RHODIUM GROUP

ENERGY & NATURAL RESOURCES

Out of the Dark

The Climate Implications of Global Electrification

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On September 25, 2015, the UN General Assembly adopted a resolution outlining a "2030 Agenda for Sustainable Development". This included 17 goals, one of which is to "ensure access to affordable, reliable, sustainable and modern energy for all". Providing electricity access to the more than 1.2 billion people that currently lack it will be central to this challenge. Given the fact that power generation is responsible for 32% of global greenhouse gas (GHG) emissions, expanding electricity access could have a material impact on another of the UN's Sustainable Development Goals—to "take urgent action to combat climate change and its impacts". This report assesses the potential climate implications of successfully closing the electrification gap. We find:

The state of global electrification: More than 1.2 billion people lack basic electricity access today, with the majority living in India and Sub-Saharan Africa. Electrifying these households would significantly improve indoor air quality and public health, and help accelerate economic development in the poorest countries. Access, however, is not the only electricity challenge developing countries face. While more than three-quarters of developing country households are connected to the grid, their average level of service is still only one-fifth that of the average developed country household. And poor grid reliability in many developing countries slows investment and employment growth.

Future pathways: The global electrification picture is rapidly evolving. Over the past two decades, the grid-connected global population has grown by nearly two billion people and average household electricity consumption in developing countries has more than doubled. We expect the grid-connected population to grow by another 1.3 billion between 2012 and 2030 due to population growth, urbanization, and economic development, and grid-connected residential electricity demand to grow by 57 to 90%. Energy access will continue to be a problem if not proactively addressed by policymakers, however, with 1 to 1.4 billion people likely to continue to live off the grid in 2030.

Climate implications: Electrifying those households not likely to be grid-connected due to urbanization, population, and income growth alone will likely increase CO_2 emissions. If electricity is supplied through the most carbon-intensive sources, achieving universal access in 2030 could increase global emissions by up to 404 million metric tons per year. While non-trivial, this pales in comparison to projected emissions from grid-connected residential electricity consumption in 2030—4,177 to 4,948 million metric tons under current policy. In the context of total energy-related CO_2 emissions, electrifying off-grid households in 2030 with a relatively carbon—intensive fuel mix would increase global emissions by 2-3%.

Conclusions: Given the dominant and growing role of the grid in global electricity supply, reducing emissions from, and improving the reliability of, a rapidly growing electrical grid in developing countries are the most important climate and human development priorities. Put another way, the mode of electrification of the household sector – whether mini-grid, off-grid or central station – is less important as a climate action lever.

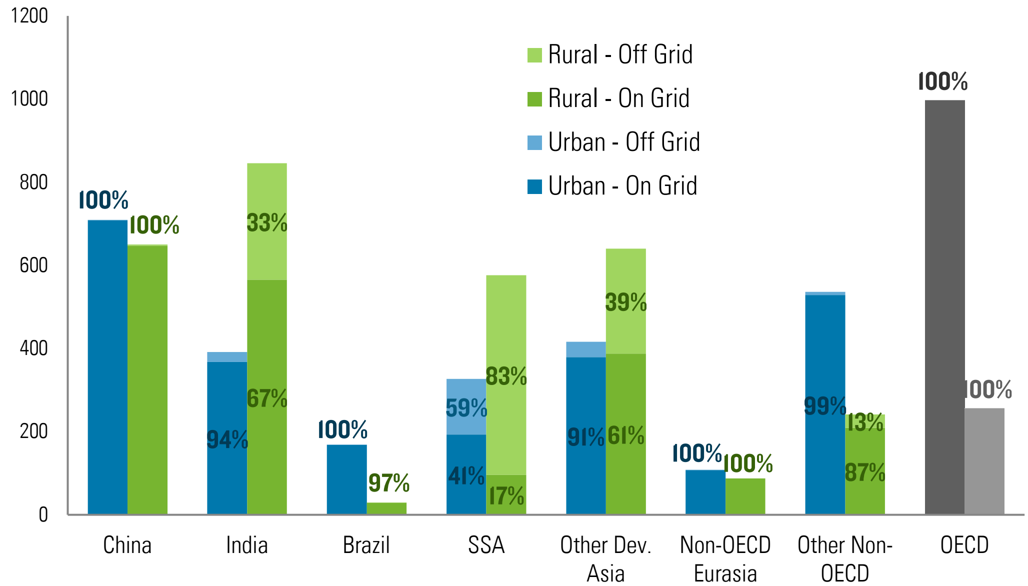
THE STATE OF GLOBAL ELECTRIFICATION

Access to reliable and affordable electricity is critical to both human and economic development. In developed countries, access is universal (Figure 1), with electricity primarily generated at central station power plants—whether coal, natural gas, nuclear, or renewable—and delivered to households through an interconnected transmission and distribution grid.

In developing countries the picture is more mixed. According to survey data from the International Energy Agency (IEA) and World Bank, 1.25 billion people in developing countries lacked electricity access in 2012 (IEA, 2014; World Bank, 2015). Nearly three-quarters live in India and Sub-Saharan Africa (SSA), and more than 80% live in rural communities. These households rely on wood, dung, and kerosene for heating, lighting, and cooking, with severe consequences for indoor air quality and public health.

Figure 1: The state of global electrification

Million people, 2012



Source: IEA, World Bank, and RHG estimates.

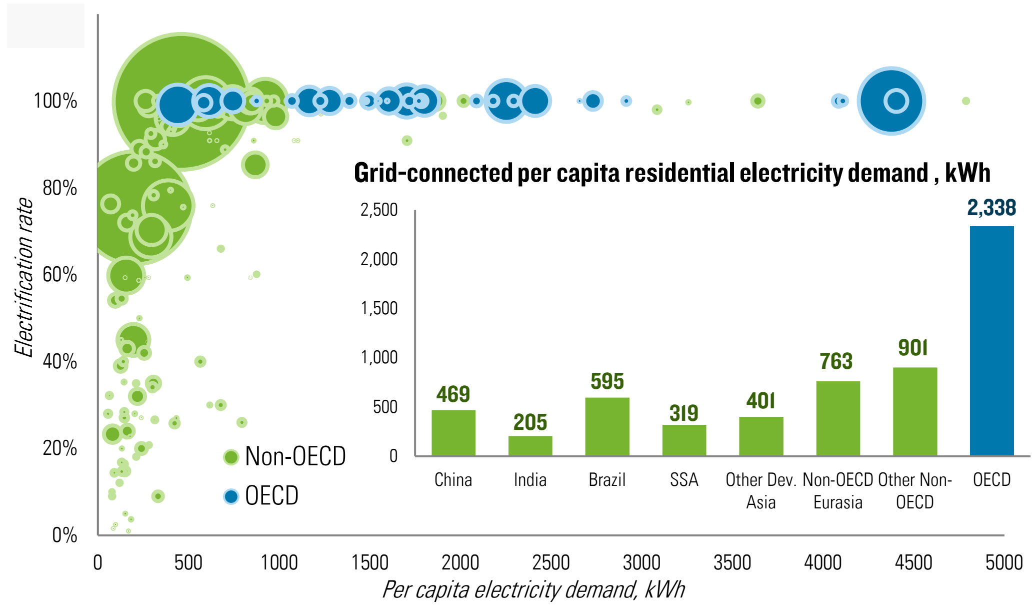
Level of service

Electricity's role in meeting the UN's Sustainable Development Goals extends beyond just providing access. The minimum level of demand at which the World Bank considers a rural household to have access is 250 kWh per year (World Bank, 2015), or 50 kWh per person. That's enough electricity to operate a couple light bulbs and a television, but not enough for even the most energy efficient refrigerator. Achieving the UN's goals of ending poverty and promoting sustained, inclusive, and sustainable economic growth will require increasing electricity service far beyond the World Bank's minimum levels.

Average per capita residential electricity demand in China is 469 kWh today (Figure 2). The OECD average is 2,338 kWh. The average American consumes 4,377 kWh per year (IEA, 2015a). Efficiency improvements can reduce the amount of electricity required to provide developing countries with modern levels of energy service, but even under the most aggressive efficiency assumptions targeted levels of economic development will result in a substantial increase in global residential electricity demand.

Figure 2: Access alone isn't enough

Per capita residential electricity demand among those with grid access in 2012, kWh; bubble size is population



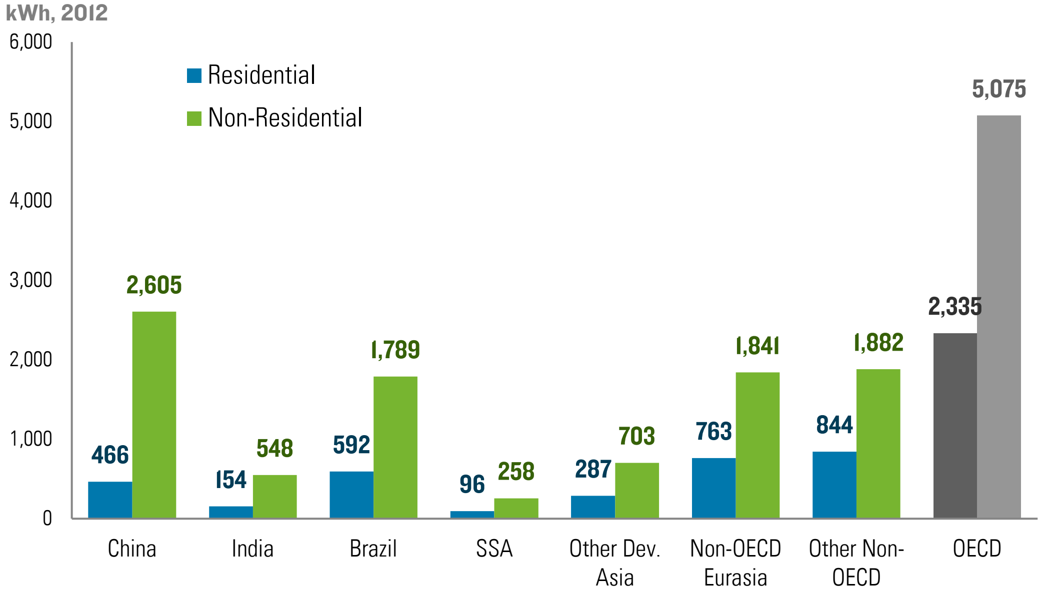
Source: IEA, World Bank, and RHG estimates.

Commercial and industrial demand

The electrification challenge extends beyond the residential sector as well. While energy access metrics are generally focused on households, the majority of electricity demand, both in developed and developing countries, comes from businesses (Figure 3). For example, in OECD countries households account for only one-third of total electricity consumption, with the rest coming from stores, office buildings, schools, and factories. Roughly the same ratio holds for most developing countries as well, though per capita levels are considerably below OECD averages (IEA, 2015a).

Figure 3: Per capital electricity demand

kWh, 2012

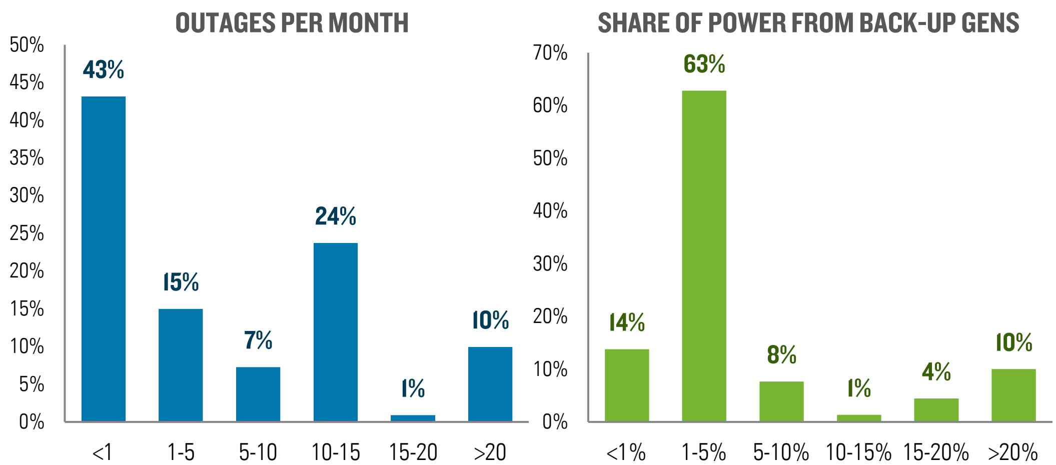


Source: IEA, World Bank, and RHG estimates.

The vast majority of commercial and industrial consumers in developing countries have grid access, but frequent brown and blackouts force many firms to rely on back-up generators for a significant share of their electricity needs. The World Bank surveys electricity reliability in nearly 120 countries home to roughly 5.6 billion people. More than one-third of businesses in these countries (weighted by population) experience more than 10 power outages per month. Roughly 10% experience more than 20 outages per month. As a result, 15% of businesses in these countries (population weighted) have to rely on back-up generators for more than 10% of their electricity (World Bank, 2014). Unreliable grid-supplied electricity in developing countries hinders investment and employment growth and presents a significant barrier to achieving the UN's economic development goals. It also needlessly increases CO_2 emissions, as back-up generators are among the most carbon-intensive forms of power generation.

Figure 4: The reliability of commercial and residential electricity delivery

Share of businesses surveyed by World Bank, weighted by population



Source: World Bank and RHG estimates.

FUTURE PATHWAYS

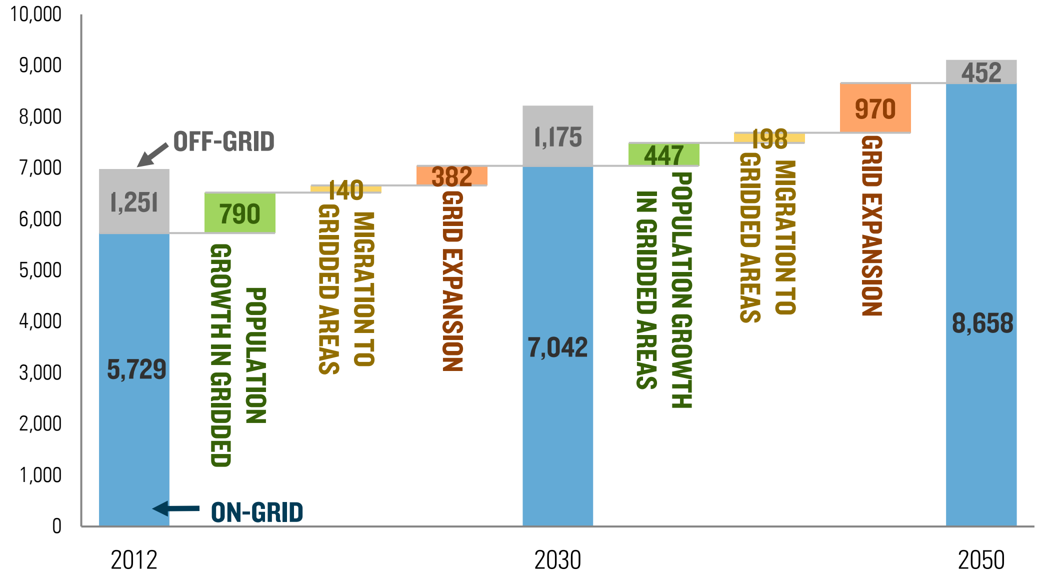
The electrification landscape is rapidly evolving. Between 1990 and 2012, the World Bank estimates the number of people with electricity access globally expanded by nearly two billion due to a combination of population growth, economic development, and urbanization (World Bank, 2015). Per capita grid-supplied electricity demand in developing countries more than doubled (IEA, 2015a). These same socioeconomic drivers will continue to shape the electrification landscape going forward. We model likely changes in the rate and level of electricity access between now and 2050 under three different socioeconomic scenarios from the Shared Socioeconomic Pathways used by the Intergovernmental Panel on Climate Change (O'Neill et al., 2015)—which we call Low, Medium, and High. The Low Scenario is characterized by a more rural, high-population, low-growth future, while the High Scenario has higher GDP and urbanization rates and lower population growth. The Medium Scenario falls between the other two on all three metrics. For these baseline estimates we assume current policy continues and that there is no concerted international push to expand electricity access and achieve the UN's Social Development Goals. A complete description of our methodology is available in Appendix A.

Electricity access

In our Medium Scenario global population grows by 1.24 billion people between 2012 and 2030, and the number of people connected to the grid grows by 1.31 billion. More than half of this is due to population growth in currently gridded areas (Figure 5). Of the remaining 522 million who gain access, 140 million do so by migrating to gridded areas (at urbanization rates projected in the Medium Scenario) while income-driven grid expansion provides coverage to another 382 million. That leaves 1.18 billion people without access in 2030 under current policy, largely unchanged from today's levels.

Figure 5: On-grid vs. off-grid population

Million people, current policy, Medium Scenario

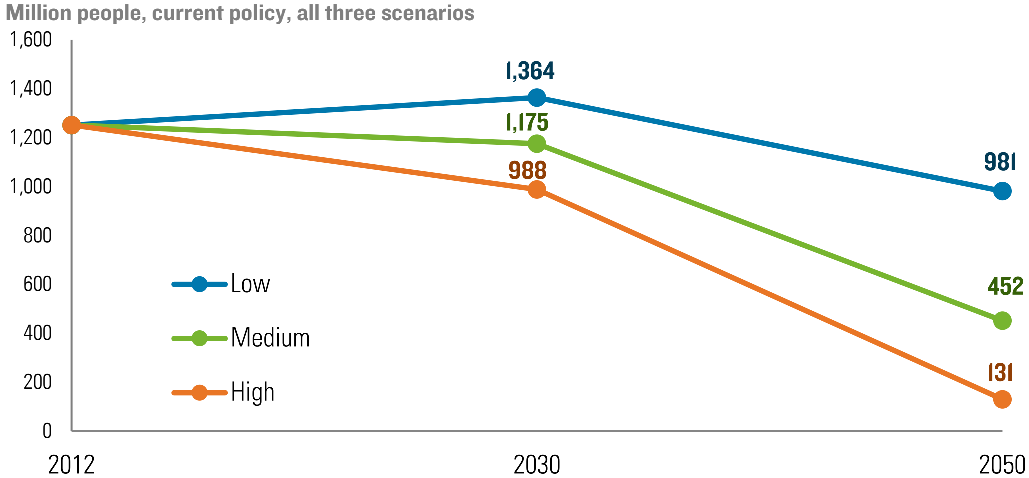


Source: IEA, IIASA, World Bank, and RHG estimates.

Between 2030 and 2050, however, the picture is a bit different. Global population expands by 893 million during that period in our Medium Scenario, and 1.62 billion people get connected to the grid. Of that, only one-quarter comes from population growth in areas already gridded in 2030 and less than 15% from urbanization. 60% is due to income-driven grid expansion. It's between 2030 and 2050 that developing country incomes rise enough to make a significant dent in the electrification challenge, assuming current policies continue. As a result, the size of the global off-grid population in our Medium Scenario drops from 1.18 billion to 452 million.

Figure 6: Off-grid population

Million people, current policy, all three scenarios



Source: IEA, IIASA, World Bank, and RHG estimates.

This same dynamic holds in our Low and High scenarios as well. In the Low Scenario, the off-grid population grows by a little over 100 million between 2012 and 2030, but then declines by 383 million between 2030 and 2050 (Figure 6). In the High Scenario, the off-grid population falls by 263 million between 2012 and 2030 and by another 857 million between 2030 and 2030.

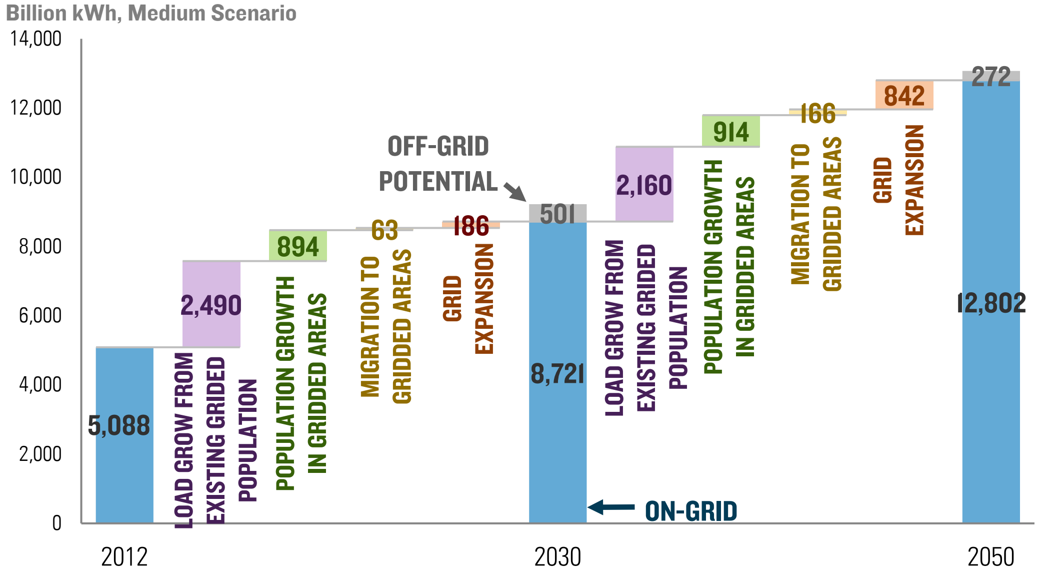
Electricity demand

In 2012, households around the world consumed 5,088 billion kWh of electricity, nearly all of which was generated by central station power plants and delivered through an interconnected electrical grid (IEA, 2015a). In our Medium Scenario, we project grid-connected residential electricity demand will increase by 3,633 billion kWh between 2012 and 2030, assuming no major changes in national energy policy. Of this, nearly 70% comes from higher demand among households currently connected to the grid due to an income-driven increase in energy services (Figure 7). An additional 25% comes from population growth in currently gridded areas. Broadening grid access to an additional 522 million people through urbanization and income-driven grid expansion accounts for only 7% of projected global load growth. Between 2030 and 2050, income and urbanization-driven grid expansion plays a larger role in driving global residential electricity demand growth (25% in our Medium Scenario), as more households cross the income threshold at which grid access has traditionally occurred. The majority of global grid-connected residential load growth, however, continues to come from households already connected to the grid.

To quantify the additional electricity demand that would come from providing access to the 452 million to 1.18 billion people who are projected to still be off grid in 2030 and 2050 respectively in our Medium Scenario, we explored three possible levels of consumption: 1) a 750 kWh minimum per household threshold, 2) an assumption that all off-grid households consume at the same level as on-grid households within that country, and 3) that all off-grid households consume at current Chinese levels. This results in a global estimate of potential off-grid residential electricity demand ranging from 176 to 660 billion kWh in 2030, increasing overall global residential electricity consumption by 2-7%. By 2050, that falls to 68 to 321 billion kWh, or a 0.5-2.5% increase in global demand.

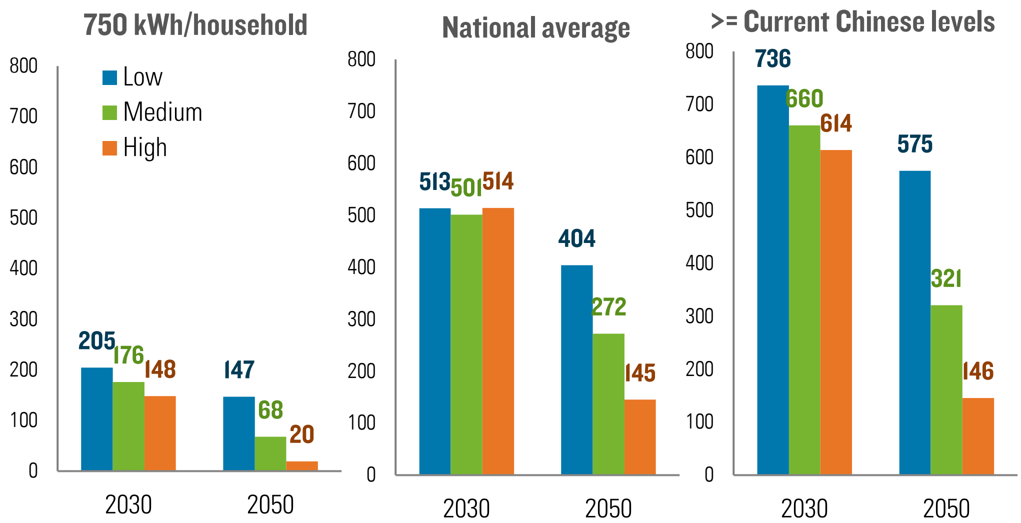
Figure 7: Growth in residential electricity demand under current policy

Billion kWh, Medium Scenario



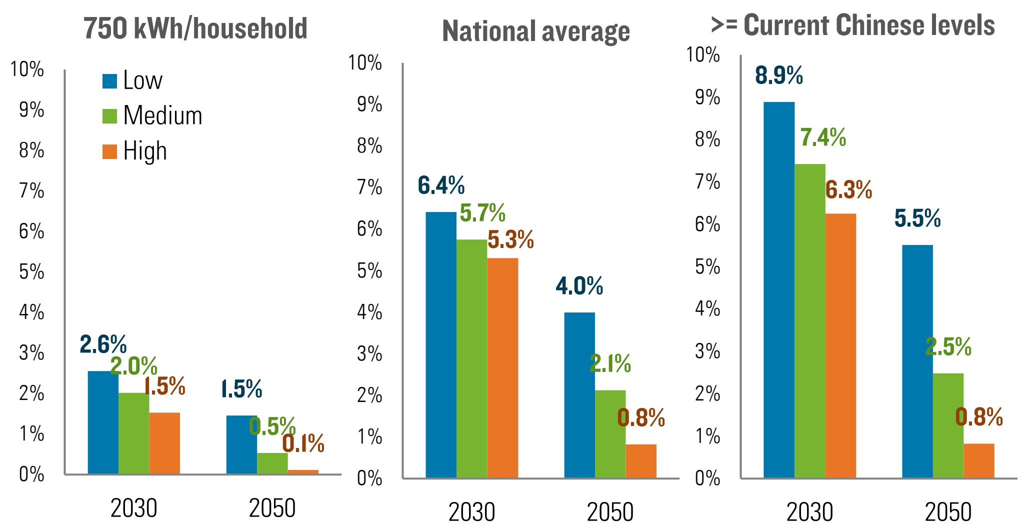
Source: IEA, IIASA, World Bank, and RHG estimates.

Figure 8: Potential off-grid residential electricity demand—billion kWh
Assumes current policy



Source: IEA, IIASA, World Bank, and RHG estimates.

Figure 9: Potential off-grid residential electricity demand—percent of global residential total
Assumes current policy



Source: IEA, IIASA, World Bank, and RHG estimates.

As discussed previously, households account for only one-third of current electricity demand globally. We did not model future changes in commercial, industrial, and transport-related electricity consumption for this report. While non-residential electricity demand is harder to forecast due to changes in industrial production and the potential for long-term electrification of the passenger vehicle fleet, we expect non-residential electricity demand growth in developing countries to be substantial. Indeed, in their most recent World Energy Outlook (WEO) the IEA projects that more than 70% of electricity demand growth in developing countries in the coming decades will come from outside the residential sector (IEA, 2015b).

CLIMATE IMPLICATIONS

To assess the climate implications of the electrification projections outlined above, we rely on regional emissions factors (the amount of CO_2 emitted for every kWh of electricity consumed) from the IEA's most recent WEO. We used the IEA's "Current Policies Scenario," which assumes no change in national energy or climate policies beyond those announced by summer 2015. The WEO projections only extend to 2040, so we use 2040 emissions factors to estimate 2050 emissions levels.

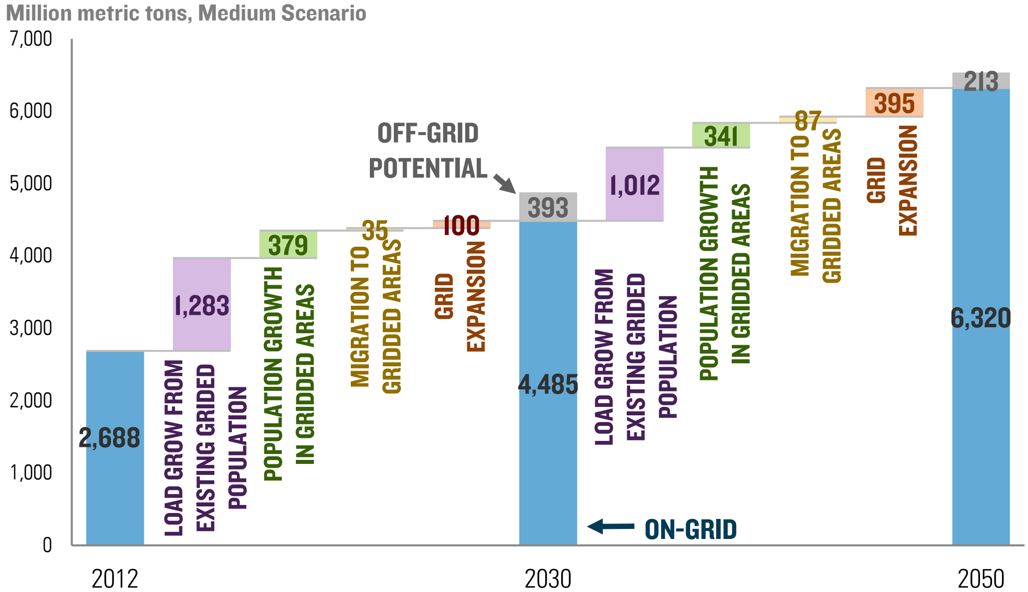
Emissions scenarios for residential electricity consumption

Grid-connected residential electricity consumption resulted in 2,688 million metric tons (mmt) of CO_2 emissions in 2012 (Figure 10). In our Medium Scenario, that grows to 4,485 mmt by 2030. Mirroring the growth in generation shown in Figure 7, the majority of the increase comes from higher demand among households already connected to the grid, followed by population growth in currently gridded areas. Income and urbanization-driven expansion of the grid accounts for only 8% of the growth.

To calculate the maximum potential increase in emissions from expanding electricity access to those remaining off-grid in 2030, we assume all potential demand is met with power generated by small-scale diesel generators. That would result in 393 mmt of additional emissions in 2030 in our Medium Scenario (assuming off-grid populations in a given country consume electricity at the same level as their on-grid counterparts). Between 2030 and 2050, load growth among those households already connected to the grid in 2030 continues to be the largest source of additional residential electricity-related emissions, though grid expansion becomes a more important driver. Maximum potential off-grid emissions decline to 213 mmt in our Medium Scenario as more households are connected to the grid.

Figure 10: CO2 emissions from residential electricity consumption

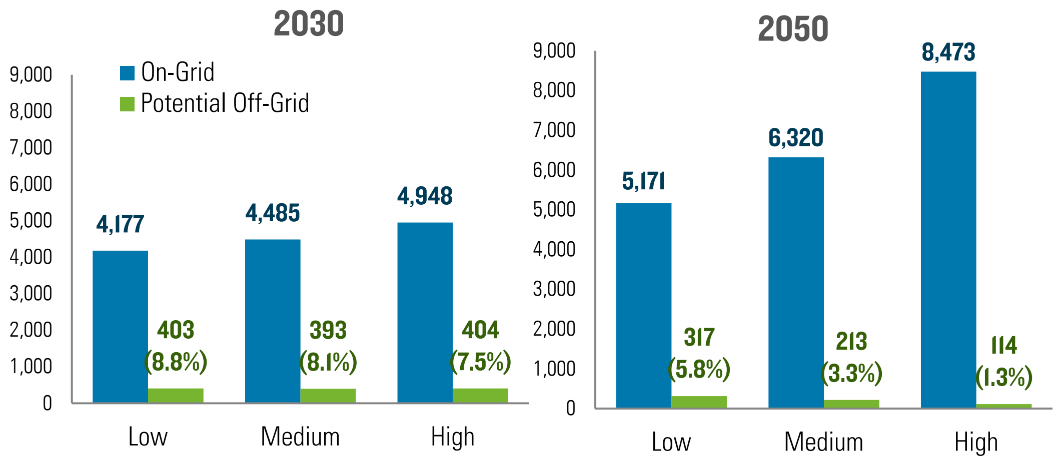
Million metric tons, Medium Scenario



Source: IEA, IIASA, World Bank, and RHG estimates.

Across scenarios we find that if all projected off-grid households are electrified, global emissions could increase by as much as 393 to 404 mmt in 2030 if all the power they consumed was produced with diesel generators, a 7.5 to 8.8% increase in total residential electricity-related emissions projected for that year (Figure 11). By 2050, potential off-grid emissions fall to between 114 and 317 mmt, depending on scenario, or 1.3-5.8% of the projected total for global residential electricity consumption. There are a growing number of low-carbon off-grid alternatives to diesel generators available, thanks in large part to the dramatic decline in the cost of batteries and solar PV panels. Meeting potential off-grid electricity demand with low-carbon solutions could significantly reduce its climate footprint.

Figure 11: Residential electricity-related CO2 emissions across scenarios
Million metric tons

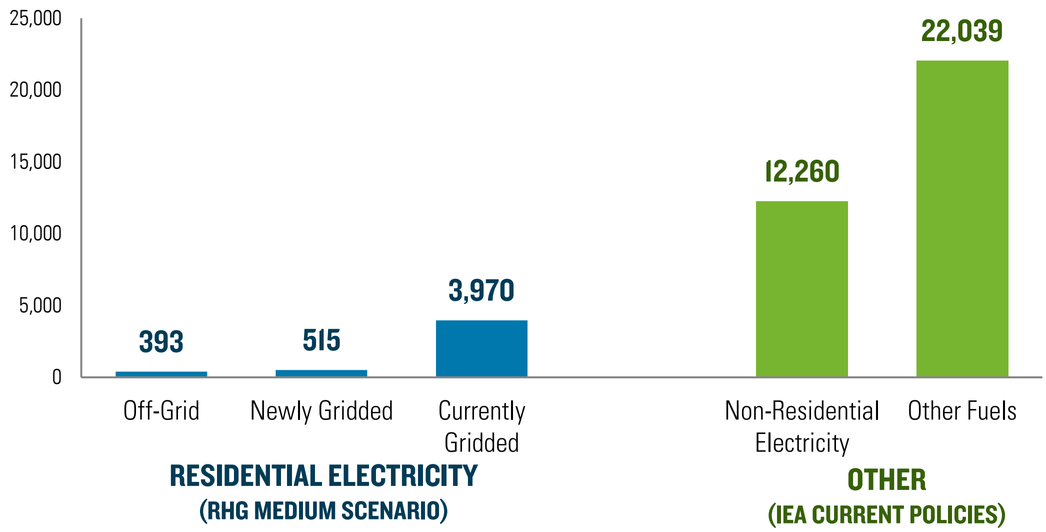


Source: IEA, IIASA, World Bank, and RHG estimates.

Residential electricity-related emissions in context

To put these projections in context, we compare residential electricity results from our Medium Scenario in 2030 to the IEA's World Energy Outlook projections for CO2 emissions from non-residential electricity consumption and non-electricity energy consumption in 2030 under their Current Policies Scenario (Figure 12). While the economic and population growth assumptions vary between the two analyses, this comparison provides a rough approximation of the relative importance of expanded electrification from a climate perspective.

Figure 12: Energy-related CO2 emissions in 2030
Million metric tons



Source: IEA, IIASA, World Bank, and RHG estimates.

In our Medium Scenario, expanding electricity access to all households that currently lack it could result in up to an additional 908 mmt of CO_2 per year in 2030. Of this, 515 mmt comes from households likely to become grid connected between 2012 and 2030 (assuming no new policy-driven change in the carbon-intensity of grid-supplied electricity), and up to 393 mmt coming from electrifying off-grid households with high-carbon distributed energy solutions (e.g. diesel generators). In this scenario, emissions from currently grid-connected households would be 3,970 mmt that year. Under the IEA's Current Policies Scenario, other energy-related CO_2 emissions are projected to reach 34,299 mmt in 2030 (IEA, 2015b). Using those estimates, the maximum potential increase in global energy-related CO_2 emissions from achieving the UN's goal of providing universal electricity access by 2030 is 2.3%.

CONCLUSION

Meeting the UN's goal of ensuring access to affordable, reliable, sustainable, and modern energy for all is critical from both a humanitarian and economic development standpoint. But from a climate standpoint, given that the vast majority of projected growth in electricity-related emissions comes from areas currently connected to the grid, decarbonizing grid-tied electricity remains the most pressing power sector-related priority.This includes improving grid reliability to reduce the need for back-up generation and accelerating deployment of low-carbon grid-connected generation, whether distributed or central station.While climate should be one consideration in strategies for expanding electricity access to those that currently lack it, given the relatively small potential emissions impact, its important to balance this with affordability, speed of deployment, and public health considerations.

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APPENDIX A: METHODOLOGY

Estimating even current electricity access and consumption in low-income and rural areas is notoriously difficult—for a more complete discussion of the data challenges, see the World Bank's discussion of its own methodology detailed in the Global Tracking Framework report (2013). These challenges only grow when attempting to project these quantities into the future—large uncertainties in fundamental socioeconomic drivers such as economic, population, and urbanization growth can play as large a role as energy policy, if not larger, in the development of energy systems and the populations able to access them.

Quantifying the relative importance of grid-tied and off-grid electricity consumption, however, does not require a perfect projection of absolute quantities, but only a study of their relative magnitudes. We exploited this fact by conducting a scenario analysis in our examination of residential access and consumption. In each scenario, we examine the factors that drive increases in access to electricity and the patterns of consumption that characterize populations with access. This allowed us to separate scenario uncertainty from the uncertainty observed in our statistical models. We found that while significant differences do exist in the sizes of populations with and without access and the quantity of electricity they consume, the relative importance of off-grid consumption to grid-tied consumption remains very small across all scenarios.

Modeling the share of current residential population with access to electricity

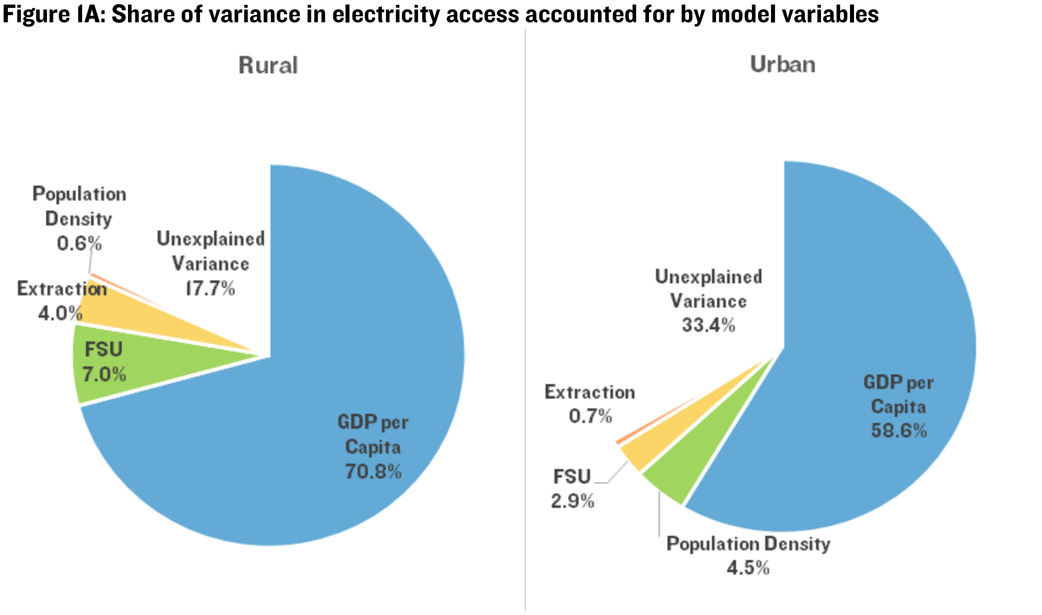
We modeled current electricity access rates for urban and rural populations separately as a function of GDP per capita, population density, and the World Bank's measure of adjusted net national savings as a share of GDP, which represents the share of gross national product coming from the value of raw materials extracted through forestry, metals and mineral mining, and oil, gas, and coal production. Additionally, we added dummy variables to the regression to indicate a country's membership in the Former Soviet Union or the UN's list of Small Island Developing States.

Table 1A: Electricity access logistic model regression results

	Urban	Rural
(Intercept)	-11.22 (1.56) ***	-14.52 (1.93) ***
GDP/capita [ln(2011 PPP)]	1.40 (0.16) ***	1.69 (0.20) ***
Population Density [ln(persons/km^2)]	0.31 (0.12) *	0.15 (0.15)
Adjusted Savings [% of GDP]	-2.05 (1.57)	-5.13 (2.19) *
Former Soviet Union [Flag]	5.72 (7.38)	18.92 (1948.46)
Small Island Developing States [Flag]	-0.07 (0.36)	-0.13 (0.42)

Source: Rhodium Group Analysis.
Estimates shown with standard error in parentheses
P-values: *** < 0.005 < ** < 0.01 < * < 0.05 < · < 0.1 <   < 1

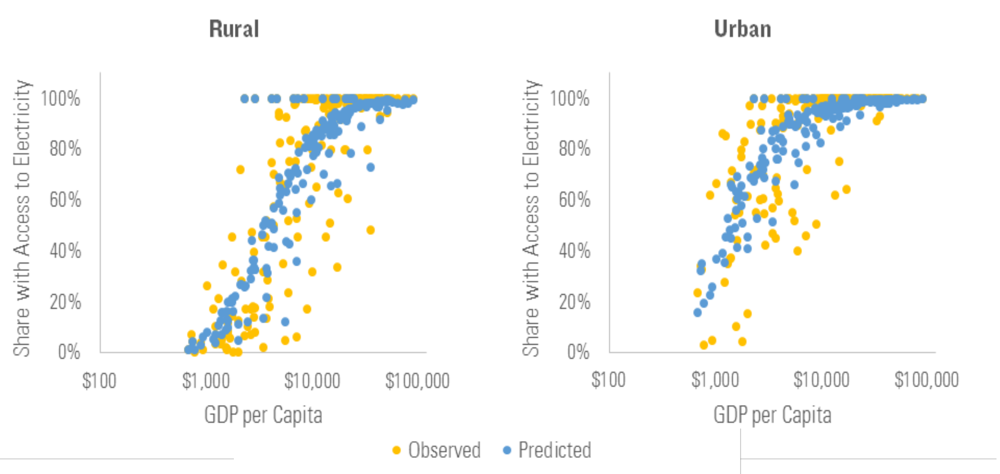
Figure 1A: Share of variance in electricity access accounted for by model variables



Electricity access rates were obtained from the International Energy Agency (IEA)'s WEO 2014 *Electricity Database* (IEA 2014) and World Bank's "Access to electricity (% of population)" indicator (World Bank 2015). The IEA electricity access data does not have complete global coverage, so for every country in this analysis, the IEA data was used when available and the World Bank data was used elsewhere. Population, GDP, population density, and adjusted net national savings data were obtained from the World Bank (World Bank 2015). While electricity access and population data are available separately for urban and rural areas, GDP, population density, and adjusted savings are only available nationally. Despite this shortcoming in the data, our models of urban and rural electricity access still predict observed electrification rates well. This is because electrification rates are more a function of national rather than local policy, and the pathways for both urban and rural electrification, while distinct, are determined by these national variables.

The data was modeled using a logistic regression, with equal weight given to each country. This model explains the majority of the observed variation in electricity access rates across countries (we found adjusted R-squared values of 0.82 and 0.66 for rural and urban populations, respectively). For both rural and urban models, the largest share of variance is explained by GDP per capita; membership in the Former Soviet Union (FSU), population density, extraction share, and Small Island States (SIDS) membership explain smaller portions of variance (see Figure 1A). The residual variation by country lacks significant patterns and trends for a number of candidate variables, including region of the world, GINI coefficient, foreign direct investment (FDI), official development assistance (ODA), and adjusted savings from mineral extraction and forestry as a share of GDP, as well as all variables modeled in this analysis.

Figure 2A: Predicted and observed access rates by country, plotted against GDP per capita



Source: Rhodium Group Analysis.

Projecting socioeconomic data

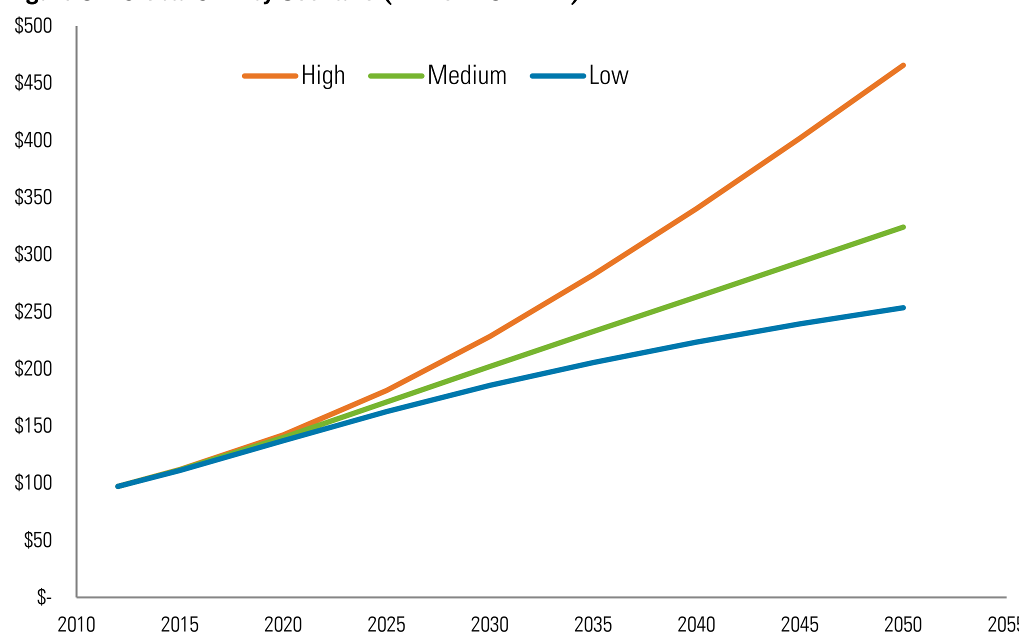
Our projections of the key indicators used to model electricity access—population, GDP, and urbanization—were taken from the Shared Socioeconomic Pathways (SSPs), which are the socioeconomic scenarios underlying the IPCC's climate projections (O'Neill et al., 2015). The actual data for these projections was obtained from IIASA's "SSP Database" (IIASA 2015). We have chosen to use SSPs 3, 2, and 5 as our Low, Medium, and High scenarios (see Figures 3-6A). SSP 3 is described as the "Regional Rivalry" scenario, in which mitigation and adaptation challenges dominate, and both urbanization and economic growth are slow. In this case, population growth is high, consistent with a low-urbanization future. SSP 5 is called the "Fossil-fueled Development" scenario, consistent with a high-growth, highly urban future. SSP 2, "Middle of the Road," is just that—it lies between the other two scenarios for all key indicators we used.

To develop estimates of 2030 and 2050 population and GDP by country, we applied the growth rates observed in the SSPs for these variables by country. For example, 2050 GDP for the United States in the low scenario is equal to 2012 World Bank US GDP times the growth in US GDP from 2012 to 2050 in the low SSP scenario. The SSPs only provide data in 5-year time steps, so we interpolated 2012 values between 2010 and 2015 using a compound annual growth rate (CAGR).

The SSP data is provided for 175 countries, while the World Bank data used to perform the initial-year regressions includes 186 countries. For countries present in the World Bank data but missing in the SSP data, we extrapolated from the base year to 2030 and 2050 using the weighted average growth rate for the region that each missing country belongs to. For example, Bermuda's 2050 GDP is equal to Bermuda's 2012 GDP according to the World Bank times the weighted average GDP growth rate from 2012 to 2050 of the "Other Non-OECD Countries" present in the SSP data set.

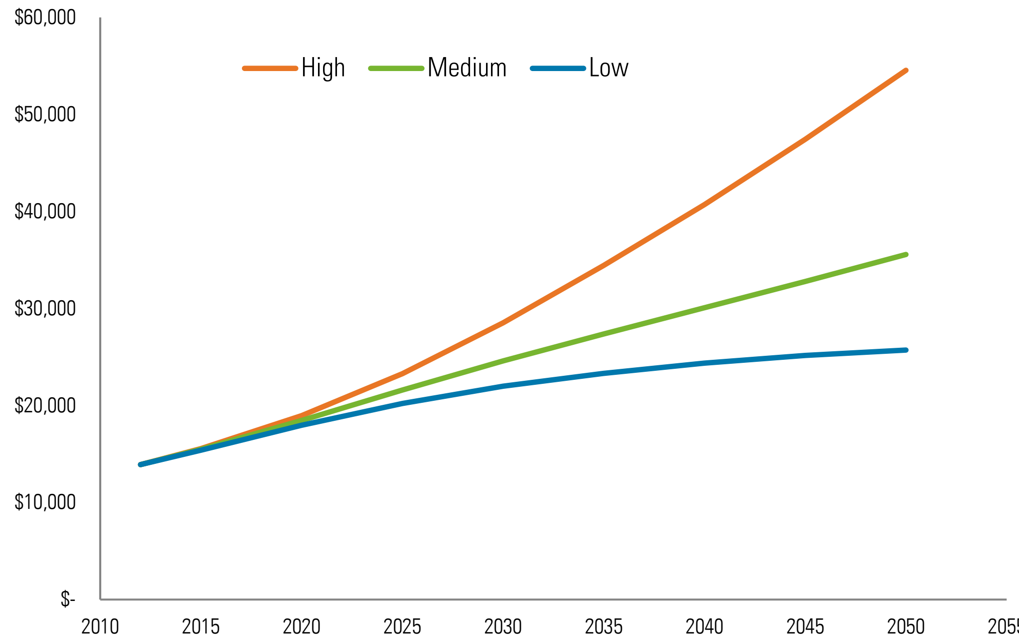
We used a different approach to project urbanization rates, since the rate must be bounded between zero and one. In 2012, we applied the current urbanization rate published by the World Bank, ensuring that both 2012 population and 2012 urban population agree with current data. The 2012 urbanization rate was obtained by linearly interpolating between the 2010 and 2015 values by country and scenario. We then used the difference between the SSP urbanization rates in each year from the rate in 2012, and added this to the World Bank urbanization rate in 2012, with the constraint that rates be between 0 and 1. For example, the US urbanization rate is currently 81.1%, and the high SSP scenario projects urbanization rates of 82.8% and 91.3% in 2012 and 2050, respectively. Therefore, our 2050 urbanization rate projection is (91.3% - 82.8%) + 81.1%, or 89.6%. For countries not present in the SSP data, we used population and urbanization rates from the median case of the UN Population Division's World Population Prospects: 2015 Revision (UN 2015).

Figure 3A: Global GDP by Scenario (Trillion 2011 PPP)



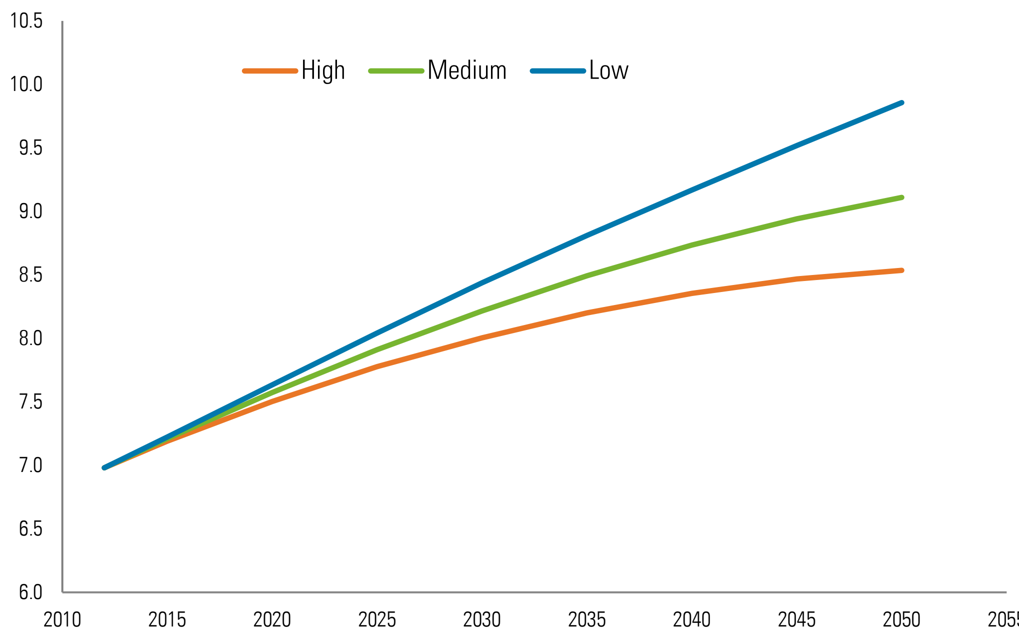
Source: World Bank, IIASA, and Rhodium Group Analysis.

Figure 4A: Global GDP per Capita by Scenario (2011 PPP)



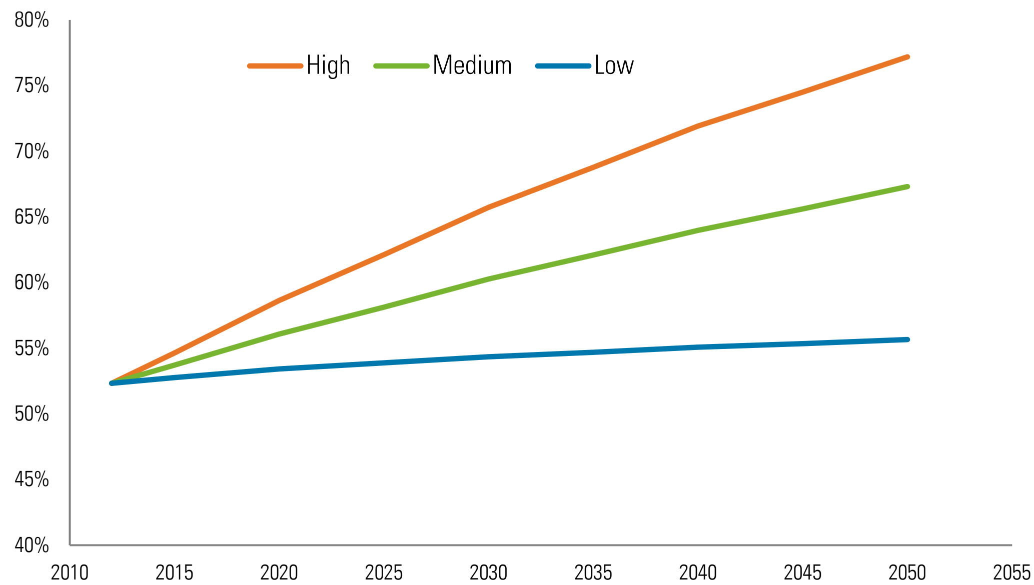
Source: World Bank, IIASA, and Rhodium Group Analysis.

Figure 5A: Global Population by Scenario (Billion)



Source: World Bank, IIASA, and Rhodium Group Analysis.

Figure 6A: Urban Share of Global Population by Scenario



Source: World Bank, IIASA, and Rhodium Group Analysis.

Populations with access to grid-tied and off-grid electricity

We modeled urban and rural electrification rates using projected changes in GDP per capita and population density. We assumed that adjusted savings as a share of GDP will remain constant. FSU and SIDS statuses do not change. To maintain consistency with current electricity access rates, we set each country's final projected access rate to the maximum of the modeled rate and the current observed access rates from IEA and the World Bank. Because we used a max function there is an upward bias to our population projections, but this method significantly improves the fit to some individual countries and the effect on global electrification rates is less than 1 percent in 2050.

This model gave us the share of the population that we project will be connected to the grid by a given year, assuming grid connection growth is driven purely by forces that can be observed in the historic data. In effect, this represents a business-as-usual case. In reality, changes in electricity generation, distribution, storage, and consumption technologies may increase penetration rates beyond those projected in this analysis, especially in rural areas where off-grid solutions may be cost effective in the near- or medium-term. These additions would fall into one of two categories—off-grid or micro-grid installations in areas that will become economic grid-connected areas by 2050, and those in areas that will not fall into economic grid-connected areas by 2050. As is shown in our analysis, those falling into the latter category represent a small share of total electricity consumption, and increases in access represent significant humanitarian and development gains while contributing minimally to global GHG emissions.

We estimated the grid-tied population at current electrification rates by multiplying the population in a given projection year by the current IEA and World Bank estimates of 2012 electrification rates. We estimated the new grid-tied population by multiplying projected population in each year by the projected electricity access rate in that year, and subtracting the grid-tied population at current electrification rates. The off-grid population is the remainder of the population that is not connected to the grid. We assumed that by 2050, this population will have acquired access to electricity, but did not make an assumption about whether the access will come in the form of grid-tied, micro-grid, or distributed electric power.

Electricity consumption for on-grid residential consumers

We represented current (2012) residential consumption per capita (with access to electricity) as a linear function of per capita GDP, the urbanization rate, and access to electricity. This model explains the majority of the variability in the data with an adjusted R2 value of 73% (see Table 2A for additional regression results).

Table 2A. Consumption per grid-connected person regression results

	Urban
(Intercept)	-13.69 (0.50) ***
GDP/capita [ln(2011 PPP)]	0.84 (0.08) ***
Urbanization [% of population]	-0.23 (0.27)
Access to Electricity [% of population]	0.06 (0.31)

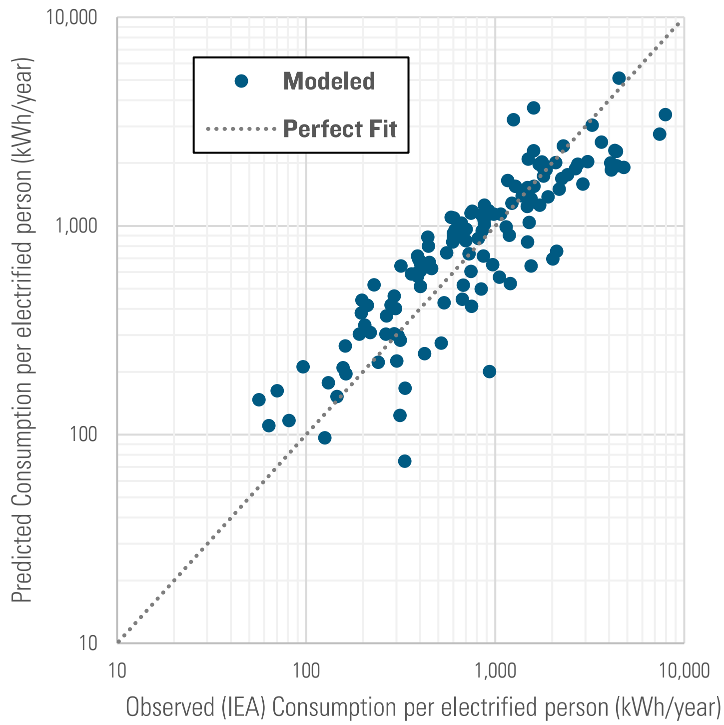
Source: Rhodium Group Analysis.
Estimates shown with standard error in parentheses
P-values: *** < 0.005 < ** < 0.01 < * < 0.05 < · < 0.1 <   < 1

Our analysis of current consumption data led us to model consumption per person with access to electricity rather than on a per capita basis. This indicates that increasing access to electricity will increase consumption through two pathways—first, it will increase the number of consumers of electricity, and second, it will increase the consumption rate of those consumers.

All three of these variables are represented explicitly in our socioeconomic projections and our electricity access projection. We represented growth in per capita consumption as the change in the modeled value with changes in per capita GDP, urbanization, and access to electricity. For example, 2050 consumption per capita is equal to IEA-reported 2012 consumption per capita (IEA 2015) times the ratio of modeled consumption per capita using 2050 values to modeled consumption per capita using 2012 values. The IEA consumption dataset contains only 130 countries; for countries not available in the IEA dataset we used the modeled per capita consumption values directly.

Finally, we made an energy efficiency adjustment to the projections. Specifically, we assume that all countries increase in energy efficiency at a constant compound annual growth rate, such that by 2050 each country's consumption per capita is 10% lower than it would be without energy efficiency.

Figure 7A: Consumption per grid-connected person model fit



Source: Rhodium Group Analysis.

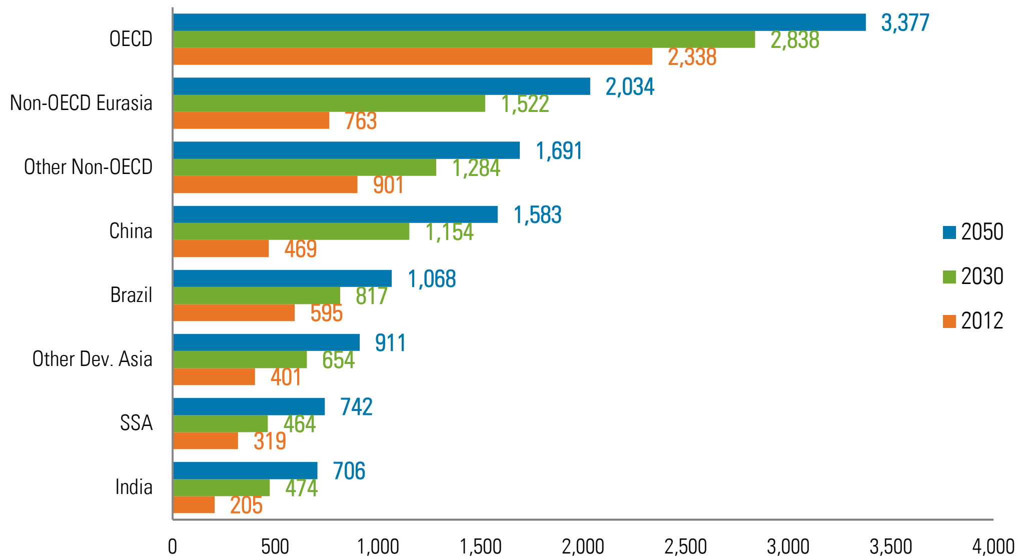
Electricity consumption for off-grid residential consumers

We examined three scenarios for 2050 off-grid electricity consumption. The first assumes the value used by the Sustainable Energy for All initiative in their Global Tracking Framework report (IEA and World Bank, 2015), which assumes that newly-connected electricity consumers globally will use 750 kWh per five-person household by 2030. As a lower bound, we applied this assumption to 2050 as well, assuming no growth in consumption per capita for those not connected to a national grid. This represents a scenario in which off-grid residences have limited access to electricity, such as through distributed intermittent resources without storage or through an unreliable or prohibitively expensive micro-grid.

Our second scenario, which represents a high, but conceivable, scenario of off-grid consumption, assumes that those not connected to the national grid use the same amount of electricity per capita as the national average of those connected to the grid. We applied the projection of country-specific consumption per grid-connected person in 2030 and 2050 to our off-grid populations as well. This represents a scenario in which off-grid residences are most likely connected to well-established micro-grids, or have affordable access to dispatchable generation (e.g. a diesel generator) or storage-backed intermittent generation (e.g. rooftop solar with sufficient battery storage).

Finally, we provide a high scenario in order to quantify the highest conceivable upper-bound of off-grid consumption. This scenario assumes that globally no one uses less electricity than current grid-tied consumers in China. This is calculated by using the same per capita demand projections as in our second off-grid scenario, but providing a floor on per capita demand at the current (2012) per capita level of grid-tied residential consumers in China.

Figure 8A: Annual per capita consumption for on-grid consumers in the mid scenario



Source: IEA and Rhodium Group Analysis.

Figure 8A shows per-electrified-capita consumption for on-grid consumers by region in the mid-growth scenario. Off-grid consumption in 2050 in the mid off-grid consumption case is equal to these on-grid values in 2050; in the high case, consumption throughout each country is equal to the maximum of these modeled values and 469 kWh/capita per year, the current level of consumption per person with access to electricity in China. The low off-grid consumption case assumes all off-grid residential consumers use 150 kWh per person per year. Note that off-grid consumption per capita values only play a significant role in our projections for Sub-Saharan Africa, India, and the Other Developing Asia region—all other regions have grid access rates of more than 95 percent by 2030 and 99 percent by 2050.To derive the projection of total electricity consumption by off-grid residential consumers, we multiplied these consumption rates by the estimates of off-grid population described above.

On-grid residential GHG Emissions

To estimate the emissions from grid-tied residential electricity consumption we assume that countries have the average electric power-sector emissions factor for the country's corresponding region in the *World Energy Outlook 2015* "Current Policies" Scenario (IEA, 2015b). This emissions factor is derived by dividing total power-sector emissions by electricity generation. The *World Energy Outlook 2015* only projects these quantities to 2040 and we assumed that the emissions factor by region in 2050 is equal to the value reported for 2040.

Off-grid residential CO2 Emissions

To provide an upper-bound estimate of the emissions from off-grid residential electricity consumption, we assume that all of the electricity consumed in this sector is produced by low-capacity diesel generators. The emission factor used for this analysis is derived from the median *2006 IPCC Guidelines for National Greenhouse Gas Inventories* tier 1 emission factor for Gas/Diesel Oil Stationary Combustion (IPCC, 2006). We assume these generators operate at 34% electrical efficiency, which is the assumed efficiency of current-vintage oil-fired engines in the EIA's National Energy Modeling System (EIA, 2015). This likely represents a gross overestimate of average off-grid emissions factors, as emissions on a per-kWh basis from renewables, biomass, and natural gas would be lower than those of small-scale diesel generators.

APPENDIX B: DISCLOSURES

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