployment of more efficient end-use technologies and building practices could significantly reduce the economic and environmental costs of meeting growing demand for energy services in LMICs.[10]

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[8] These investments span appliances and equipment, lighting, building and heating, energy supply and services, and industrial processes.

[9] ESCO projects in China received over 200 million dollars (ESMAP, 2016) and since the 2009 creation of the Indian Energy Efficiency Services Limited, hundreds of millions of LED bulbs have been deployed (GEF, 2014).

[10] Craine et al. (2014) estimate that energy efficiency investments could reduce the costs of extending energy access by as much as 70 percent.

In areas plagued by supply constraints and reliability issues, demand-side efficiency improvements could also offer a cost-effective means of increasing the reliability of energy service delivery (Phadke et al., 2019). The jumping off point for this paper is that the perceived potential for welfare-improving energy efficiency investments in LMICs is high, but it is not yet clear how much of this potential can be cost-effectively realized.

The paper is organized around three observations, all of which have implications for empirical research design, welfare impacts, and policy implementation:

First, empirical research to date has generated valuable insights into the microeconomics of private energy efficiency investments. Section 2 introduces a conceptual framework that elucidates the connections between key concepts that have been investigated empirically in both HICs and LMICs. These include energy savings, demand 'rebound', and households' willingness to pay for energy efficiency improvements. A survey of the empirical literature highlights both similarities and differences in empirical findings across a variety of contexts. For example, researchers have documented economically significant gaps between ex ante predicted energy savings and ex post realized savings in both high and low income settings. But the underlying mechanisms can vary. In HICs, errors in model calibration, installation error, and principal-agent problems have all been identified as factors contributing to this 'realization gap' (see, for example, Fowlie et al. (2018); Blonz (2019)). In LMICs, a broader range of explanations have been investigated, such as technological externalities (Carranza and Meeks, forthcoming), rebound effects (Davis et al., 2014), and complementarities between energy and other factors of production (Ryan, 2018).

Second, barriers to – and returns on – energy efficiency investments can manifest very differently in high income countries versus developing and emerging economies. With regards to barriers, Section 3 highlight the potential role of energy price subsidies, the prevalence of non-technical losses, poor power quality, and capital market failures in LMICs. Section 4 argues that standard approaches to measuring the returns on efficiency investments, which emphasize reductions in energy expenditures and associated environmental impacts, fail to capture value streams that are potentially important in LMIC settings. In areas where budget constraints bind and power supply quality is poor, returns on energy efficiency investment could manifest as increased access to affordable energy services and reliability improvements. In commercial and industrial applications, energy efficiency investments could compensate for other constraints on productivity (Ryan, 2018). We review the limited evidence on these topics and point to lines of inquiry that could benefit from further empirical investigation.

Finally, substantive differences in policy priorities and institutional capacity constraints across low and high income settings could have implications for energy efficiency program design and implementation. In Section 5, we note that energy efficiency program designs which have found success in HICs (e.g., building codes and efficiency standards) may be ill-suited to many LMIC contexts. Ideally, energy efficiency programs should be designed to accelerate progress on context-specific policy priorities subject to institutional and resource constraints. We highlight two working examples of energy efficiency programs that are demonstrating some success. We also emphasize the importance of empirical research that rigorously explores unfolding policy experimentation in LMICs.

2 A Microeconomic Model of Energy Efficiency Investment

In this section, we introduce a conceptual framework which nests an engineering model of a technological energy efficiency improvement within a standard micro-economic model of household utility maximization. We use this framework to integrate and interpret recent empirical evidence on microeconomics of energy efficiency investments in LMICs. For conceptual clarity, the model focuses narrowly on the trade-off between up-front investment costs and operating cost savings. We introduce a broader set of trade-offs in Section 3.

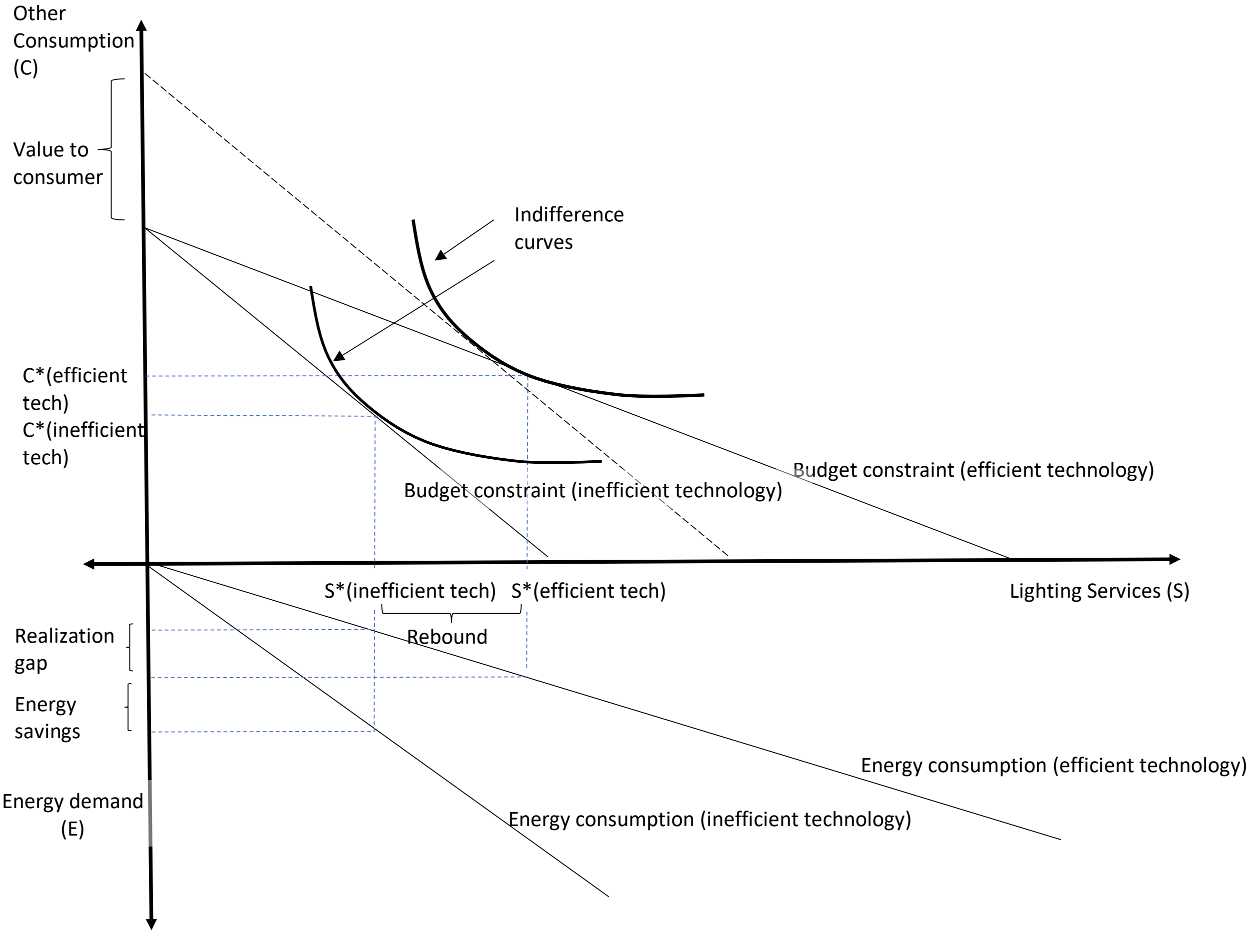

Figure 3: Willingness to pay for an energy efficiency improvement

Notes: Budget constraints and indifference curves for a representative consumer are plotted in the top quadrant. A linear relationship between lighting services and energy consumption is plotted in the bottom quadrant. Please see text for details. This figure is a modified version of (Fowlie and Phadke, 2018)

We compare the consumption behavior of a representative household across two scenarios that differ only in terms of appliance energy efficiency. The bottom panel of Figure 3 summarizes the technological relationship between the quantity of energy services supplied (S) and energy inputs required (E) per consumption period (e.g., an hour) for two appliance alternatives that vary in terms of energy efficiency but provide the same quality of energy service (e.g., lighting, space cooling). To fix ideas, we consider the example of a household choosing between a low efficiency lighting fixture (e.g. an incandescent lamp) or high efficiency fixture (e.g., light-emitting diode [LED]).[11] The more efficient fixture requires less electricity per hour of lighting service delivered. It follows that the implicit price per hour of lighting (i.e., the electricity price times the quantity of electricity required to operate the bulb for an hour) will be lower for the more efficient appliance.

We nest this physical relationship within an economic model of a representative household's utility maximizing energy consumption decision. Utility depends on the consumption of lighting services (S) and all other consumption (denoted by C). For expositional clarity, the unit price of this other consumption (the numeraire good) is normalized to one. We assume the household allocates a fixed daily income across lighting expenses and other consumption. The concentric curves (indifference curves) in the top panel connect different combinations of S and C that generate the same level of utility for the household. The budget constraint determines which consumption choices are affordable given the energy price, the price of the numeraire good, income, and the efficiency level of the lighting appliance owned by the household. The figure illustrates how the budget constraint associated with the more efficient appliance is less steep (because more energy services can be purchased with a fixed income).

Our representative household chooses the combination of other consumption and lighting services that maximizes utility given the budget constraint (denoted S^* and C^*). The figure illustrates two types of benefits generated by the more efficient appliance. The first manifests as a reduction in energy consumed (denoted as energy savings in the figure). A reduction in energy expenditures implies that the household has more to spend on other consumption. The second benefit manifests as increased consumption of energy services (denoted as 'rebound' in the figure). Taken together, the value of these benefits for a single consumption period can be measured as the increase in income that the household would require to achieve the higher level of utility using the less efficient appliance (i.e., the equivalent variation). We can interpret this as the maximum price the consumer would be willing to pay (per consumption period) to achieve the level of utility associated with the more efficient appliance.

This conceptual model elucidates the relationships between four important concepts that have been evaluated in the empirical literature: energy savings; rebound effects; the energy savings realization rate, and consumers' willingness to pay (WTP) for an efficiency

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[11] The framework can be generalized to a wide range of energy services and associated technologies.

improvement. In what follows, we summarize the evidence on each.

2.1 Energy Savings

Reductions in energy expenditures are the most direct benefits generated by energy efficiency investments. Efficiency-induced reductions in energy consumption are measured on the vertical axis in Figure 3. In principle, these can be estimated using careful comparisons of energy consumption across efficient versus inefficient appliances. A small but growing literature quantifies and evaluates these direct returns in LMIC contexts.

Several recent studies evaluate the energy savings associated with the adoption of more efficient lighting appliances. Lighting has become an important focus of energy efficiency programs in developing and emerging economies because lighting is ubiquitous and lighting efficiency improvements are relatively inexpensive. Another important consideration is that lighting demand is often coincident with peak electricity consumption, such that lighting efficiency improvements can deliver energy reductions when they are most valuable (Boomhower and Davis, 2020). Carranza and Meeks (forthcoming) conducted a randomized experiment in the Kyrgyz Republic that was designed to evaluate both direct and indirect impacts of replacing incandescent lighting with more efficient CFLs. They estimated direct energy savings of approximately 11.4 kWh per bulb per month. Iimi et al. (2019) estimated similar energy savings using a quasi-experimental research design in Ethiopia. In both contexts, these investments were found to be highly cost effective at prevailing electricity prices. Related work investigates the benefits of transitioning from kerosene lighting to electric lighting. Rom and Günther (2019) conducted a randomized field study in rural Kenya where they found that households switching from kerosene lighting to more efficient solar light reduced kerosene use by 1.47 liters per month. Households reduced their energy expenditures by 42% as a consequence.

Researchers have also investigated the energy savings associated with the adoption of more efficient cooking appliances in LMICs. With nearly 2.7 billion people worldwide using solid fuels – biomass or coal – for cooking or heating (IEA, 2019), the goal of accelerating the adoption of more efficient stoves has attracted attention. Cooking fuel savings can be substantial. Bensch and Peters (2015) found that households' total firewood consumption was reduced by 30% after replacing a traditional cooking stove with a more fuel efficient version in Senegal. Berkouwer and Dean (2020) document how an upgrade to a more efficient cookstove delivers a 40% decrease in charcoal expenditures, on average, for households in

Kenya.[12]

In addition to lighting and cooking stoves, researchers have estimated the energy savings associated with efficient refrigerators and air conditioners (Davis et al., 2014); building insulation (Davis et al., 2018); and industrial efficiency improvements (Ryan, 2018) in emerging economies. In contrast to lighting and cook stoves, efficiency-induced energy savings are found to be negligible- or even negative- across these applications.

2.2 Energy Demand 'Rebound'

If a consumer has not fully satiated her demand for an energy service, she may respond to an efficiency-induced reduction in the cost of this service with an increase in consumption (Borenstein, 2015). For example, a consumer might prefer to light all of the rooms in her house, but choose to light only the most important living spaces due to a binding budget constraint. With more efficient lighting (and thus lower lighting service costs), she might choose to light more rooms. In Figure 3, this direct rebound in demand for energy services is represented by the increase from S^*(inefficient tech) to S^*(efficient tech).[13]

When energy demand rebounds following an efficiency improvement, observed energy savings will fall below ex ante projections (assuming that projections do not anticipate a behavioral response). An energy efficiency improvement could even induce a net increase in energy use, which is referred to as 'backfire' in the literature. Rebound effects and the potential for backfire are sometimes construed as a negative phenomenon because they imply that projected energy savings are not fully realized. But this demand response can be an important source of household utility gains, particularly in low income countries that have made increased access to energy services a development priority.

The extent to which rebound effects manifest will vary across contexts, making it difficult to draw general conclusions with respect to size and importance. The bulk of the empirical evidence on direct rebound comes from developed country contexts. A comprehensive review of 500 studies suggests that direct rebounds are likely to be over 10% (IPCC, 2014). For household-level efficiency measures, the majority of studies conducted in HICs estimate rebound effects in the range of 0% to 45% (Sorrell et al., 2009; Fowlie et al., 2018; Freire-

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[12] Studies have also estimated the impacts of adopting cooking stoves that use alternative fuels, such as LPG and biogas, and find reductions in the consumption of biomass fuels (Brooks et al., 2016; Meeks et al., 2019; Somanathan and Bluffstone, 2015).

[13] It is worth noting that our simple model abstracts away from income effects, and therefore could overstate the extent of demand rebound. If energy efficient appliances are more expensive, adopters of the more efficient technology will have less disposable income to spend on energy services and other goods. This will reduce the level of energy services demanded (and the extent of rebound).

González, 2010). Rebound effects could be much larger in developing and emerging economies where budget constraints are more likely to bind (IPCC, 2014). Some recent empirical work provides some evidence that is consistent with this idea (see, for example, Ouyang et al. (2010); Davis et al. (2014)).

If rebound effects are significant, measured reductions in energy expenditures will significantly under-estimate the private returns on efficiency investments. This complicates the empirical quantification – and welfare interpretation – of realized returns on energy efficiency investments. In contrast to electricity consumption, which can be measured directly using administrative data, energy service consumption is difficult to measure. Researchers have begun to experiment with new data collection methods such as appliance-level monitoring (see, for example, Romm 2019 and Berkouwer, 2020). Methodological innovations along these lines could play an important role in constructing more comprehensive measures of the returns on energy efficiency investments.

2.3 Realization Gaps

If demand for an energy service responds to an efficiency-induced reduction in energy service cost, ex ante engineering predictions could over-estimate realized energy savings. Figure 3 shows how engineering estimates that do not account for the behavioral demand response overstate realized savings by a 'realization gap' which corresponds to the extent of the demand rebound.

Demand rebound offers one possible explanation for a realization gap (as in Figure 3). But recent studies have identified additional mechanisms and explanations.[14] Davis et al. (2018) find that the engineering estimates of building envelope improvements calibrated to developed country settings significantly overstate savings realized in low income settings when income and behavioral differences are not accounted for. Other examples of modeling miscalibration includes ex ante calculations for improved cookstoves which often omit cooking practices common in LMICs such as stove-stacking (the use of multiple stoves, which may use different types of fuel, simultaneously), product failure and unexpected maintenance (Hanna et al., 2016), and other cultural considerations (Bensch and Peters, 2013).[15] Davis et al.

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[14] Ex ante expected energy savings are calculated in multiple ways, depending on the technology. For example, fuel savings from improved cooking stoves are estimated following controlled cooking tests (CCTs), which are undertaken in standard lab setting. Calibrated engineering models of energy use in buildings are used to simulate how energy efficiency improvements will reduce energy consumption and expenditures.

[15] An important exception is Berkouwer and Dean (2020) who find that ex ante estimates of charcoal savings associated with more efficient stoves align well with observed savings.

(2014) find that realization gap between projected and realized energy savings associated with air conditioners and refrigerators in Mexico can partly be explained by savings projections that underestimate the efficiency of appliances that are replaced.

Some explanations for documented realization gaps point to potentially significant but indirect benefits that extend beyond energy savings. For example, Carranza and Meeks (forthcoming) document the role of technological externalities in rationalizing the gap between projected and realized impacts of lighting efficiency improvements on energy consumption. They find that intensive energy efficiency improvements on a congested electricity distribution system reduced outages and improved service reliability. Ryan (2018) finds that energy efficiency improvements at Indian textile firms *increase* energy consumption due to complementarities between energy, labor, and capital inputs to production.

2.4 Willingness to Pay for Energy Efficiency

Figure 3 illustrates the value generated by an energy efficiency improvement for a representative household over a single consumption period. In theory, a household's total willingness to pay (WTP) for the efficiency improvement can be estimated as the discounted sum of these per period gains over the life of the appliance. More precisely, absent market failures, information failures, or other distortions, a utility maximizing consumer should be willing to adopt the more efficient technology if the discounted sum of private benefits exceed the additional investment cost. A sizeable literature has investigated households' WTP for efficiency improvements in HIC settings (see, for example, Greene et al. (2013), Busse et al. (2013), Hausman (1979)). However, empirical findings need not translate across contexts that differ in terms of income levels, consumer preferences, and other factors.

In general, empirical measures of households' WTP for new technologies are important for projecting private demand and assessing the importance of possible market failures. A growing empirical literature in development economics uses experimental methods to elicit revealed preference measures of consumers' willingness to pay for potentially welfare-improving technologies. Many of these applications are health related, such as de-worming medicines (Kremer and Miguel, 2007), bed nets (Cohen and Dupas, 2010), or "clean" cook stoves (Mobarak et al., 2012) and technologies to provide improved drinking water (Berry et al., 2020).

There is relatively little experimental evidence on households' demand for energy efficiency improvements in LMICs. We are aware of only two field experiments that have sought to estimate households' WTP for energy efficiency: an experimental evaluation energy efficient lightbulbs in the Kyrgyz Republic (Carranza and Meeks, forthcoming) and a study of energy efficient cooking stove adoption in Kenya (Berkouwer and Dean, 2020).[16]

In the interest of extracting additional insights into households' WTP for energy efficiency from available data, we revisit the Kyrgyz Republic study. The demand elicitation component of the study surveyed 470 residents living in owner-occupied and individually metered homes. At the time of the study (which was conducted in 2013), very few households had invested in energy efficient lightbulbs, even though these compact fluorescent lights (CFLs) delivered energy savings (relative to standard incandescent bulbs) in excess of their costs.[17] At the beginning of the study, households owned 6 light bulbs on average. Additional statistics on the study sample are included in Appendix 1.

This field experiment used the Becker-DeGroot-Marschak (1964) method to elicit households' willingness to pay for CFLs.[18] Household responses to this demand elicitation can be used to trace out an aggregate demand curve for CFLs in the study population. Figure 4 illustrates the demand curve implied by household responses.

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[16] There is also a contingent valuation study of willingness to pay for energy efficient lighting in Saint Lucia (Reynolds et al., 2007). And, in a high income country context, Davis and Metcalf (2016) investigate whether state-specific information on energy costs (relative to average national energy prices) leads to more informed valuation on the part of households using a stated choice experiment.

[17] Incandescent bulbs cost between 15 to 20 Kyrgyz soms, while CFLs were selling at prices in the range of 100 to 170 Kyrgyz soms (KGS) in local markets. The exchange rate at the time was 1 USD = 46 KGS. LEDs were not readily available in the country in 2013, so CFLs were the most energy efficient option.

[18] The experimental method works as follows: (1) individuals state the price they are willing to pay for a good, $\mathrm{p_i}$ (2) a random price is drawn, $\mathrm{p_r}$; (3) the individual purchases the good(s) if $\mathrm{p_i} \leq \mathrm{p_r}$, but otherwise cannot buy the good; (4) individuals pay $\mathrm{p_r}$ if $\mathrm{p_i} \leq \mathrm{p_r}$. The procedure has been used to measure WTP for health-related products such as insecticide treated bednets (Hoffman, 2009), water filters (Berry et al., 2020), and clean water (Guiteras et al., 2016). The BDM experiment occurred immediately after households completed a survey, for which respondents were compensated 150 KGS.

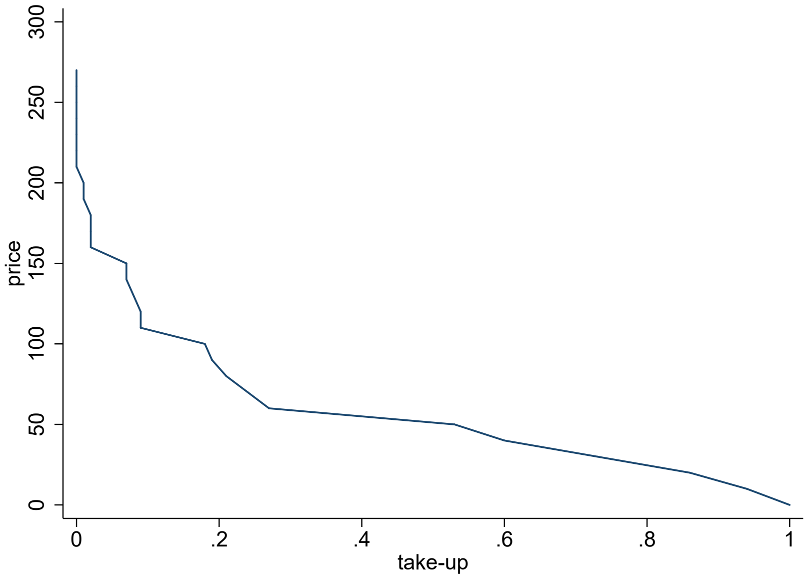

Figure 4: Demand for CFLs

Notes: The figure plots the range of households' revealed willingness to pay (WTP) for one CFL. Take-up is estimated using bids made through an experimental elicitation using the Becker-de Groot-Marschak method in the Kyrgyz Republic. Prices are in Kyrgyz soms (KGS).

Variation in the size of the CFL subsidy generated random variation in technology adoption. This experimental variation in appliance holdings can be used to estimate energy savings. Table 1 reports the estimated net present value (NPV) of benefits associated with CFL adoption. The lower bound estimates include only the benefits associated with observed energy savings and associated reductions in electricity expenditures. The most conservative estimate of the average NPV of the direct benefits generated by a CFL is 268 KGS per household over a two year time horizon. This conservative benefits estimate is approximately twice the CFL market price. The higher bound estimates include a monetized estimate of the additional technological externality benefits identified by the authors. As noted above, Carranza and Meeks (forthcoming) document a positive network externality whereby reduced lighting consumption increases reliability of supply.

Comparing the estimated benefits in Table 1 with the elicited demand in Figure 4 illustrates the extent to which households seem to discount the returns on this efficiency investment. Even the maximum WTP for CFL bulbs among these survey respondents falls below our most conservative empirical estimates of the discounted private returns on invest-

Table 1: Net present value (KGS) of CFL benefits, by expected CFL lifespan

	6 year	4 years	2 years
Lower bound	606.02	462.96	268.25
Higher bound	916.85	692.58	396.02

Notes: Calculations are based on the estimated benefits presented in Carranza and Meeks (forthcoming). All calculations assume a discount rate of 12% and an avoided cost of purchasing an incandescent lightbulb in year 0 and replacements every 2 years thereafter. The lower bound estimates include the benefits only from the electricity savings resulting from replacing 1 incandescent lightbulb with a CFL. The higher bound estimates include the electricity savings as well as reliability improvements. All values are in Kyrgyz soms (KGS). At the time of the experiment, 1 USD=48 KGS.

ment.[19] These findings imply a sizeable 'efficiency gap' between consumer valuation and estimated returns.

To shed some light onto what factors might explain this gap in this setting, we investigate some observable correlates in this surveyed population. In particular, we focus on income and learning. We find that household-level WTP for the efficient lighting appliance is positively correlated with our measure of wealth (we use the house construction material indicator as a crude wealth proxy). We speculate that capital constraints and credit market failures could explain this relatively low demand among low income customers.[20]

Another possible explanation is that households are uninformed about the private returns on this efficiency investment. The experimental design provides an opportunity to assess the potential role of learning about a technology, albeit indirectly. Households that were randomly assigned to receive CFLs at subsidized prices in the first phase of the study – and therefore experienced the impacts of the energy efficiency within their households – were subsequently more likely to report a preference for CFLs over incandescent bulbs at the end of the study (Carranza and Meeks, forthcoming). This suggests a role for learning in increasing demand for new efficient appliances. Although it is important to note that simply providing information on energy efficiency may not be sufficient to increase demand. In Kenya, Berkouwer and Dean (2020) found that providing information on potential energy

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[19] The NPV discounted energy savings is 404.6 and 547.6 KGS, assuming CFL lifespans of 4 and 6 years, respectively.

[20] Survey respondents were paid 150 KGS prior to the demand elicitation, so participants had cash available to purchase CFLs at a price that is considerably higher than the average bid price. We speculate that cash-constrained households wanted to allocate scarce cash resources to alternative uses that deliver larger utility benefits on the margin.

savings to households did not increase their demand for efficient cook stoves in Kenya.

There remains tremendous scope for additional evidence on willingness to pay – and the factors impacting it – for efficiency improvements across a range of LMIC settings. The existing evidence is suggestive but incomplete. This body of work would benefit from a richer investigation of heterogeneity in demand across energy sources (e.g. grid versus off-grid electricity sources) and types of households (e.g. those with reliable versus unreliable energy access). Evidence on the demand for relatively substantial energy efficiency investments (e.g. efficient air conditioners, refrigerators, building shell improvements), would also be useful for targeting efforts at the most promising efficiency improvements.

3 Under-explored Barriers to Efficiency Investments

In the previous section, we summarized the available evidence on consumers' willingness to pay for energy efficiency improvements in LMICs, all of which is consistent with an efficiency gap. This suggests a role for market failures and other barriers to efficient investment. Identifying what those barriers are will be important to guide policy interventions that aim to mitigate or these barriers.

A large empirical literature has explored the market failures and barriers that can open up a gap between observed levels of energy efficiency investments and socially optimal levels (see, for example, Allcott and Greenstone (2012), Gerarden and Stavins (2017)). The majority of this work has been done in highly industrialized countries. In these settings, researchers have investigated the role of incomplete information and myopia (Allcott and Sweeney, 2016; Houde and Myers, 2019), inattention (Sallee, 2014), energy use externalities (Allcott and Greenstone, 2012), and credit constraints (Boregeson et al. 2012).[21]

Lessons learned in HICs need not transfer. Consumer preferences and behaviors differ across country contexts. Countries can differ starkly in terms of how electricity is generated and supplied to consumers, how households and firms use energy, and how capital markets operate. In what follows, we highlight barriers and benefits that could be broadly important. We review the evidence on each and highlight potentially important lines of empirical inquiry that are relatively under-explored.

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[21] Alcorta et al. (2014) discuss some of these market failures in the context of industrial energy efficiency.

3.1 Inefficient energy pricing

When the retail price of energy falls below the true social cost, private investment in energy efficiency investments will likely fall short of the socially efficient level. Inefficient energy pricing in LMICs is well-documented (Bates and Moore, 1992) and can occur for multiple reasons. Energy subsidies are one important example. In LMICs, subsidies are sometimes used to make energy services more accessible to low income households (Komives et al., 2005).

McRae (2015) shows how electricity subsidies for low income households can have perverse and unintended impacts on power quality and reliability. If electricity providers receive additional subsidies for serving marginalized neighborhoods, they will have little incentive to invest in the infrastructure and improve the quality of service for those areas. This phenomenon can leave subsidized customers ‘trapped’ in a poor power quality equilibrium.

Our theoretical model of the returns on investment in energy efficiency serves to motivate a different kind of vicious cycle. In theory, energy price subsidies will reduce consumers’ willingness to pay for energy efficiency improvements because the consumer will not fully capture the returns on her investment. It follows that households paying subsidized energy prices will under-invest in efficiency.[22] If consumers are under-invested in efficiency, this could make it more difficult to reduce energy price subsidies. We posit that subsidizing energy efficiency improvements, versus energy prices, could offer a more sustainable path to affordable energy service access.

We are not aware of any research that tests for a causal relationship between energy subsidies and energy efficiency investments. But recent empirical findings are broadly consistent with this idea. For example, in the Kyrgyz Republic study, authors document an economically significant reduction in electricity consumption following a reduction in energy subsidies (McRae and Meeks, 2016). In a related but different setting, (Chakravorty et al., 2019) find that farmers in Bangladesh place more value on a water saving technology when they pay a higher (less subsidized) marginal price for water.

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[22] This assumes consumers are attentive to pricing. Inattention to energy subsidies and pricing structure may further complicate this relationship. Behavior consistent with inattention to energy prices has been documented in LMICs with increasing block price structures (Stojanovski et al., 2018; McRae and Meeks, 2016).

3.2 Non-technical losses

Electric power transmission and distribution sector losses are substantial in low and middle income countries – averaging 18.4% and 10.3%, respectively in 2014.[23] Distribution sector losses include metering inefficiencies, billing inefficiencies, and electricity theft. If consumers do not pay for all the electricity that they consume (either because they are not metered, or do not receive bills, or have little incentive to pay the bills that they receive), this amounts to another form of subsidy that will reduce willingness to pay for energy efficiency improvements.

Governments have begun to pursue a variety of reforms aimed at improving efficiency in electricity distribution and revenue collection, such as replacing fixed monthly fees with metered consumption (McRae, 2015) and installing pre-paid meters (Jack and Smith, 2019) and smart meters (Meeks et al., 2020). If these reforms are successful at eliminating these implicit subsidies, more consumers will be required to pay for their energy consumption. To the extent that revenue collection efficiency improvements raise energy costs for low-income households, this could undermine energy access objectives. Combining energy efficiency investments with distribution sector reform offers a way to mitigate these impacts.[24] We are unaware of any empirical research investigating the impacts of distribution sector reforms on energy efficiency investments and note that this could be a fruitful area for future work.

3.3 Poor power quality

Within our conceptual framework, a household's WTP for an efficiency improvement is defined to be the sum of benefits delivered across all hours in which energy services are consumed. In many LMICs, power supplies are unavailable or intermittent, sometimes for hours each day (Allcott et al., 2016; Samad and Zhang, 2017). Absent storage solutions, poor power quality reduces the utilization rates of electric appliances. In theory, this reduces the returns on capital investments in more energy efficient appliances.

Does poor power quality actually reduce demand for energy efficiency investments? We are unaware of any direct empirical test of this hypothesis, although there is some evidence that unreliable power supply (e.g., frequent outages) and poor power quality (e.g., voltage

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[23] Electric power transmission and distribution losses include losses in transmission between sources of supply and points of distribution and in the distribution to consumers. Data are reported as a % of output. Calculations are for 2014 and based on the IEA Statistics (OECD/IEA, 2018) (http://www.iea.org/stats/index.asp).

[24] https://www.usaid.gov/energy/efficiency/developing-programs

spikes) can influence the kinds of appliances a household chooses to own (McRae, 2010). If there is also a causal relationship between power quality and demand for energy efficiency improvements, this would have broader implications for the social costs imposed by poor power quality because it suggests that reliability improvements could enhance access to energy services through multiple channels.

3.4 Capital market failures

In OECD countries, interventions that aim to mitigate capital market failures and relieve credit constraints have had minimal impacts on demand for energy efficiency improvements (Borgeson et al., 2012). In contrast, research exploring similar questions in developing and emerging economies find that capital constraints can be a significant limiting factor.[25] Gertler et al. (2016) show that credit constraints impact the timing of asset acquisitions. Berkouwer and Dean (2020) find that limited access to capital can explain low adoption of highly cost-effective, energy efficient cooking stoves in Nairobi. More precisely, these authors find that providing access to short-term credit doubles households' WTP and closes the energy efficiency gap over the period of the loan. This suggests that providing access to credit could accelerate adoption of cost-effective energy efficiency improvements in contexts where credit constraints bind.

4 Returns on Energy Efficiency Investments

Empirical analysis of the economic impacts of energy efficiency improvements typically emphasize reductions in energy consumption and expenditures, associated reductions in emissions (such as reduced pollution from electric power plants), and to a lesser extent, the welfare gains associated with demand rebound (see, for example, (Allcott and Greenstone, 2017)). These are first-order benefits in HIC settings. However, in LMIC settings, there are other considerations and value streams that could be potentially important. In what follows, we identify three in particular: enhanced access to energy services, hyper-local health impacts of fuel switching, and industrial productivity enhancements.

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[25] There is an extensive literature in development economics addressing the role of credit in technology adoption. For examples see: Duflo et al. (2008), de Mel et al. (2008), Karlan et al. (2014), Giné and Yang (2009), Banerjee et al. (2015), and Ben Yishay et al. (2017).

4.1 Energy efficiency investments can expand energy access:

Enhanced access to affordable and reliable energy services is an important policy priority in many LMICs. In some areas, expanded access is being achieved via increased investment in off-grid sources. Between 2010 and 2017, the percentage of low energy access countries that have adopted measures in support of mini-grids and solar home systems increased from 15 to 70 percent.[26]

Electricity supply from these off-grid sources is often capacity constrained. When supply is constrained, the returns on an energy efficiency investment can manifest not only in the form of reduced energy service costs, but also as an increase in the level of feasible energy service consumption. Consider, for example, a household that accesses electricity via a micro-grid or private solar home system. Desirable energy services, such as a television or refrigeration or space cooling, are highly valued by off-grid consumers and can provide informational and health benefits.[27] When power supply is limited, however, these energy services may be hard to access with standard appliances. Super-efficient appliances can bring these energy services within reach. This represents a form of rebound, but one that stems from addressing physical capacity (along with budget) constraints.

The potential for efficiency investments to expand energy service access is not limited to off-the-grid market segments. Energy efficiency improvements can also play an important role in compensating for a weak grid. Battery storage costs have dropped by more than 80% over the past decade.[28] If costs continue to fall, battery storage could provide a cost-effective way to compensate for unreliable grid services (Phadke and Park, 2019). But demand-side storage solutions will be of limited use when paired with inefficient appliances. In contrast, demand-side investments in battery storage coupled with super-efficient appliances could offer substantial improvements in the reliability of energy service delivery.

Adoption of energy efficient technologies, especially those that reduce peak demand, can also reduce the intermittency of electricity services delivered by a congested grid. Such positive externalities, which have provided an important rationale for investments in lighting efficiency improvements among multilateral donors (World Bank, 2016; Sarakar and Sadeque, 2010), were documented by Carranza and Meeks (forthcoming). They found that intensely

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[26] This is from the World Bank RISE Executive Summary (2018). Found here: https://rise.worldbank.org/data/files/reports/rise$_2$018$_{-e}xecutive_{s}ummary.pdf$

[27] Per the 2018 appliance sales database compiled by GOGLA, the global association for the off-grid solar energy industry.

[28] Bloomberg New Energy Finance - https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf

distributing energy efficiency lightbulbs in the Kyrgyz Republic alleviated demand congesting the electricity distribution system, such that outages were reduced.

It seems clear that energy efficiency investments offer one approach to expanding energy access. But can efficiency improvements offer a more cost effective means of advancing energy access objectives (as compared to supply side investments in infrastructure expansion and improvements)? In our view, we do not yet have the evidence we need to assess this important cost-effectiveness comparison.

Whether households and firms are willing and able to pay for the efficiency improvements that can deliver reliability improvements or increased access to energy services is another open question. If private WTP is not sufficient to cover cost, energy efficiency investments could still offer a socially cost-effective way to meet energy access goals. But more empirical evidence is needed to ascertain whether policy interventions to accelerate energy access through increased efficiency investments are warranted.

4.2 Energy efficiency investments can deliver local health benefits:

In low income countries, some important efficiency improvements involve switching away from (or reducing) the use of traditional fuels such as kerosene, charcoal, and biomass. Indoor air pollution generated by these fuels is considered a leading environmental cause of deaths in the developing world (Hanna et al., 2016). If switching to an improved cooking stove that burns less of a given fuel – such as charcoal (Bensch and Peters, 2013) or firewood (Bensch and Peters, 2015) – releases less indoor air pollution, one might reasonably expect that this would lead to improved health outcomes.

The empirical evidence on these direct health benefits is mixed. A study of improved cooking stoves in India found no long-run health improvements, likely because households did not maintain the stoves or continue their use (Hanna et al., 2016). The practice of stove stacking provides another reason cookstoves may not result in health benefits. In contrast, studies on the impacts of shifting households away from kerosene to fuel lighting services indicate evidence of health benefits. Barron and Torero (2017) found that household electrification, which shifted lighting services from kerosene to electricity, reduced fine particulate matter concentrations and decreased acute respiratory infections in El Salvador.[29] Rom and Günther (2019) conduct a randomized field study in rural Kenya where they measure the impact of households switching from kerosene lighting to solar. They find a moderate re-

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[29] The extent to which the intervention reduced the cost per unit of lighting services, and therefore constitutes an energy efficiency improvement, is unclear however.

duction in symptoms related to dry eyes for both children and adults as well as a reduction with symptoms related to respiratory illnesses for children.

In sum, the available research suggests that hyper-local health benefits are potentially important source of benefits in some settings. Where appropriate, these benefits should be incorporated in an comprehensive evaluation of the returns on efficiency-enhancing investments.

4.3 Energy efficiency investments can enhance productivity:

We have argued that energy efficiency improvements can be welfare enhancing in the residential sector when households face energy supply constraints or intermittent supply. There is also some early evidence that energy efficiency investments can alleviate binding constraints on firm productivity in LMIC settings.

One source of productivity gains has been traced back to the impacts of more efficient lighting on working conditions. Consider, for example, a factory operating in a hot climate. In a HIC, factories typically have have air conditioning to ensure comfortable working environments. In LMICs, however, it is not uncommon for factories to operate without cooling. This has potential implications for industrial productivity because high temperatures have been shown to reduce cognitive abilities and labor productivity (Somanathan et al., 2018). Adhvaryu et al. (2019) document worker productivity increases in Indian garment factories following a switch to more efficient lighting. They attribute these increases to improved working conditions. Because efficient lighting emits less waste heat than traditional bulbs, more efficient lighting reduces indoor temperatures in the workplace.

Ryan (2018) investigates the impacts of energy efficiency improvements among energy-intensive Indian manufacturing plants. He uses an experimental research design to generate random variation in energy efficiency improvements across firms. Whereas projected energy savings are on the order of ten percent, Ryan estimates a 9.5 percent *increase* in energy consumption once factor inputs (e.g., skilled labor) had adjusted. He argues that this sizeable realization gap is consistent with moderate increases in energy productivity leading to higher capacity utilization and energy use, as well as a re-optimization of the input mix following the efficiency upgrade that involved increasing skilled labor inputs.

The existing empirical literature on the productivity impacts of energy efficiency investments is insightful but limited. We speculate that there could be other sources of productivity benefits associated with energy efficiency improvements in the agricultural sector. For example, in weak-grid and off-grid areas, energy efficient water pumps may enable different crops to be grown than previously were feasible or enable agricultural activity to occur throughout more months of the year. Energy efficient refrigeration could permit shops to stock and sell different types of produce, which may have health and nutrition benefits. These channels could positively impact food security, a concern common to many LMICs.[30]

4.4 Reframing the research agenda

We have highlighted three potential sources of benefits that could play a role in driving demand for energy efficiency investments - and rationalize policy interventions aiming to accelerate these investments. In our view, these potential sources of value have been understudied. Credible evidence of the relative importance of these and other benefit streams could usefully guide future policy intervention.

Advancing research along these lines is easier said than done. For example, disentangling the productivity implications of energy efficiency investments is far more complicated than estimating net impacts on energy demand. The causal effect of a weak grid on demand for energy efficiency is more challenging to isolate as compared to the relationship between income and willingness to pay for efficiency improvements. We are starting to see researchers rise to these challenges. Further progress along these lines will be important as LMIC policy makers work to negotiate tensions between economic development and sustainability objectives.

5 Rethinking Energy Efficiency Policy

Energy access is seen as a critical input to sustaining basic needs and accelerating economic development. The United Nations has adopted the 2030 Agenda for Sustainable Development, which includes the goal of providing universal access to affordable, reliable, sustainable, and modern energy. Investments in energy efficiency have the *potential* to advance these energy access goals by expanding energy service consumption possibilities and compensating for a weak grid. With this potential in mind, organizations such as CLASP and Efficiency for Access are actively promoting the dual goals of increasing energy access and energy efficiency.[31]

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[30] This is discussed further here: https://efficiencyforaccess.org/themes/agriculture-energy-efficiency

[31] For example, the Efficiency for Access website states "With similar shifts in efficiency and cost, other appliances appropriate for off- and weak-grid settings can enable consumers to reach even higher levels of energy access faster."(https://efficiencyforaccess.org/why-efficiency-for-access)

It is important to acknowledge that energy access objectives are not perfectly aligned with the energy savings goals that more typically motivate energy efficiency programs and policies. For example, in settings where poverty alleviation via improved energy access is a central objective, policies should target those technologies that can have the largest impact on the welfare of disadvantaged households (e.g., lighting and fans demanded by low-income families who tend to consume relatively little energy). But these need not be the interventions that deliver the largest energy savings.

In addition to cost effectiveness considerations, the distribution of policy impacts will be of particular concern in settings where poverty alleviation is the driving impetus for policy intervention. Assuring fairness in the distribution of policy impacts may require some efficiency trade-offs. For example, raising electricity prices to more accurately reflect supply costs and energy-use externalities is a standard economic prescription for efficient policy. But if this policy results in an inequitable or regressive distribution of benefits, this would run counter to the larger policy goals and objectives.

The appropriate balance to strike between access goals and sustainability objectives – or economic efficiency and equity concerns – will vary across LMIC settings. Ideally, energy efficiency policies and programs will be designed to accommodate the political and institutional context in which they are being deployed. In what follows, we first discuss how more standard approaches to energy efficiency program evaluation may be ill-suited to contexts in which energy access goals are a development priority. We then offer some examples of policy designs that respond directly to LMIC priorities and challenges.

5.1 Aligning Metrics with Policy Objectives

An extensive amount of work has been done to evaluate a range of energy efficiency programs and policies in North America and Europe. The standard evaluation approach compares energy efficiency investments and program costs against social benefits (which typically emphasize reduced energy consumption and associated reductions in environmental damages). If the stream of discounted benefits exceeds costs, the program is deemed socially cost effective.

To implement this cost-benefit comparison empirically, the efficiency-induced energy savings must be estimated. Reductions in energy consumption caused by a proposed efficiency improvement or program are either calibrated using ex ante projections or estimated ex post using comparisons between the efficient technology adopters and non-adopters.[32] These es-

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[32] Ideally, experimental and quasi-experimental research designs are used to mitigate biases introduced by unobservable differences in adopters and non-adopters that can confound these comparisons (see, for

timates can be augmented to account for other sources of benefits, such as rebound effects (Fowlie et al., 2018).

This standard approach will fail to capture the potential benefits we introduce in Section 4. Consider, for example, an energy efficiency program that is designed to increase access to affordable energy services in an area served by capacity-constrained distributed generation or an unreliable grid. Such a policy would be predicated on the assumption that increased access to reliable energy service supply will generate quality of life enhancements and other benefits (such as productivity improvements or positive network externalities) through increased consumption of energy services. The challenge is that the benefits of improved energy access are notoriously hard to measure or capture.

One approach to assessing the value of the contributions made by efficiency improvements would compare the costs of efficiency investments against the costs of providing increased energy service provision via supply-side investments. Suppose, for example, we take as given a goal of improving the reliability of electricity services by a well-defined increment. We can compare the costs of achieving this objective via demand-side investments in energy efficiency and storage against the costs that would be incurred to achieve the same improvement with investments in power system infrastructure. This can offer a pragmatic and tractable alternative in cases where the welfare benefits delivered by an access improvement are difficult to measure.

A second concern with applying standard cost-benefit evaluation in LMIC contexts is that the standard approach takes electricity supply and the price of electricity as exogenous. In fact, widespread energy efficiency improvements could impact these supply-side parameters via economic, political, or institutional channels. Across a number of LMIC contexts, the prior literature has demonstrated how electricity infrastructure investments can be disproportionately allocated according to potential for economic growth (Dinkelman, 2011) and political and institutional factors (Min and Golden, 2014; Baskaran et al., 2015; Mahadevan, 2019; Min, 2019). Taken together, these empirical findings suggest that an efficiency-induced change in energy consumption patterns could impact the electricity supply equilibrium in unexpected ways. The direction of these supply-side effects are ex ante ambiguous. If efficiency improvements increase revenue collection, electricity supply could improve. If efficiency improvements increase electricity demand (i.e., backfire), this could exacerbate reliability issues. Research that investigates the equilibrium effects of widespread energy efficiency improvements would be an important complement to microeconomic studies

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example Raina Gandhi (2016)).

of household and firm level impacts.

5.2 Energy Efficiency Policy Innovation

The past several decades have witnessed a proliferation of policies that aim to increase the level of investment in demand-side energy efficiency improvements.[33] Policy designs vary in terms of how they aim to influence or change private investment decisions. Some are designed to correct market failures that stand in the way of efficient investment. Others are designed to compensate for barriers and distortions that are difficult to eliminate. Increasingly, governments are deploying a mix of policy instruments to promote energy efficiency improvements.

Until recently, most of these policy interventions could be found in HICs. But the percentage of countries with advanced energy efficiency policy frameworks is quickly growing, up from 2 percent in 2010 to 25 percent in 2017 (World Bank RISE, 2018). Although the value added by policy intervention in LMIC settings is potentially large, so are program implementation challenges (Singh et al., 2012). For example, a limited capacity to raise revenues limits the government's ability to finance energy efficiency subsidies, tax incentives, and other programs commonly deployed in HICs. Limited resources and governance challenges can limit the effectiveness of building codes and appliance standards which rely on meaningful enforcement and program oversight.

In the longer run, investments in capacity building and improved governance can create an enabling environment for a broader range of policies. More research will be needed to identify the institutional constraints that stand in the way of high impact policy interventions. In the short run, energy efficiency programs and policies must work within these constraints.

An early example of a program that was designed specifically for low income country contexts is the Clean Development Mechanism (CDM). This program allows HICs with commitments to reduce their emissions under the Kyoto Protocol to meet those commitments by investing in projects, including energy efficiency interventions, in developing countries. These projects earn a certified emission reduction (CER) credit for each ton of GHGs that they mitigate.[34] Although advocates of the CDM have argued that the program has accelerated the diffusion of "clean" technologies to LMICs, there is evidence to suggest that energy efficiency investments supported by CDM would have been made regardless (Popp, 2011).

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[33] A detailed discussion of energy efficiency policies can be found in Chapter 9 of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

[34] Specifics on the CDM can be found through the United Nations Framework Convention on Climate Change website: https://cdm.unfccc.int/index.html.

The inability of project proponents to definitively demonstrate the 'additionality' of CDM investments has been a leading concern. Another concern is that other potential benefits from CDM investments, such as poverty alleviation, are under-emphasized by the program, such that CDM investments are not targeted in a way that maximizes social impact in the host countries (Zhang and Wang, 2011).

Since the CDM's introduction in 2007, we have seen further experimentation with energy efficiency programs that are designed specifically to suit LMIC contexts. In what follows, we consider two examples that take an unconventional approach to mobilizing energy efficiency investments. Both policies target investments that have the potential to confer both energy access and sustainability benefits.

Energy efficiency revolving funds: The available evidence suggests that capital constraints may be a significant barrier to cost-effective investments in energy efficiency in LMIC settings. In HICs, funding from government budget allocations or revenues collected via higher electricity rates are routinely used subsidize increased energy efficiency. In LMICs, the ability for governments' to raise taxes or increase electricity rates to finance energy efficiency is generally more limited.

Energy efficiency revolving funds (EERFs) are designed to work within these binding resource constraints. EERFs are funded through an initial capitalization, often with the support of multilateral donors and banks, such as the World Bank or Global Environment Fund. After the initial funds injection, EERFs are designed to be financially self-sustaining. The replenishment of the EERFs relies on borrowers repaying their loans.

EERF loans are targeted exclusively towards energy efficiency upgrades. The financing model is based on the premise that, once the energy efficiency investment has been made, the borrower's energy expenditures will be lower than they would have been without the investment. As a borrower benefits from the energy savings via a lower energy bill, she can repay her debt to the revolving fund. As loans are repaid, more funding is available for the next borrower.

Although this EERF model does not require a steady stream of government revenue to sustain its operation, there are other challenges that can complicate implementation. For example, writing a legally binding contract to establish the terms of repayment requires sufficient institutional or legal capacity to underwrite and enforce these contracts. EERFs often use electricity bills as the vehicle for loan repayment. Installments are added to the electricity bill. For this to work well, electricity consumption must be reliably metered and collected. Lastly, to establish a credible contract for repayment, the projected energy savings from a particular efficiency upgrade should be well-calibrated to the setting. This will provides the potential borrower with the information she needs to evaluate the EERF value proposition. As we note above, non-technical losses, billing inefficiencies, and energy modeling calibration errors can be substantial in LMIC settings.

To date, the empirical evidence on these EERF programs is limited to case studies tracking program operations.[35] Case studies documenting the performance of EERFs across a range of locations – including Armenia, Romania, India, and Mexico – indicate that these programs have been 'successful' insofar as the revolving funds continue to revolve. We are not aware of any empirical studies investigating the causal impacts of EERFs. This presents an opportunity for empirical researchers to investigate how this policy intervention is impacting investment choices and subsequent demand for energy services with an eye towards the nuanced set of potential benefits that we have discussed.

Bulk procurement and distribution programs: A large scale initiative currently underway in India, the Unnat Jyoti by Affordable LEDs for All (UJALA) program, provides another example of how an energy efficiency program can be tailored to leverage strengths and work within the constraints of an LMIC setting. This program targets lighting which accounts for an estimated 18 to 27% of the total residential electricity consumption in India (PEG, 2017). Prior to the introduction of the program, incandescent lighting was ubiquitous. Since the program launched in 2014, more than 350 million LED bulbs (which require one seventh of the energy required by incandescents) have been purchased. UJALA has been credited with transforming the Indian lighting market.

The program was designed to sustain markets for energy efficiency and significantly reduce the energy costs paid by Indian consumers.[36] Notably, energy savings over the life of the technology easily offset the additional upfront cost of LED bulbs even *before* the program was introduced in 2012. Market failures, such as asymmetric information, fragmented retail markets, credit constraints, and transaction costs, presumably explain the low adoption rates prior to the program.

UJALA combines three important components to address these barriers. The first is bulk procurement. The implementing agency issues online tenders requesting bids from LED bulb manufacturers. Suppliers are selected through online reverse auctions. Procurement volumes have rapidly increased over the course of the program, and now exceed 50 million bulbs per

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[35] See for example, the discussion in the ESMAP/World Bank's Live Wire Note Series. 2018/88. Aditya Lukas. "Financing Energy Efficiency, Part 1: Revolving Funds."

[36] Source: http://www.pmindia.gov.in/en/news$_{u}pdates/pm - launches - scheme - for - led - bulb - distribution - under - domestic - efficient - lighting - programme - in - delhi/$.

auction. Procurement auctions have been highly competitive, presumably because bulk procurement puts the implementing agency in a strong bargaining position. LED prices have dropped by more than 80% since the start of the program. In 2019, UJALA LEDs were selling at a price of 70 Indian rupees per LED bulb.[37]

A second distinguishing feature of the program is the distribution model which leverages government networks and infrastructure. The implementing agency, together with electricity distribution companies, distribute the LED bulbs across Indian service territories via pre-existing customer service networks. This reduces distribution and transaction costs on both the supply and demand side.

A third component of the program addresses potential information barriers and failures. UJALA bulbs are highly standardized so that the value proposition is uniform across India. This facilitates mass marketing initiatives via television, newspapers, mobile advertising vans, and other channels. Marketing materials convey essential information about the bulbs: what they cost, how they perform, and where they are available.

UJALA has many moving parts, and it is not obvious which elements have contributed to the rapid increase in LED penetration over the course of the program. It is also not clear what impacts the program has had on electricity consumption or access to lighting services. As of 2020, the Indian Government estimates that LED bulbs promoted by the UJALA program are saving 47 billion kWh of electricity annually. However, these estimates assume that LED bulbs replace inefficient incandescent bulbs. In fact, market data indicate that LED bulbs are disproportionately replacing CFL purchases. Moreover, concerns have been raised that UJALA bulbs are not reaching low income households in rural areas (Chunekar et al., 2017).

Empirical evaluations of CDM projects' impacts have generated valuable insights into what elements have worked (or failed to work) within that landmark program (Sutter and Parreno (2007), Dechezleprtre et al. (2008), Zhang and Wang (2011), Popp and Tang (2016), PEC (2018), and Mori-Clement (2019)). There is great interest in understanding how more recent policy experimentation is working. For example, the apparent success of the UJALA program has fueled interest in extending the scope to include more technologically complex appliances such as energy efficient televisions and fans. Rigorous empirical research investigating how these newer programs are impacting technology adoption, access to services, and electricity consumption patterns will be important to inform policy refinements and further

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[37] It is difficult to disentangle the effect of bulk procurement on purchase prices from the secular downward trend in LED prices. Notably, UJALA retail prices are are less than half that of the retail (Fowlie and Phadke, 2018).

experimentation going forward.

6 Conclusions

As economies develop and incomes rise, demand for energy services will continue to increase. The extent to which this increase will drive increases in energy consumption and associated environmental impacts will depend to a significant extent on the investment choices of households and firms. Several decades of empirical economics research has explored how agents make energy efficiency investment choices and how these investments generate private and social returns. However, much of this work has been conducted in high income countries, raising questions about the transferrability of past research insights to LMIC contexts.

In some respects, the basic neoclassical framework that underpins much of the empirical research on energy efficiency investments can be readily applied to any context. Questions about how efficiency investments impact energy consumption patterns, or how households value efficiency improvements, are equally relevant across high and low income contexts and have been usefully applied in each. Our survey of the empirical work conducted in LMICs highlights some instances where energy savings manifest as expected and other instances where realized savings fall below projections. Rigorous empirical evidence on the extent of the efficiency gap in LMICs is limited, but the existing evidence suggests the gap could be substantial.

Recent studies conducted in low income areas have found that consumers' willingness to pay for energy efficiency improvements falls below private benefits. This suggests an important role for market failures and barriers. It is difficult to design interventions to accelerate efficient investments if we do not understand what stands in the way. We argue that energy subsidies, poor power quality, non-technical losses, and capital constraints are all potentially important barriers that have been under-explored empirically.

On the benefits side, policymakers and donors are highlighting energy access benefits as an important rationale for accelerating efficient investments in LMIC contexts. However, research investigating the extent to which this potential can actually be realized lags behind. Standard approaches to evaluating the returns on efficiency investments are not well suited to capturing reliability improvements or access enhancements or productivity increases. Researchers are developing innovative ways to measure and evaluate these indirect impacts. This line of research is exciting and critical to informing policy design and implementation.

Finally, once programs and policies have been put in place, there is also tremendous value in ex post evaluations of energy efficiency programs. Increasingly, LMICs are experimenting with the energy efficiency programs. We highlight two examples that have been designed to accommodate policy priorities and capacity constraints in LMIC settings. Empirical research that objectively evaluates the impacts that these and other programs are having will inform the course of future policy initiatives.

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APPENDIX:

Table A1: Summary statistics from WTP experiment in Kyrgyz Republic

	Mean	Std dev
Household characteristics		
Own not rent	0.91	0.29
Individually metered	0.99	0.10
Adobe material	0.42	0.49
Number rooms	4.36	2.06
Detached house	0.76	0.42
HH size (people)	3.47	1.74
HH Head sec school	0.82	0.39
Average electricity consumption		
Summer (kWh/month)	245.79	133.07
Winter (kWh/month)	567.30	441.49
Electricity-using durables		
Appliances total	8.25	3.23
Total bulbs	5.99	2.36
Total incandescent	5.85	2.30
Total CFLs	0.13	0.67
Electricity-saving behaviors		
Think about saving	0.96	0.21
Do something to save	0.89	0.31
CFL familiarity & beliefs		
Know of CFLs	0.54	0.50
Know stores to purchase	0.44	0.50
CFLs use less electricity	0.29	0.46
Saving payback CFL cost	0.20	0.40
Report using CFLs	0.01	0.12

Table A2: Correlates of demand: bids for CFL and baseline characteristics

	(1) Bid	(2) Bid	(3) Bid
Educ HH Head (years)	1.313	1.095	1.125
	(0.687)	(0.683)	(0.668)
Adobe house	-9.395*	-8.940*	-8.431*
	(4.449)	(4.302)	(4.158)
Know stores to buy CFLs		13.05**	14.34**
		(4.220)	(4.362)
Number bulbs total		2.149*	
		(0.881)	
Days w/out elec			3.231*
			(1.228)
Constant	44.05***	27.30**	33.89***
	(9.179)	(9.527)	(8.543)
N	470	470	470

Notes: Bids are for 1 CFL and in Kyrgyz soms. 1 USD = 48 KGS.
Household characteristics collected via survey in spring 2013.
Standard errors are clustered by transformer and in parentheses:
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$