Bridging the Cooling Gap: Energy Efficiency as a Driver for Appliance Access

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Abstract
Minimum energy performance standards and other appliance energy efficiency policies accelerate efficiency improvements and long-term trends in affordability. This study builds upon CLASP's 2023 publication, "Net Zero Heroes: Scaling Efficient Appliances for Climate Change Mitigation, Adaptation & Resilience," which defines ambitious efficiency targets for ten appliances to meet global net-zero emissions goals and reduce access gaps. It provides estimates of the impact that efficiency-induced affordability improvements can have on cooling appliance access in India, Indonesia, and Nigeria, and presents a long-term policy scenario model with adoption accounting to estimate increases in cooling appliance access by 2050. Doubling the energy efficiency of room air conditioners, fans, and refrigerators by 2030 in line with the SEAD Product Efficiency Call to Action would reduce lifecycle costs by 60% for air conditioners and refrigerators and 58% for fans, expanding access to an additional 320 million, 100 million, and 90 million people, respectively, by 2050—20 percent of the total population for the three countries. The consumer economic benefits are estimated as 210 billion USD per year, 40 billion USD per year, and 35 billion USD per year for room air conditioners, fans, and refrigerators, respectively. The model estimates a decrease in heat-related deaths from increased cooling appliance adoption of approximately 20,000 per year by 2050. Most critically, the analysis shows that with the appropriate increases in air conditioner efficiency, a more than 6x increase in air conditioner use[1] is possible by 2050, while total residential air conditioner energy consumption increases by a factor of less than 2x.

Introduction & Background
As the planet warms, access to cooling appliances and equipment will continue to shift from a luxury service to a necessity. Heatwaves have increased in frequency over the last century due to human influence [1], and 2023 was the hottest year on record [2] [3] [4]. Exposure to dangerous heat can have serious negative impacts on human health [5] [6], global food security [7], and the electric grid [8].

Cooling appliances such as room air conditioners, fans, and refrigerators, play a critical role in building resilience to climate change. Room air conditioners maintain a comfortable indoor climate and significantly reduce exposure to dangerous levels of heat and humidity. In Europe and India alone, expanded room air conditioner ownership could reduce heat exposure for 150 million and 3.8 billion person degree-days[2], respectively [9]. For those unable to afford a room air conditioner, fans offer an affordable cooling alternative. Fans help to regulate core body temperature and reduce the likelihood of heat strokes when the ambient temperature is at or below 42°C [10]. By circulating air, fans also offer a simple defense against disease-carrying insects like mosquitos, which can carry serious vector-borne diseases like dengue fever and malaria [11] [12]. Finally, refrigerators have the potential to unlock an array of social and economic benefits for households by changing the way they secure, prepare, and store food. This can especially liberate women and children from domestic chores and may allow households to generate income through new business opportunities, improving climate change resilience [13] [14].

Many of the people that stand to benefit the most from cooling appliances have yet to purchase them. As temperatures rise and economies develop, a growing number of households will simultaneously need and be able to afford cooling appliances. Of the 2.8 billion people living in the hottest parts of the world, only 8%

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[1] Air conditioner use is the amount of kilowatt hour (kWh) of cooling performed by air conditioners each year.

[2] Person degree days (PDDs) is calculated based on the number of people without AC in their homes who are exposed to maximum daily temperatures above 24 °C.

owned a room air conditioner in 2018 [15]. The International Energy Agency projects the global average rate of household room air conditioner ownership will more than double from just over 30% in 2016 to almost 66% in 2050, with the lion's share of that growth occurring in China, India, and Indonesia, while the United Nations Environment Programme predicts a threefold increase in residential space cooling equipment demand from 2022 through 2050 [16] [17]. For refrigerators, historical appliance acquisition data suggest that adoption will mirror that of televisions, with most households eventually owning the appliance [18].

Expanding access to cooling appliances can address climate and cooling equity concerns and help facilitate a just energy transition by enabling people in the regions most susceptible to climate change to better adapt to rising temperatures. However, failure to achieve improvements in energy efficiency alongside access improvements would have far-reaching negative effects on energy systems and global greenhouse gas emissions. CLASP estimates that global energy demand for room air conditioners, refrigerator-freezers, and fans will increase by 57% from 2023 to 2050 [19]. The pressure to meet this growing demand will make it harder to decarbonize the energy sector and mitigate the effects of climate change.

A complete transition to energy-efficient cooling solutions is needed to both meet the current and future demand for cooling appliances and reduce emissions in line with a global net-zero emissions target. In 2023, CLASP published ambitious net-zero-compatible energy efficiency targets for 10 appliances in its report, *"Net Zero Heroes: Scaling Efficient Appliances for Climate Change Mitigation, Adaptation & Resilience"* (Net Zero Heroes). The efficiency targets for cooling appliances are aligned to existing goals outlined in the Super-Efficient Equipment and Appliance Deployment Initiative's Product Efficiency Call to Action, which aims to double the efficiency of air conditioners, lighting, electric motors, and refrigerators by 2030. The policy ambition required to meet a doubling target will require efficiency improvements at an unprecedented rate. Modeling the impact of such policies requires new impact modeling that is global in scope, focused on long-term change in technology trajectories, and capable of estimating the impact of efficiency on appliance access. This study addresses that need by estimating the impacts that achieving Net Zero Hero (NZH) targets for cooling appliances would have on lifecycle costs, appliance ownership, and climate resilience in three countries with currently low cooling adoption but high projected demand: India, Indonesia, and Nigeria [20]. Cooling appliances were selected because of their direct impact on climate adaptation for globally vulnerable populations.

This study builds upon existing literature that highlights the role that learning curves play in lowering the cost of energy efficiency investments and connects those concepts to a growing body of research on the causes and drivers of energy and appliance access in emerging economies. Van Buskirk et al. found appliance energy efficiency standards have led to long-term declines in lifecycle costs [21]. Abhyankar et al. present examples of accelerated efficiency improvement from policy in Japan and South Korea and demonstrate the potential for policy to double the rate of efficiency improvement and produce significant reductions in energy demand [22]. Similar trends in declining levelized costs have been observed in utility-scale wind and solar in the United States [23]. Other studies have demonstrated the potential to expand or enhance energy access through energy efficiency and provide energy services to more households [24], [25], [26] [27], while Rue du Can et al. have documented a connection between energy efficiency and improvements in the affordability of energy services and access [28]. Finally, Rao and Ummel show that income is the predominant driver of appliance growth in emerging economies [29], while Davis et al. model the projected inequality in air conditioner access and heat exposure between low- and high-income countries and households [30]. This paper builds on these concepts and offers an initial exploration of how the widespread adoption of ambitious appliance energy efficiency policies could affect learning and long-term lifecycle cost trends, thereby enabling greater access to cooling appliances worldwide.

Model Structure, Assumptions, and Limitations

This study assumes that lifecycle cost, i.e., the cost required to purchase and operate a product over its lifetime, is a key driver of adoption and that long-term trends in adoption are driven by the ratio of lifecycle cost to income. Based on this assumption, we developed a stock and financial flows accounting model of how a global acceleration in appliance energy efficiency between 2023 and 2030 or 2035, combined with accelerated long-term trends in energy efficiency improvement, could affect cooling appliance adoption[3] across five income quintiles in three key markets—India, Indonesia, and Nigeria—over the next 26 years. The model asks the question: "If a combination of appliance first cost and operating cost relative to income is the primary constraint on product adoption, how might aggressive efficiency policy acceleration affect the long-term adoption of cooling appliances?" Please see this paper's supplemental materials for the details of the model formulation.

We developed three policy scenarios to model appliance energy use, lifecycle cost, and appliance access over time: business-as-usual (BAU), Net Zero Hero High (NZH-High), and Net Zero Hero Medium (NZH-Medium).

- **BAU:** This scenario assumes appliance efficiency improvements will follow a similar trend to how they did in the past.
- **NZH-High:** This scenario doubles efficiency by 2030—in line with the goals and targets in CLASP's Net Zero Heroes report and the SEAD Initiative's Product Efficiency Call to Action—and then selects the long-term efficiency improvement rate that minimizes appliance lifecycle costs in 2050, leading to the largest improvements in appliance access. Different long-term trends are largely determined by how quickly the price increases with efficiency (i.e., the price elasticity with respect to efficiency), which we estimated from recent market data.
- **NZH-Medium:** This scenario assumes that the doubling of efficiency is accomplished by 2035 (instead of 2030) and that the long-term annual rate of improvement after 2035 is halfway between the rates in the BAU and the NZH-High scenarios.

In the following section, we present the impact of the NZH-High scenario compared to BAU for each appliance. We close with a comparison between the NZH-High and NZH-Medium scenarios to illustrate the effect a five-year delay in achieving the NZH targets would have. These results provide an initial estimate of the magnitude of these effects, and some of the key policy and market parameters that are likely to affect future adoption rates.

While the scenarios in the model are extremely ambitious, and likely politically impractical at the present time, scenarios similar to what are presented here may become more practical in the future as the climate crisis becomes more urgent and more resources become available for accelerating progress in efficiency.

When estimating appliance lifecycle cost, we used commercial electricity tariffs in place of residential energy tariffs. In many countries, governments apply broad based subsidies to address energy affordability concerns in the residential sector. We opted to use commercial electricity tariffs in our analysis because we believed they more accurately reflected the true cost of electricity. However, we acknowledge that cross subsidization may occur in some countries, resulting in higher electricity tariffs in the commercial and industrial sector.

One limitation of the modeling is the assumption of a multi-year payback time in consumer decision-making where the household budget for appliance operating costs limits the ability of consumers to purchase and operate an appliance. Theoretically this limitation could be overcome by policies that "buy down" the incremental cost of efficiency for higher performing products. The model used for this study allows examination of variations in consumer decision-making and policies that can be used to incentivize the purchase of more efficient appliances.

Another limitation to the modeling is that we assumed an increase in the number of appliance users but little change in appliance usage. As a result, the model does not take into account any energy rebound effect that may result from lower operating costs.

[3] When examining changes in appliance adoption, we are interested solely in ownership of the appliance in question irrespective of its efficiency level or star rating.

Finally, the authors also recognize that enforcement and implementation of appliance efficiency policies is unlikely to be 100% enforced. Thus, progress towards meeting ambitious efficiency targets requires a collaborative international effort that can accelerate the rate of efficiency progress for appliances globally. Global efforts will help decrease the supply of less efficient appliances faster making the least efficient designs obsolete and largely unavailable in global markets over the coming decades.

Results

Room Air Conditioners

Impact on Lifecycle Cost: Doubling the efficiency of new room air conditioners globally by 2030 would substantially reduce consumer lifecycle costs. In all three countries, consumer lifecycle cost is more than halved between 2023 and 2050 under the NZH-High scenario (Figure 1). In India, we predict the lifecycle cost of owning and operating a room air conditioner would be 620 United States Dollars (USD) less than under business as usual in 2050.[4] In Indonesia, lifecycle cost declines 54% under the NZH-High scenario, resulting in a 298 USD difference compared to business as usual. Finally, in Nigeria, room air conditioner lifecycle cost is more than 340 USD lower in 2050 compared to business as usual. The consumer economic benefits in our NZH-High scenario are estimated at 200 billion USD per year in India, 7 billion USD per year in Indonesia, and 3 billion USD per year in Nigeria in 2050.

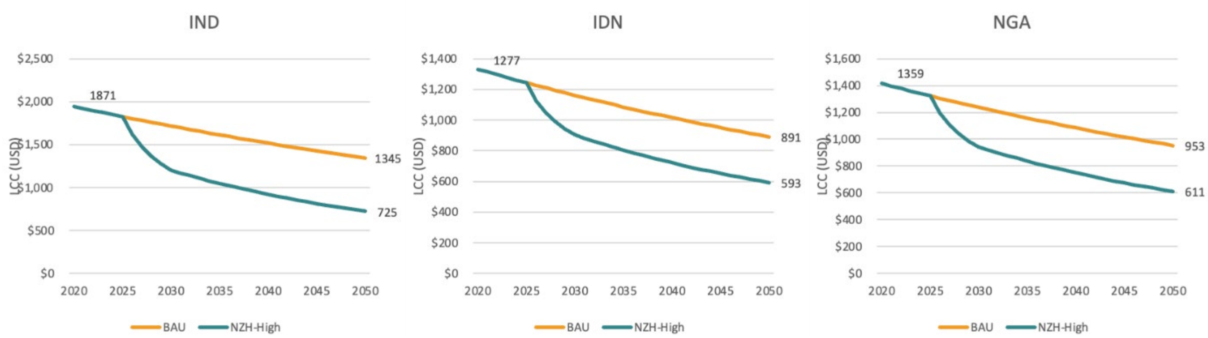

Figure 1: Room Air Conditioner Lifecycle Costs 2020-2050
Source: Authors' analysis
Note: To meet the doubling target, we assume that room air conditioner energy efficiency improves rapidly through 2030, which stimulates a long-term trend of continued improvement at a rate of 4.2% per annum through 2050. In our BAU scenario, we assume a constant efficiency improvement rate of 1% per annum. The labeled values in the figure represent room air conditioner lifecycle costs in 2023 (left) and 2050 (right).

Impact on room air conditioner access: Under business as usual we estimate that 224 million households across India, Indonesia and Nigeria will gain access to room air conditioners by 2050 due to increasing incomes and lifecycle cost declines. If the efficiency of new room air conditioners were doubled by 2030, the additional efficiency gains and corresponding lifecycle cost decreases would make them affordable for more households, accelerating access. In India, room air conditioner access increases 4x from 85 million households in 2023 to 334 million households in 2050 under the NZH-High scenario. In Indonesia, access increases 5x from over 7 million households in 2023 to over 40 million households in 2050. Finally, in Nigeria, room air conditioner access increases by a staggering 8x, growing from nearly 2 million households in 2023 to nearly 16 million households in 2050. We estimate that, across the three countries, an additional 72 million households—approximately 310 million people—would have access to a room air conditioner in 2050 under the NZH-High scenario compared to business as usual.

We divided households into five quintiles of equal size based on household income and estimated room air conditioner access for each to assess the differential impact that meeting the doubling target would have across income groups. Figure 2 shows the percentage of households in each income quintile with room air

[4] All dollar values in 2050 are adjusted for inflation.

conditioner access in 2050 in the BAU scenario and the percentage point increase in access under the NZH-High scenario. Increases in room air conditioner access are smallest for groups that have low incomes in absolute terms. While the access benefits from improved efficiency are substantial, it appears that without additional intervention, room air conditioners will remain unaffordable for many lower-income households. Achieving the doubling target for room air conditioners would have the greatest impact on low- and middle-income quintiles in India. In Nigeria, the middle- and upper-income quintiles would benefit most. In Indonesia, all five income quintiles would experience large access gains.

Expanding access to air conditioning can reduce the heat burden during heat waves. Room air conditioners have the potential to reduce mortality by alleviating extreme indoor temperatures. Between 2022 and 2050, we estimate that achieving the NZH target for room air conditioners would help to avoid over 377,000 premature heat-related deaths across the three countries studied, including 321,000 premature deaths in India, 8,150 in Indonesia; and 48,100 in Nigeria.

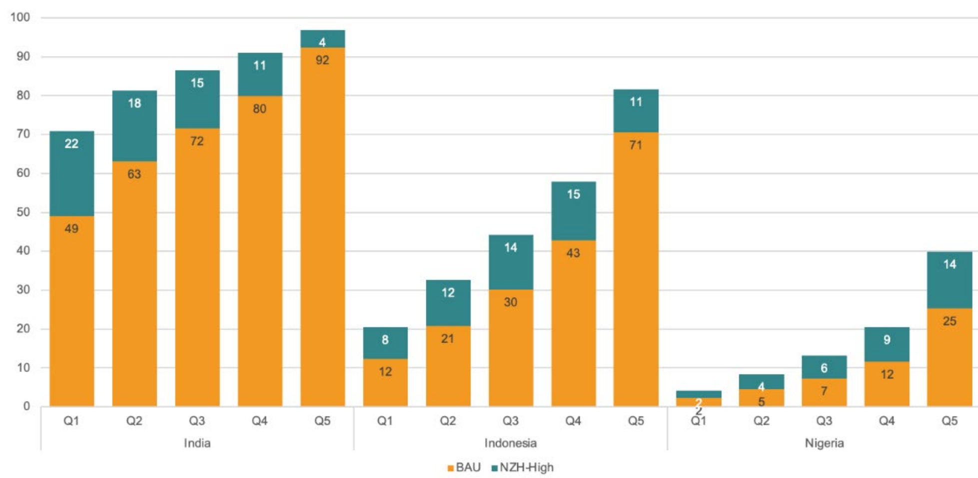

Figure 2: Room Air Conditioner Access by Income Quintile in 2050
Source: Authors' analysis
Note: This figure shows the percentage of households with access under BAU in 2050 (orange) and the additional households that would gain access if room air conditioner energy efficiency were doubled by 2030 under the NZH-High scenario (teal). The estimated households per quintile in 2050 is 78,240,857 in India, 17,050,132 in Indonesia, and 18,121,819 in Nigeria.

Impact on National Energy Use: Across the three countries, room air conditioner ownership increases substantially in the NZH-High scenario due to declines in lifecycle cost. By 2050 the average household in India and Indonesia will own more than one air conditioner. Despite these large increases in access and ownership, we estimate significantly smaller increases in national room air conditioner energy use under the NZH-High scenario compared to business as usual. Figure 3 shows the relative increase in national room air conditioner energy use from 2020 to 2050. For all three countries, energy use is significantly lower in the NZH-High scenario compared to the BAU scenario.

According to our model, we estimate a 1.8x increase in room air conditioner energy use across all three countries under the NZH-High scenario. In India we predict a 1.8x increase in national room air conditioner energy use from 482 gigawatt hours per year in 2023 to 885 gigawatt hours per year in 2050. In Indonesia, we estimate that national room air conditioner energy use will climb to 73 gigawatt hours per year in 2050 from 40 gigawatt hours per year in 2023, a 1.8x increase. In Nigeria, we predict a 2.4x increase in national room air conditioner energy use from nearly 9 gigawatt hours per year in 2023 to 21 gigawatt hours per year in 2050. In all three countries, there is an initial surge in energy use as more households purchase room air conditioners. However, growth in energy use after this initial 10-year period flattens or increases more modestly as efficiency improves. Under business as usual, room air conditioner ownership would increase 4x between 2023 and 2050, resulting in a 3.8x increase in energy use. This surge in demand would put significant strain on the electric grid and lead to higher emissions if the power sector has not yet decarbonized.

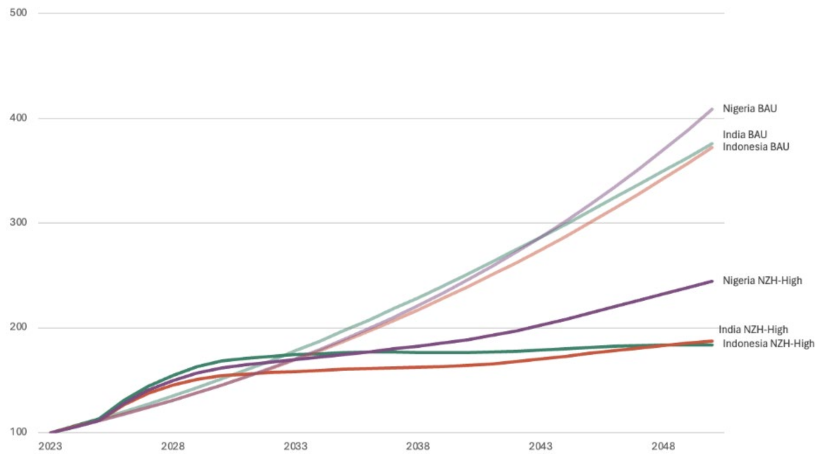

Figure 3: National Room Air Conditioner Energy Use 2023-2050 (Indexed)
Source: Authors' analysis
Note: All room air conditioner energy use values (in gigawatt hours per year) were indexed to room air conditioner energy use in 2023.

Fans
Impact on Lifecycle Cost: Doubling the efficiency of fans by 2030 would reduce fan lifecycle costs significantly between 2023 and 2050 (Figure 4). In India, we predict fan lifecycle costs will be 70 USD lower under the NZH-High scenario in 2050 compared to business as usual. In Indonesia, lifecycle cost declines 45% under the NZH-High scenario, resulting in a cost that is 33 USD lower compared to BAU in 2050. In Nigeria, consumer lifecycle cost is 38 USD lower in 2050 compared to BAU. Overall, the consumer economic benefits for fans are estimated at 36 billion USD per year in India and 3 billion USD per year in both Indonesia and Nigeria in 2050.

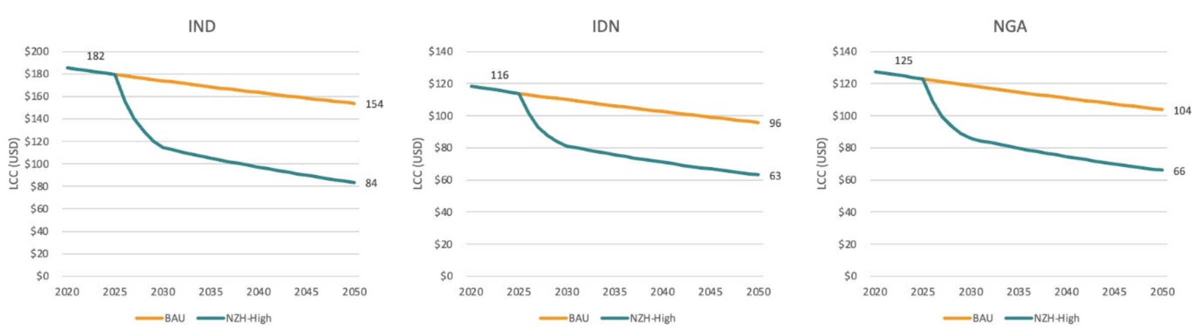

Figure 4: Fan Lifecycle Cost 2020-2050
Source: Authors' analysis
Note: In the NZH-High scenario we assume that fan energy efficiency improves rapidly through 2030, which stimulates a long-term trend of continued improvement at a rate of 2.5% per annum through 2050. In the BAU scenario, we assume a constant efficiency improvement rate of 0.5% per annum. The labeled values in the figure represent fan lifecycle costs in 2023 (left) and 2050 (right).

Impact on Fan Access: We predict that fan access will increase significantly in all three countries under business as usual due to rising household incomes and lifecycle cost declines. Under the BAU scenario, we estimate that an additional 164 million households in India, Indonesia and Nigeria will have access to fans in 2050. However, access can be accelerated in all three countries if a collective global doubling target is met by 2030. We predict that an additional 24 million households—approximately 105 million people—across the three countries would own a fan by the end of 2050. In India, fan access increases 1.4x from 258 million households in 2023 to 365 million households in 2050. In Indonesia, fans access increases 1.5x under the NZH-High scenario from over 48 million households in 2023 to over 71 million households in 2050. Finally, we estimate Nigeria will witness a nearly 3x increase in fan access from 24 million households in 2023 to nearly 65 million households in 2050.

Doubling fan efficiency by 2030 would lead to higher fan access across all income quintiles, with the largest improvements in the bottom two income quintiles. Figure 5 shows the additional gains in fan access by income quintile for each country. In the NZH-High scenario, fan access would increase by an additional 5 to 11 percentage points in the first income quintile and an additional 4 to 11 percentage points among households in the second income quintile.

Expanding access to fans can reduce the heat burden during periods of elevated ambient temperatures brought on by heat waves and other severe weather events. Between 2023 and 2050, fans would avoid over 47,300 premature heat-related deaths across the three countries studied under the NZH-High scenario, including over 23,000 premature deaths India, 1,300 in Indonesia, and 23,000 in Nigeria.

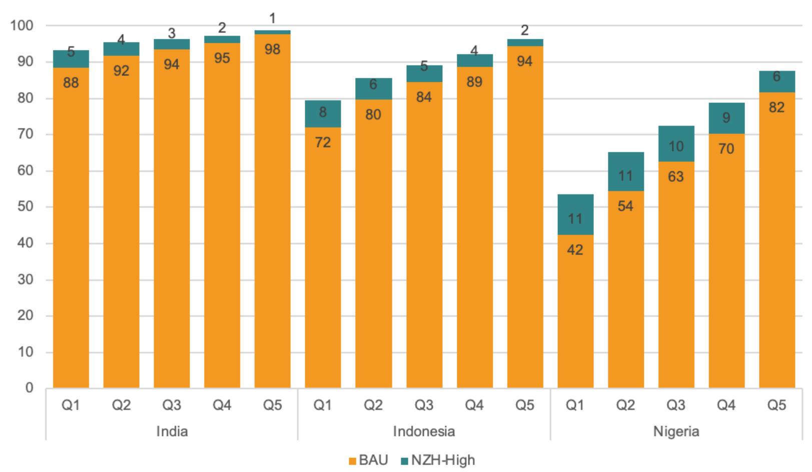

Figure 5: Fan Access by Income Quintile in 2050
Source: Authors' analysis
Note: This figure shows the percentage of households with access under BAU in 2050 (orange) and the additional households that would gain access if fan energy efficiency were doubled by 2030 under the NZH-High scenario (teal). The estimated households per quintile in 2050 is 78,240,857 in India, 17,050,132 in Indonesia, and 18,121,819 in Nigeria.

Impact on National Energy Use: Our model predicts a surge in fan ownership across all three countries between 2023 and 2050 under both the BAU and NZH-High scenarios. By 2050, we estimate that fan ownership will grow from 1.4 fans per household to 2.2 fans per household under business as usual and 2.4 fans per household under the NZH-High scenario in the three countries. However, only under the BAU scenario and NZH-High scenario of Nigeria does national fan energy use increases. Figure 6 shows the relative changes in national energy use for fans between 2023 and 2050. According to our model, we estimate that national fan energy use would decline by 33% from 2023 to 2050 under the NZH-High scenario. Under business as usual, we estimate fan energy use would grow 1.4x from 2023 to 2050.

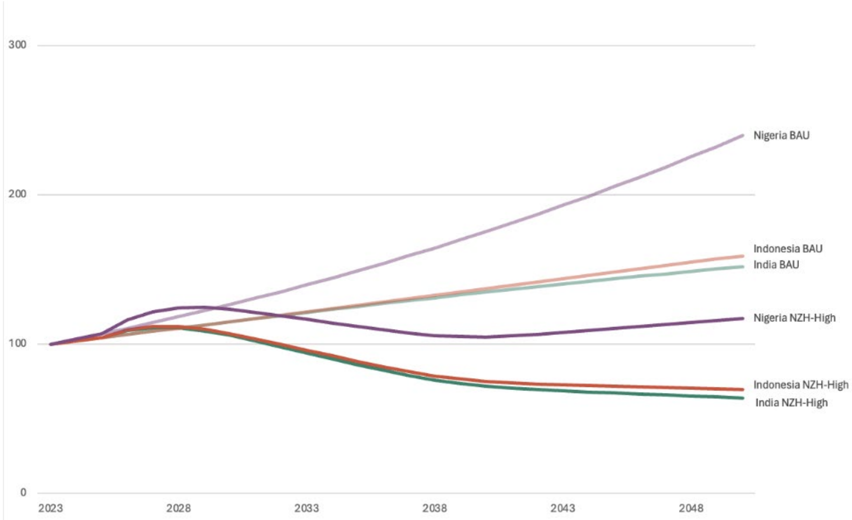

Figure 6: National Fan Energy Use 2023-2050 (Indexed)
Source: Authors' analysis
Note: All fan energy use values (in gigawatt hours per year) were indexed to 2023 values.

Refrigerators
Impact on Lifecycle Cost: Doubling refrigerator efficiency globally by 2030 would reduce consumer lifecycle cost by 60% across all three countries from 2023 to 2050, compared to a 40% reduction under business as usual. In India, we predict refrigerator lifecycle cost will be 166 USD lower under the NZH-High scenario in 2050 compared to business as usual (Figure 7). In Indonesia, lifecycle cost declines 53% over the same period, resulting in a lifecycle cost in 2050 that is 68 USD lower. In Nigeria, refrigerator lifecycle cost is 82 USD lower in 2050 compared to BAU. Overall, the consumer economic benefits for refrigerators in 2050 are estimated at 30 billion USD per year in India, 2 billion USD per year in Indonesia and 3 billion USD per year in Nigeria under our NZH-High scenario.

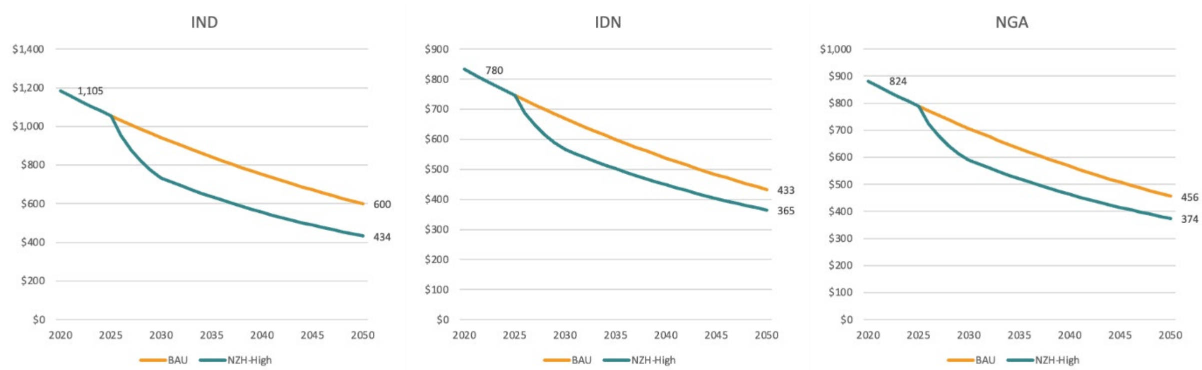

Figure 7: Refrigerator Lifecycle Cost 2020-2050
Source: Authors' analysis
Note: To meet the doubling target, we assume that refrigerator efficiency under the NZH-High scenario improves rapidly through 2030, which stimulates a long-term trend of continued improvement at a rate of 4.5% per annum through 2050. In the BAU scenario, we assume a constant efficiency improvement rate of 2.5% per annum. The labeled values in the figure represent refrigerator lifecycle costs in 2023 (left) and 2050 (right).

Impact on Refrigerator Access: Achieving a global doubling would have a large impact on refrigerator access in India, Indonesia, and Nigeria. In 2023, we estimate household refrigerator-freezer access to be 43% in India, 53% in Indonesia, and 27% in Nigeria. Under business as usual we estimate refrigerator access will increase to 89% in India and Indonesia and 56% in Nigeria in 2050. Under the NZH-High scenario, we predict that an additional 21.8 million households—approximately 96 million people—across the three countries would own a refrigerator by 2050. We estimate that refrigerator access would increase to 93% in India, 91% in Indonesia, and 62% in Nigeria in 2050 under the NZHigh scenario.

Doubling the efficiency of refrigerators by 2030 would be particularly beneficial for lower income households. Figure 8 shows the additional gains in refrigerator access by income quintile. In India and Indonesia, the decrease in refrigerator lifecycle cost under the NZH-High scenario allows a greater number of households in the lowest income quintiles to afford refrigerators, leading to a respective 7 and 4 percentage point increase in access in the first quintile in 2050. In Nigeria, refrigerator access will increase most among both lower- and middle-income quintiles under the NZH-High scenario.

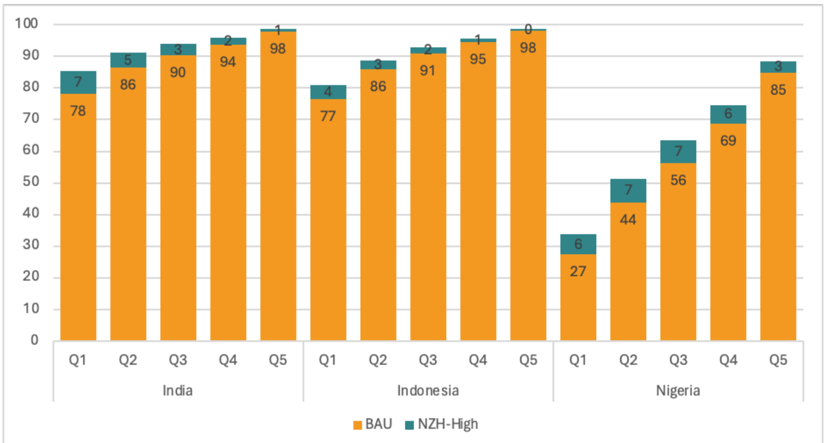

Figure 8: Refrigerator Access by Income Quintile in 2050
Source: Author's analysis
Note: This figure shows the percentage of households with access under BAU in 2050 (orange) and the additional households that would gain access if refrigerator energy efficiency were doubled by 2030 under the NZH-High scenario (teal). The estimated households per quintile in 2050 is 78,240,857 in India, 17,050,132 in Indonesia, and 18,121,819 in Nigeria.

Impact on National Energy Use: Across the three countries, refrigerator access and ownership increase substantially in the NZH-High scenario due to declines in lifecycle cost and increases in income. By 2050 we estimate household refrigerator ownership under the NZH-High scenario will be 1.18 refrigerators per household in India, 1.15 per household in Indonesia, and 0.73 per household in Nigeria. Despite these increases in ownership, we estimate no or small increases in refrigerator energy use under the NZH-High scenario in all three countries at the national level (Figure 9).

We estimate a 30% decrease in refrigerator energy use across all three countries under the NZH-High scenario. In India, refrigerator energy use declines 27% from 386 gigawatt hours per year in 2023 to 279 gigawatt hours per year in 2050. In Indonesia, refrigerator energy use declines nearly 50% from 117 gigawatt hours per year in 2023 to 60 gigawatt hours in 2050. In Nigeria, refrigerator energy use increases slightly from 25 gigawatt hours to 28 gigawatt hours over the same period.

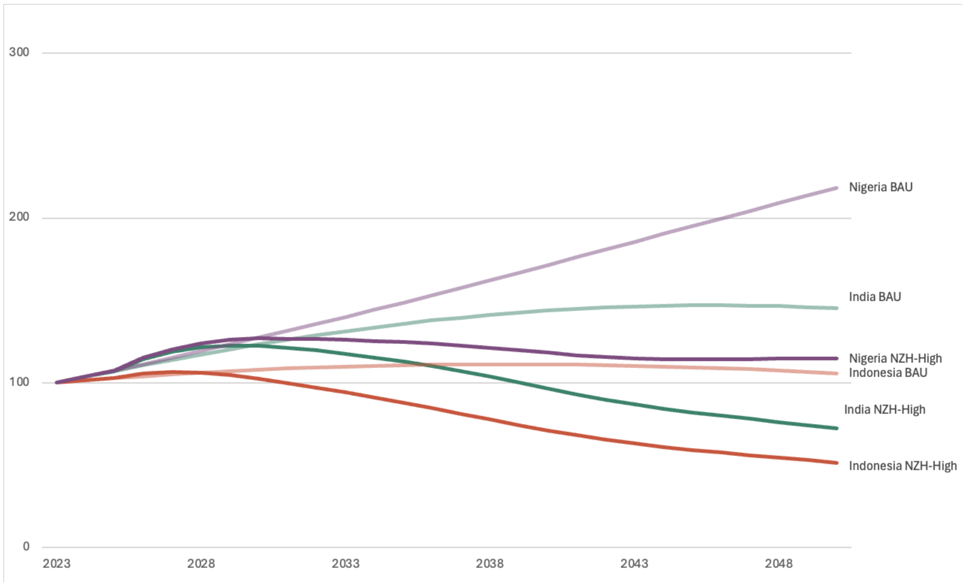

Figure 9: National Refrigerator Energy Use 2023-2050 (Indexed)
Source: Authors' analysis
Note: All refrigerator-freezer energy use values (in gigawatt hours per year) were indexed to 2023 values.

Failure to Meet Net Zero Hero Targets by 2030

Doubling the efficiency of all new cooling appliances sold by 2030 would require governments to prioritize appliance energy efficiency and rapidly mobilize the resources and expertise necessary to draft, approve, and implement policies as soon as possible. For comparison, we also modeled a moderately ambitious policy scenario that would achieve the same doubled efficiency targets with a five-year delay—a 2035 doubling date instead of 2030. This section discusses the impact of that delay on appliance affordability, energy use, and access.

Under both the NZH-High and NZH-Medium scenarios, we observe similar lifecycle cost declines that help make appliances more affordable to larger shares of the population. As a result, the percentage of households with access to cooling appliances in 2050 is similar (Table 1). From an access perspective, the impact of a delayed doubling of efficiency from 2030 to 2035 will have a small negative effect.

When we assess the impact of a five-year delay on energy demand, however, there is a clear benefit of taking a more aggressive approach. Aggregate energy use across all three cooling appliances in 2050 is 32% greater in the NZH-Medium scenario than in the NZH-High scenario (Table 1). Increases in appliance access and ownership will create additional demand for electricity. If this demand is not met by zero-emissions sources, the climate benefits of efficiency improvements may be offset or overshadowed. By aggressively prioritizing energy efficiency now, governments can further expand access to appliances while minimizing the impact of increasing future energy demand and resulting emissions.

Table 1: Comparison of consumer lifecycle cost, appliance access, and energy use in three scenarios, 2023 and 2050

Category	Appliance	2023	2050		
			BAU Scenario	NZH-Medium Scenario	NZH-High Scenario
Consumer lifecycle cost (USD)	Room Air Conditioner	1720	1214	768	687
	Fan	165	137	64	69

	Refrigerator	1022	611	445	414
Access (% of households)	Room Air Conditioner	21%	56%	67%	69%
	Fan	74%	87%	91%	91%
	Refrigerator	43%	84%	87%	88%
Energy Use (gigawatt hours per year)	Room Air Conditioner	530	1992	1309	979
	Fan	301	432	249	201
	Refrigerator	529	739	490	368

Source: Authors' analysis

Discussion

Continued improvement in the energy efficiency of new cooling appliances, in line with historical trends, will make cooling appliances – room air conditioners, fans, and refrigerator-freezers – less expensive to operate. Household incomes are expected to increase at the same time. These two trends taken together are expected to lead to significant expansions in access, ownership, and usage of these appliances under business as usual.

We modeled the effects of a concerted global effort to collectively double the energy efficiency of cooling appliances in the very near term. We expect such an effort to have multiple effects. First, it would have important near-term CO_2 mitigation benefits. Second, it would drive economies of scale in the production of more efficient appliances, enabling manufacturers to innovate on cost, stimulating greater demand for more efficient appliances, creating a "virtuous cycle" and further accelerating rates of energy efficiency improvement. With faster rates of efficiency improvement (coupled with no real equipment price increases), consumer lifecycle cost would fall further and faster. As a result, even more households would be able to afford these appliances, while at the same time limiting electricity demand growth.

Understanding Appliance Efficiency and Price Trends

We formulated long-term price and efficiency projections based on historical trends and how they may be affected by changes in efficiency policy regimes. The BAU scenario in our model uses a baseline efficiency improvement rate of 1% for room air conditioners, 0.5% for fans, and 2.5% for refrigerators based on Van Buskirk et. al [31]. We assume that a collective global doubling of efficiency in cooling appliances by 2030 will result in an accelerated learning trend globally, leading to a higher efficiency improvement rate in the NZH scenario. We selected an ambitious long-term efficiency improvement rate for each appliance that would reflect an acceleration in learning and result in the lowest lifecycle cost, maximizing access. We assume a long-term efficiency improvement rate of 4.2% for room air conditioners, 2.5% for fans, and 4.5% for refrigerators. Van Buskirk et al. suggest that the selected efficiency improvement rate for refrigerators is realistic, given the energy efficiency of refrigerators in the United States has improved at a rate of 4% long-term [32]. The long-term energy efficiency improvement rate for air conditioners, however, is optimistic, based on historical trends. Van Buskirk et. al. found that efficiency improvement rates range from just 0.7% per year to 1.1% per year for room and central air conditioners, respectively. Here we assume that a global effort to increase efficiency would accelerate the rate at which room air conditioner efficiency improves.

We find that for room air conditioners and refrigerators, a long-term global trend in efficiency improvement can be attained with no real equipment price increase because policy would be accelerating learning at a large scale. This assumption is supported by the available historical evidence, e.g., Van Buskirk et. al. [33]. However, between 2026 and 2031, real equipment prices would increase to reflect the initial rapid period of efficiency improvement needed to double energy efficiency. Please see the supplemental material for this paper, which refers to Van Buskirk et. al. and contains further explanation of how accelerating change in cost-efficiency can lead to a step change in the long-term rate of improvement in the cost-efficiency curves. Unlike room air conditioners and refrigerators, our fan prices rise steadily under the NZH-High scenario, nearly doubling in all three countries between 2023 and 2050. However, the increasing first costs are offset by lower operating costs driven by improvements in energy efficiency, resulting in significant reductions in lifecycle costs between 2023 and 2050.

Closing Appliance Access Gaps

Standards and labels may not be sufficient to lower cooling appliance lifecycle costs and shift demand as quickly as needed to close appliance access gaps. In 2050, we predict there will still be sizeable cooling access gaps in India, Indonesia, and Nigeria for the lowest income quintiles. For example, in Nigeria, only 3% of households in the lowest income quintile in 2050 will own a room air conditioner, compared to 29% of households in the highest income quintile. If universal access to cooling appliances is a priority, complementary policies and programs will be needed to specifically target these groups.

There are several options available to accelerate the uptake of efficient appliances. Complementary efforts such as research and development funding, financing and financial incentives, bulk procurement schemes, awards, and informational tools are proven solutions with a track record of success for driving market uptake of efficient appliances. We will focus our discussion on solutions that can lower the first cost of efficient appliances and drive sales in nascent markets. A summary of other complementary policies and incentives for energy-efficient appliances may be found in chapter four of CLASP's report, *"Net Zero Heroes: Scaling Efficient Appliances for Climate Change Mitigation, Adaptation & Resilience".*

Innovative financing schemes can be directed to reduce first-cost barriers. Ghana's ECOWAS Refrigerators and Air Conditioners Initiative provided flexible financing to reduce the initial purchase price of efficient refrigerators and air conditioners through an interest-free loan that borrowers repaid through monthly paycheck reductions. Between October 2020 and July 2023, 1,984 new energy-efficient refrigerators and 1,460 room air conditioners were sold [34].

Governments with high access gaps could reduce or eliminate tariffs for efficient appliances and equipment, thereby lowering the cost for companies to import and sell their products locally. Tariffs may hinder growth in nascent markets. One analysis of tariffs for solar home systems in East Africa found that a 20% tariff on solar home systems would yield an 18% reduction in sales of basic systems with panel, lights, and phone charging equipment, and a 32% decrease in sales of larger kits with televisions [35].

Most households without access to cooling appliances in 2050 in our analysis are low-income. Low-income households in India, Indonesia, and Nigeria and are more likely to reside in communities with unreliable or no access to electricity. Decentralized energy solutions, like solar home systems and mini-grids, can help these communities access energy services more readily. While specific policies for decentralized energy systems and compatible appliances are limited, recent efforts including subsidy facilities for off-grid appliances show promise. The Global LEAP Awards use a competition-based approach to drive innovation and performance in early-stage product markets. The associated results-based financing mechanism reduces financial risks associated with large-scale procurement. To date, Global LEAP has catalyzed the sale of more than 280,000 off-grid appliances in seven countries, benefiting nearly 1.3 million people [36]. The Productive Use Financing Facility provides financial support to small and medium-sized companies in East, West and Central Africa through upstream subsidies, capacity building grants, and concessional debt. The program's 10-year market potential is expected to crowd in more than 3 billion USD in private capital for new appliance markets in emerging economies, create over 10 million jobs and improve livelihoods, and benefit 30 million people via access to appliances. Finally, end user subsidies will play a key role in ensuring that no one is left behind, but these solutions must work alongside other 'pro-poor solutions' (e.g., financial innovations, supply-side subsidies, etc.), and be developed carefully to avoid impeding other energy access efforts.

Limitations and Opportunities for Further Research

The results of the modeling exercise discussed in this paper indicate that an ambitious efficiency improvement scenario, like our NZH-High and NZH-Medium scenarios, would lead to accelerated declines in lifecycle costs that would expand cooling appliance ownership and access across all income levels in the three countries studied without significantly increasing energy demand long-term. Under the NZH-High scenario, a more than 6x increase in room air conditioner access is possible by 2050, while limiting total room air conditioner energy use growth to 2x. To confirm and provide further nuance to these findings, we suggest expanding the analysis to include other countries with high cooling needs and moderate to low access rates along the development spectrum, where the relative impact of efficiency improvements could better be estimated for lower-, middle- and high-access regions. The model also does not account for countries with a large informal appliance market, which has the potential to alter modeling results significantly in these contexts.

This research does not offer pathways to attaining the ambitious NZH-High scenario modeled. Therefore, as a next step to actioning a pathway to doubled efficiency, we suggest developing roadmaps – where possible in collaboration with policymakers from countries studied – to identify what exact policies may be required and applicable in which country contexts to meet these goals effectively. Where appropriate, roadmaps should leverage existing international test methods and standards, use performance ladders based on international standards (see the International Energy Agency's Energy Performance Ladders), and align with other guidelines (like National Cooling Action Plans). We also recommend expanding the model to explore efficiency improvement and access impacts by other demographic dimensions, e.g., urban/peri-urban/rural, gender, education, etc., for a wider lens on inclusivity dimensions.

Conclusion

A concerted near-term global effort to shift demand toward the most efficient cooling appliances would result in accelerated declines in lifecycle costs, which would expand ownership across all income levels while limiting the growth in aggregate energy demand for cooling services. If current trends in efficiency improvement and rising incomes continue, cooling appliances will become more affordable and, as a result, access to these appliances will increase. With a shared focus on shifting demand toward the most efficient fans, refrigerators, and room air conditioners, by 2050 we could, across the three countries studied:

- Drive down the total cost of ownership by 60% for room air conditioners and refrigerators and 58% for fans
- Deliver 105 billion USD in annual net consumer benefits in 2050
- Expand access by an additional 4-13 percentage points
- Avoid more than 420,000 premature deaths
- Limit the total energy consumed by these appliances to less than 50% of what it would be otherwise.

To realize these benefits, governments and other market actors must act immediately and use every mechanism at their disposal to shift demand toward the most efficient cooling appliances.

References

[1] Intergovernmental Panel On Climate Change. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 1st ed. Cambridge University Press, 2023. https://doi.org/10.1017/9781009157896.

[2] Lenssen, Nathan J. L., Gavin A. Schmidt, James E. Hansen, Matthew J. Menne, Avraham Persin, Reto Ruedy, and Daniel Zyss. "Improvements in the GISTEMP Uncertainty Model." Journal of Geophysical Research: Atmospheres 124, no. 12 (June 27, 2019): 6307–26. https://doi.org/10.1029/2018JD029522.

[3] Hersbach, Hans, Bill Bell, Paul Berrisford, Shoji Hirahara, András Horányi, Joaquín Muñoz‐Sabater, Julien Nicolas, et al. "The ERA5 Global Reanalysis." Quarterly Journal of the Royal Meteorological Society 146, no. 730 (July 2020): 1999–2049. https://doi.org/10.1002/qj.3803.

[4] NASA Goddard Institute for Space Studies. "GISS Surface Temperature Analysis (GISTEMP)." Accessed February 20, 2024. https://data.giss.nasa.gov/gistemp/.

[5] Arsad, Fadly Syah, Rozita Hod, Norfazilah Ahmad, Rohaida Ismail, Norlen Mohamed, Mazni Baharom, Yelmizaitun Osman, Mohd Firdaus Mohd Radi, and Fredolin Tangang. "The Impact of Heatwaves on Mortality and Morbidity and the Associated Vulnerability Factors: A Systematic Review." International Journal of Environmental Research and Public Health 19, no. 23

[6] E Campbell, Sharon, Tomas A. Remenyi, Christopher J. White, and Fay H. Johnston. "Heatwave and Health Impact Research: A Global Review." Health & Place 53 (September 1, 2018): 210–18. https://doi.org/10.1016/j.healthplace.2018.08.017.

[7] Lesk, Corey, Pedram Rowhani, and Navin Ramankutty. "Influence of Extreme Weather Disasters on Global Crop Production." Nature 529, no. 7584 (January 2016): 84–87. https://doi.org/10.1038/nature16467.

[8] Dumas, Melissa, Binita Kc, and Colin I. Cunliff. "Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods." Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), August 1, 2019. https://doi.org/10.2172/1558514.

[9] Colelli, Francesco Pietro, Ian Sue Wing, and Enrica De Cian. "Air-Conditioning Adoption and Electricity Demand Highlight Climate Change Mitigation–Adaptation Tradeoffs." Scientific Reports 13, no. 1 (March 17, 2023): 4413. https://doi.org/10.1038/s41598-023-31469-z.

[10] Electric fan use in heat waves: Turn on or turn off?, Temperature 2016; 3(3): 358–360. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5079223/

[11] Carrasco-Tenezaca, Majo, Musa Jawara, Daniel Sang-Hoon Lee, Matthew S. Holmes, Sainey Ceesay, Phillip McCall, Margaret Pinder, et al. "Effect of Passive and Active Ventilation on Malaria Mosquito House Entry and Human Comfort: An Experimental Study in Rural Gambia." Journal of the Royal Society Interface 20, no. 201 (n.d.): 20220794. https://doi.org/10.1098/rsif.2022.0794.

[12] Jatta, Ebrima, Majo Carrasco-Tenezaca, Musa Jawara, John Bradley, Sainey Ceesay, Umberto D'Alessandro, David Jeffries, et al. "Impact of Increased Ventilation on Indoor Temperature and Malaria Mosquito Density: An Experimental Study in The Gambia." Journal of the Royal Society Interface 18, no. 178 (n.d.): 20201030. https://doi.org/10.1098/rsif.2020.1030.

[13] Greenwood, Jeremy, Ananth Seshadri, and Mehmet Yorukoglu. "Engines of Liberation." The Review of Economic Studies 72, no. 1 (January 1, 2005): 109–33. https://doi.org/10.1111/0034-6527.00326.

[14] Efficiency for Access, Schatz Energy Research Center, and 60 Decibels. "Use Cases and Cost Breakdown of Off-Grid Refrigeration Systems." Efficiency for Access Coalition, 2020.

https://efficiencyforaccess.org/publications/use-cases-and-cost-breakdown-of-off-grid-refrigeration-systems/.

[15] IEA. “The Future of Cooling.” Paris, France: International Energy Agency, 2018. https://www.iea.org/reports/the-future-of-cooling.

[16] IEA. “The Future of Cooling.” Paris, France: International Energy Agency, 2018. https://www.iea.org/reports/the-future-of-cooling.

[17] Environment, U. N. “Global Cooling Watch 2023.” UNEP - UN Environment Programme, December 4, 2023. http://www.unep.org/resources/global-cooling-watch-2023.

[18] Rao, Narasimha D., and Kevin Ummel. “White Goods for White People? Drivers of Electric Appliance Growth in Emerging Economies.” Energy Research & Social Science 27 (May 1, 2017): 106–16. https://doi.org/10.1016/j.erss.2017.03.005.

[19] CLASP. “Mepsy: The Appliance & Equipment Climate Impact Calculator,” 2021. https://clasp.shinyapps.io/mepsy/.

[20] Parkes, Ben, Jennifer Cronin, Olivier Dessens, and Benjamin Sultan. “Climate Change in Africa: Costs of Mitigating Heat Stress.” Climatic Change 154, no. 3 (June 1, 2019): 461–76. https://doi.org/10.1007/s10584-019-02405-w.

[21] Buskirk, R. D. Van, C. L. S. Kantner, B. F. Gerke, and S. Chu. “A Retrospective Investigation of Energy Efficiency Standards: Policies May Have Accelerated Long Term Declines in Appliance Costs.” Environmental Research Letters 9, no. 11 (November 2014): 114010. https://doi.org/10.1088/1748-9326/9/11/114010.

[22] Abhyankar, Nikit, Nihar Shah, Won Young Park, and Amol A. Phadke. “Accelerating Energy Efficiency Improvements in Room Air Conditioners in India: Potential, Costs-Benefits, and Policies,” 2017. https://escholarship.org/uc/item/8710154k.

[23] Bolinger, Mark, Ryan Wiser, and Eric O’Shaughnessy. “Levelized Cost-Based Learning Analysis of Utility-Scale Wind and Solar in the United States.” iScience 25, no. 6 (June 17, 2022): 104378. https://doi.org/10.1016/j.isci.2022.104378.

[24] De La Rue Du Can, Stephane, David Pudleiner, and Katrina Pielli. “Energy Efficiency as a Means to Expand Energy Access: A Uganda Roadmap.” Energy Policy 120 (September 2018): 354–64. https://doi.org/10.1016/j.enpol.2018.05.045.

[25] World Bank, and CLASP. “EA+EE: Enhancing the World Bank’s Energy Access Investments Through Energy Efficiency.” World Bank Group, 2015. https://documents1.worldbank.org/curated/en/875391468186565552/pdf/98193-WP-P151483-Box391505B-PUBLIC-World-Bank-EA-EE-Enhancing-WBs-Energy-Access-Investments-Through-Energy-Efficiency-FINAL-25-June-2015.pdf.

[26] Pachauri, Shonali, Diana Ürge-Vorsatz, and Michael LaBelle. “Synergies between Energy Efficiency and Energy Access Policies and Strategies.” Global Policy 3, no. 2 (2012): 187–97. https://doi.org/10.1111/j.1758-5899.2011.00165.x.

[27] Dagnachew, Anteneh G, Miguel Poblete-Cazenave, Shonali Pachauri, Andries F Hof, Bas Van Ruijven, and Detlef P Van Vuuren. “Integrating Energy Access, Efficiency and Renewable Energy Policies in Sub-Saharan Africa: A Model-Based Analysis.” Environmental Research Letters 15, no. 12 (December 1, 2020): 125010. https://doi.org/10.1088/1748-9326/abcbb9.

[28] Rue du Can, Stephane de la, Virginie Letschert, Shreya Agarwal, Won Young Park, and Usamah Kaggwa. “Energy Efficiency Improves Energy Access Affordability.” Energy for Sustainable Development 70 (October 1, 2022): 560–68. https://doi.org/10.1016/j.esd.2022.09.003.

[29] Rao, Narasimha D., and Kevin Ummel. “White Goods for White People? Drivers of Electric Appliance Growth in Emerging Economies.” Energy Research & Social Science 27 (May 1, 2017): 106–16. https://doi.org/10.1016/j.erss.2017.03.005.

[30] Davis, Lucas, Paul Gertler, Stephen Jarvis, and Catherine Wolfram. “Air Conditioning and Global Inequality.” Global Environmental Change 69 (July 1, 2021): 102299. https://doi.org/10.1016/j.gloenvcha.2021.102299.

[31] Buskirk, R. D. Van, C. L. S. Kantner, B. F. Gerke, and S. Chu. “A Retrospective Investigation of Energy Efficiency Standards: Policies May Have Accelerated Long Term Declines in Appliance Costs.” Environmental Research Letters 9, no. 11 (November 2014): 114010. https://doi.org/10.1088/1748-9326/9/11/114010.

[32] Buskirk, R. D. Van, C. L. S. Kantner, B. F. Gerke, and S. Chu. “A Retrospective Investigation of Energy Efficiency Standards: Policies May Have Accelerated Long Term Declines in Appliance Costs.” Environmental Research Letters 9, no. 11 (November 2014): 114010. https://doi.org/10.1088/1748-9326/9/11/114010.

[33] Buskirk, R. D. Van, C. L. S. Kantner, B. F. Gerke, and S. Chu. “A Retrospective Investigation of Energy Efficiency Standards: Policies May Have Accelerated Long Term Declines in Appliance Costs.” Environmental Research Letters 9, no. 11 (November 2014): 114010. https://doi.org/10.1088/1748-9326/9/11/114010.

[34] CLASP. “Net Zero Heroes: Scaling Efficient Appliances for Climate Change Mitigation, Adaptation & Resilience.” CLASP, 2023. https://www.clasp.ngo/report/net-zero-heroes/.

[35] Fetter, Rob, and Jonathan Phillips. “The True Cost of Solar Tariffs in East Africa.” Nicholas Institute for Environmental Policy Solutions, Duke University, February 5, 2019. https://nicholasinstitute.duke.edu/publications/true-cost-solar-tariffs-east-africa.

[36] CLASP. “Identifying the World’s Best, Most Energy-Efficient Off-Grid Appliances.” CLASP, 2024. https://www.clasp.ngo/programs/brands/global-leap-awards/.