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Energy poverty alleviation and climate change mitigation: Is there a trade off? ☆

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ABSTRACT

Energy poverty alleviation has become an important political issue in the most recent years. Several initiatives and policies have been proposed to deal with poor access to modern sources of energy in many developing countries. Given the large number of people lacking basic energy services, an important question is whether providing universal access to modern energy could significantly increase energy demand and associated CO^2 emissions. This paper provides one of the few formal assessments of this problem by means of a simple but robust model of current and future energy consumption. The model allows mapping energy consumption globally for different classes of energy use, quantifying current and future imbalances in the distribution of energy consumption. Our results indicate that an encompassing energy poverty eradication policy to be met by 2030 would increase global final energy consumption by about 7% (roughly 20 EJ). The same quantity of energy could be saved by reducing by 15% energy consumption of individuals with standards above current European levels. The additional energy infrastructure needed to eradicate energy poverty would produce 44–183 $GtCO^2$ over the 21st century and contribute at most 0.13 °C of additional warming.

1. Introduction and motivation

Understanding the distribution of current and future energy needs is an important goal for research and policy. On the one hand, lack of access to reliable energy is believed to hamper economic growth in poor economies. This is known as 'energy poverty', and has received increased political attention in most recent years. On the other hand, energy consumption met with the current fossil fuel based energy mix leads to emissions of greenhouse gases, which are accumulating in the atmosphere and are the major source of global climate change. Analyzing the extent to which these two global problems interact with each other would allow us to better understand which policy instruments can be put in place if both problems were to be tackled. The contribution of this paper is to provide some quantitative input to this discussion. We employ a reasonably simple model calibrated on data on consumption and income distributions, and show that it can replicate quite accurately the current distribution of final energy consumption by households. We use the model to assess the pressing policy issue of energy access to different parts of the society, and evaluate the impacts of energy poverty alleviation in terms of additional demand of energy and associated greenhouse gas emissions for different carbon intensity assumptions. Our tool is useful for mapping and representing global imbalances: we show that now the poorest 3 billion people have negligible energy consumption, and that the 1 billion people with energy consumption equal or above the European standards use 3/4th of total final energy. Taking as given the projections of international agencies such as the IEA, we show that in a Business as Usual scenario in 2030, minor changes would occur in the low energy consumption categories, with roughly the same number of people lacking access to basic human energy needs, though with an increased concentration in Africa. On the other hand, there will be a large number of additions in the higher energy consumption categories, mostly driven by economic development in the fast growing economies. We estimate the additional energy demand which would be required to eradicate energy poverty at about 20 EJ in 2030, less than 10% of the projected consumption in a BAU, and 15% of consumption of the most affluent categories. With different assumptions about the carbon intensity of energy infrastructure, this additional demand would generate carbon emissions over the century in the range of 44–183 $GtCO_2$. This corresponds to a relatively minor contribution to global warming. Our analysis thus supports the thesis that energy poverty and climate change policies can be set independently from each other.

2. Measuring energy needs

The debate surrounding energy access has become a key one in energy policy-making over the last few years, an acknowledgment of

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the important role of energy in development. Though energy poverty cannot be completely distinguished from traditional poverty alleviation, its independent assessment is important for various reasons. First, though poverty traps have long been recognized, their solution in terms of policy intervention is still highly debated, with the traditional divide between strong government intervention and laissez-faire being blurred by the large evidence now accumulated in randomized experiments (Duflo and Banerjee, 2011). Second, the policy relevance of the subject has motivated a push towards new measurements and data collection of energy poverty, paving the way for additional and more accurate research in the field. Finally, energy access is intertwined with other pressing global issues, in particular the fight against global climate change. A joint solution of these two issues is required even if their exact interdependence is still to be resolved. Against this background, most of the academic discussion on energy poverty has focused on measurement and policy, but has not yet developed formal tools to generate numerical estimates of the impacts of energy poverty alleviation, with only few recent exceptions (Bazilian et al., 2012). Similarly, the integrated assessment modeling community – which plays an active role in the assessment of climate mitigation scenarios in the IPCC – has recently made steps forward towards an integrated modeling approach to energy sustainability (McCollum et al., 2011), but has dealt only to a limited extent with energy poverty (Ekholm et al., 2010). The objective of this paper is to shed light on these issues by providing a quantitative assessment of the distribution of future energy needs at the global level. This allows us to pin down where energy demand growth will come from, not only in terms of country of residence but also in terms of segments of population, defined by levels of energy consumption. We estimate the energy needs of the poorest segments and the range of additional emissions, depending on the possible primary energy sources. The magnitude of global poverty cannot be exaggerated and energy poverty is no exception. The IEA estimates that about 1.3 billion people do not have access to electricity, the FAO states that 1 billion people are undernourished and the WHO estimates that 830 million urban residents live in slums. And the latest estimates of poverty measured in dollar terms from the World Bank suggest that roughly 1.3 billion people live below the poverty line of 1.25$ a day. The various dimensions of poverty – energy, food, health and sanitation – have significant overlap but are not perfectly correlated (Pachauri and Spreng, 2011). This has led to a considerable effort in the field to construct relevant measures of energy poverty. Several indices have been proposed in the past few years, among which are the Energy Indicators for Sustainable Development (Foster et al., 2000; Vera and Langlois, 2007), the Access–Consumption matrix (Pachauri et al., 2004), the Energy for Development Index (?), the Total Energy Inconvenience Threshold (Mirza and Szirmai, 2010) and the Multidimensional Energy Poverty Index (Nussbaumer et al., 2012). This incomplete list reflects the challenge of measuring and even of defining poverty: this should come as no surprise to poverty experts, who are aware that the concept of absolute poverty is a contested one, as testified by the existence of poverty glossary books (Spicker et al., 2007). The Copenhagen declaration of the world summit for social development defines absolute poverty as "a condition characterized by severe deprivation of basic human needs, including food, safe drinking water, sanitation facilities, health, shelter, education and information. It depends not only on income but also on access to social services". Strikingly, energy does not appear in the list, though its availability is instrumental for most if not all the listed basic needs. As noted above, energy poverty experts have struggled to generate indexes which capture the multidimensional essence of energy poverty, but generally speaking two main approaches have been followed (Kemmler and Spreng, 2007): either based on engineering/bottom up estimates of energy needs and access to energy services, or from standard income/consumption poverty measures. Direct estimates of energy needs and services are more accurate, but are not available for all countries, and vary in definition and measurement. Income and consumption poverty data is much richer, mostly as a result of significant data collection through surveys coordinated by the World Bank, but is an imperfect indicator of energy poverty. A trade-off between the two is unavoidable. For the sake of this paper, we will stick to the consumption poverty definition, since our intention is to build a global mapping of energy needs, and to focus not only on the poorest but across all the main different energy consumption classes, for which a strong correlation between energy and income has been established (see for example, Lenzen et al., 2006).

3. Data and methods

Our approach is to build a transparent but rigorous model which can generate global, regional and national maps of final energy consumption for households, by different classes of energy consumption. We then use it to project forward in time the distribution of energy demand. This approach builds upon and extends that of Chakravarty et al. (2009). We build distributions of household energy consumption at the country level assuming that household energy consumption and income or consumption are related by a power law relation, as suggested in several empirical studies (Lenzen et al., 2006).

In order to do so, we avail of a comprehensive database on income and consumption distributions using World Bank and UNU-WIDER income distribution survey databases. We model each country income distribution using a Beta-2 (B2) probability distribution (Chotikapanich et al., 2007). The B2 function has a small number of parameters, and is sufficiently flexible for almost all cases. The B2 function is

$$f(y) = \frac{y^{p-1}}{b^p B(p,q)\left(1+\frac{y}{b}\right)^{p+q}}, y>0 \tag{1}$$

where $b>0$, $p>0$, $q>0$ and $B(p,q)$ is the Beta function,

$$B(p,q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p+q)} = \int_0^1 t^{p-1}(1-t)^{q-1}dt. \tag{2}$$

The p and q parameters control the shape of the Lorenz curve (or the inequality) of the distribution which is independent of the parameter b. We also assume that $q>1$ which is required for the first moment (mean income) to exist. The mean income I is linear in the parameter b

$$I = \frac{bp}{q-1}. \tag{3}$$

The cumulative distribution function (c.d.f.) of the B2 function is

$$F(y) = \frac{1}{B(p,q)} \int_0^{y/(b+y)} t^{p-1}(1-t)^{q-1}dt = B_{y/(b+y)}(p,q) \tag{4}$$

where $B_t(p,q)$ is the incomplete Beta function (in Eq. (2), $B(p,q) = B_{t=1}(p,q)$). We also use the fact that the p.d.f. of $y^k f(y)$, for integer k, are themselves B2 functions.

Income distribution data is usually provided in terms of income or expenditure share of quintiles or deciles. The plot of cumulative income share vs. cumulative population share is referred to as the Lorenz curve in the income distribution literature. Essentially, it is a plot of the c.d.f. of the normalized first moment vs the c.d.f. The Lorenz curve provides a visual measure of the inequality in the distribution. The Gini coefficient is defined as twice the area between the diagonal line and the Lorenz curve. A Gini coefficient of 0 implies perfect equality and 1 implies maximum inequality. We estimate the parameters of the B2 function using a weighted non-linear least square fit of the Lorenz curve of the distribution against the Lorenz curve of the data. To take a specific example, in the case of Poland we have the following income distribution data for the year 2003.

Cumulative population	0	0.1	0.2	0.4	0.6	0.8	0.9	1
Cumulative income share	0	0.031	0.075	0.195	0.356	0.578	0.73	1

Let X and Y denote the cumulative population and income shares respectively. We estimate the parameters p and q by solving

$$\underset{p,q}{arg\min} \sum W_i (y(p,q) - Y)^2 \tag{5}$$

where

$$y(p,q) = B^{inv}_{x(p,q)}(p+1, q-1) \text{ and } x(p,q) = B_X(p,q).$$

The weights W_i are used to compensate for the fact that the higher quintiles dominate the fit. The parameter b can be obtained from Eq. (3).

In our model, household energy consumption is related to income/consumption by a constant elasticity of 0.8, in line with the central estimates of the empirical evidence based on energy surveys, though we provide a sensitivity analysis to this important parameter. The elasticity from various country level studies falls in a narrow range though one would naturally expect the elasticity to vary with income level inside countries. There have been few studies that quantify this expectation. Our approach in this paper is to make the most parsimonious and robust assumptions and minimize the number of arbitrary parameters required. Given the paucity of data, we do not take country level intra income elasticity variation into account. We also neglect different regional energy price differences, given that our focus is to capture the fundamental engine of growth of energy as a function of increased levels of well being.

Assuming a power law relationship between energy and income with elasticity e (energy~income^e), the B2 distribution can be converted to a generalized B2 distribution of population density as a function of energy consumption.

The energy distribution (i.e., the population distribution w.r.t. energy) is

$$f_E(y) = \frac{a y^{ap-1}}{\mathbf{b}^{ap} B(p,q) \left(1 + \left(\frac{y}{\mathbf{b}}\right)^a\right)^{p+q}}, y>0 \tag{6}$$

where

$$a = 1/e, \ \mathbf{b} = b^{1/e}/R, R = \frac{1}{E} b^e \Gamma(p+e)\Gamma(q-e))/(\Gamma(p)\Gamma(q))$$

and E is the average energy consumption. The data on energy consumption is obtained from the IEA (Extended World Energy Balances), measured in final energy consumption units. Since we focus on policies to provide access to modern energy, we disregard the traditional energy source component of the IEA's energy statistics. This is equivalent to counting traditional energy as having minimal useful value, which is justified given its low conversion efficiency.[1] Moreover, most of the available data on traditional energy is often sketchy and unreliable. As we are interested in household energy consumption only we consider the fraction of the final energy associated to consumption and not to production. We use the coefficients estimated in Peters and Hertwich (2008) to separate household energy consumption share, and the direct and indirect components.

[1] This also implies that traditional energy is carbon neutral. We discuss more about this in the final section on emissions.

As for future projections, we use the World Economic Outlook 2011 (IEA) energy and population projections to 2030. We aggregate the country level energy probability distributions into the 14 macro regions used in the IEA projections, and for simplicity we assume that the p and q parameters of the country level Beta-2 distributions do not change over time (i.e., we assume constant inequality). One additional assumption that we make is that the 2030 population of the energy @ poor is an upper bound on the population of the energy poor in the 21st century. The model is written in an open source language (Python), and is freely available upon request. Finally, in order to convert energy consumption to emissions of greenhouse gases, we employ different estimates for the carbon intensity of energy and the replacement of the energy infrastructure. The high emissions case derives from coal powered electricity (1 kgCO_2/KWh) and oil (3.12 kgCO_2/kg) as fuel, and the low emissions case derives from renewable (0.014 kgCO_2/KWh) and gas (2.294 kgCO_2/kg oil eq).[2] The global temperature rise associated with these emissions is estimated using the linear relationship between cumulative emissions and equilibrium temperature rise as proposed in the carbon budget approach (Allen et al., 2009).[3]

In order to simplify the representation of continuous probability density functions, and to provide a more clear connection to policy, we use five representative categories of energy consumption defined by the thresholds shown in Table 1. The first three signposts have been proposed by UN Secretary-General's Advisory Group on Energy and Climate Change (AGECC),[4] and represent key incremental steps in the energy access matrix, in terms of basic human needs, productive uses, and modern society. Basic human needs provide basic energy services in terms of electricity for lighting, health, education, communication and community services, as well as modern fuels for cooking and heating. Productive uses provide electricity and fuels to increase productivity in agriculture, commercial activities and transportation, such as access to mechanical energy for agriculture or irrigation, commercial energy, or liquid transport fuels. Modern society refers to energy services for more domestic appliances, for cooling and heating, and for private transportation. Since our scope is to provide a mapping of the whole society, we add a fourth category of 'higher energy consumers', defined by consumption equal or above the current European average.

Policies defined in terms of universal energy access by the UN encompass both the Basic Human Needs and the Productive uses.

4. Mapping energy needs globally, now and then

We are now ready to present the main results of the model used in this paper. Fig. 1 reports our main results in terms of global current and future distribution of population (left panel) and energy (right panel), across the five energy consumption categories of Table 1. The chart shows that both now and in a 2030 BAU scenario, a large fraction of global population will lack access to basic human needs (1.8 billion people) and productive uses (3.4 billion people). These numbers match quite well the current estimates of energy poverty. Between now and 2030 more than 1 billion people will be added to the global population; about 1/3 will go in the third and fourth energy

[2] We use the 50 percentile numbers from Table A.II.4, Annex II, of the Special Report on Renewable Energy Sources and Climate Change Mitigation (see http://srren.ipcc-wg3.de/report/IPCC_SRREN_Annex_II.pdf) for our estimates for the CO_2 intensity of different electricity generation technologies. The estimate for the CO_2 intensity oil comes from the fact that oil is approximately 85% carbon. For gas, we use the emissions intensity of the 1 kg oil equivalent quantity of gas. (Also see Voluntary Reporting of Greenhouse Gases Program http://www.eia.gov/oiaf/1605/emission_factors.html.)

[3] Specifically, each 1000 GtCO_2 emitted in the atmosphere generates roughly 0.48 °C of warming, with a 90% confidence interval range between 0.27 °C and 0.68 °C.

[4] The document is available at http://www.un.org/wcm/webdav/site/climatechange/shared/Documents/AGECC%20summary%20report[1].pdf.

Table 1
Categories of final energy consumption and associated emissions.

Category definition	Energy consumption (GJ/capita/year)	CO_2 emissions at current global average energy mix (tCO_2/capita/year)
Basic human needs: 100 kWh/capita/year + 100 kg oil/capita/year	5	0.41
Productive uses: 750 kWh/capita/year + 150 kg oil/capita/year	10	0.83
Modern society: 2000 kWh/capita/year + 375 kg oil/capita/year	25	2.1
EU average (half the US average)	75	6.2

consumption categories (10–25, 25–75 GJ/capita/year), reflecting the growth of the global middle class. A more modest population increase would occur in the energy poverty and in the energy rich categories (in the order of 150 million people added to each bin). Turning to the distribution of energy (right panel), the chart clearly highlights the global imbalances in energy consumption. The almost 3 and 1/2 billion energy poor contribute negligibly to global energy consumption, with less than 10% of the total household final energy demand. At the other hand of the spectrum, the 1 billion people with energy consumption levels at or above European standards is responsible for half of global energy consumption. This is also the category where most additional energy will be consumed in 2030 with respect to today (≥20 EJ), despite the limited additions in terms of population. The category of consumption between 25 and 75 GJ/capita follows close. The appendix provides some sensitivity with respect to the elasticity between income and energy consumption (assumed to be equal to 0.8 for all regions in the base case),[5] indicating that the picture shown in Fig. 1 is quite robust.

The models also allow us to determine the regional repartition of the population and the energy consumption distributions, see Fig. 2. Africa is the region where about 40% of the energy poorer (below the basic energy need consumption of 5 GJ) reside today, and this figure is projected to increase and approach 60% in 2030, due to strong population growth and moderate energy consumption increases in a BAU. India instead would reduce its significant role in the lowest category (from 25% to 10%) but would be by far the largest contributor (almost 50%) of the second category with consumption levels still below productive uses. Moving up in the categories, the most notable change is perhaps unsurprisingly China, which would increase its share in the upper two categories, reaching 30% and 6% in 2030 respectively. In the top category with energy consumption levels above those of European standards, the OECD countries will continue to remain the largest contributors, with 60% of the population in the top bin being from the OECD in 2030. Energy exporting countries like Russia, and Middle East also play an important role in the top categories, despite lower average per capita income, due to high energy intensity.

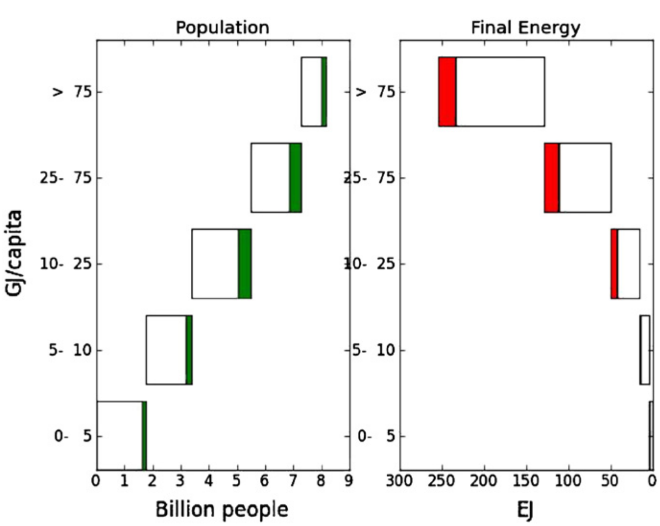

Fig. 1. Global distribution of population (left panel) and HH final energy (right panel) across the 5 energy consumption categories, in 2009 (white bars), and additions from 2009 to 2030 (colored bars).

5. The energy and climate impacts of poverty alleviation

Our analysis of current and future individual energy consumption indicates that energy poverty is, and will continue to remain prominent in the years to come without targeted policy interventions (and provided that such policies would work). However, it is important to keep in mind that alleviating energy poverty is not just a tremendous challenge per se, but that it also inter-relates to other key pressing issues related to sustainability. It is thus important to be able to quantify the implications of poverty alleviation on future energy consumption and on associated emissions of greenhouse gases. The available literature provides a contrasting picture. Most assessments by international organization and experts' activities in the field suggest these to be quite moderate. For example, the IEA estimates that universal access by 2030 would increase electricity by 2.5%, and fossil fuels by 0.8%. The World Bank estimates that the additional emissions needed to provide universal access to electricity could be offset by a switch of the US vehicle fleet to European standards.[6] However, the impacts might be substantial at the regional level: for example it has been estimated that power installed capacity in Africa 2030 would increase from 79 to 500 GW to provide full electricity access (Bazilian et al., 2012). Moreover, poverty alleviation measures might promote economic growth and yield an increase in energy demand beyond expectations provided that the elasticities between income and energy are sufficiently high. This has led some researchers to go as far as suggesting that neglecting poverty reduction and pro-poor growth policies is leading us to grossly underestimate future energy use (Gertler et al., 2011; Wolfram et al., 2012). Several targets can be defined when dealing with poverty alleviation. Here we retain the one in line with the UN categories of Table 1, and work out the implications of a policy which would grant universal access by 2030 to a minimum of 10 GJ/capita $*$ year, so as to ensure productive uses of energy. In the jargon of our graphs, this would correspond to providing additional energy to the roughly 3.5 billion people, so that by 2030 no one would be left in the lowest two categories; the additional energy would be directed mostly to the 1.8 billion energy poorer, but also to those who

[5] Specifically, we lower it for all countries (to 0.5), increase it to all countries (to 1), and differentiate between developing (=1) and developed countries (=0.5). This covers most of the spectrum of parameter estimates, though we always retain the basic assumption of the paper of a constant elasticity relation between income and energy consumption.

[6] See the World Development Report 2010, http://wdronline.worldbank.org/worldbank/a/c.html/world_development_report_2010/abstract/WB.978-0-8213-7987-5.abstract.

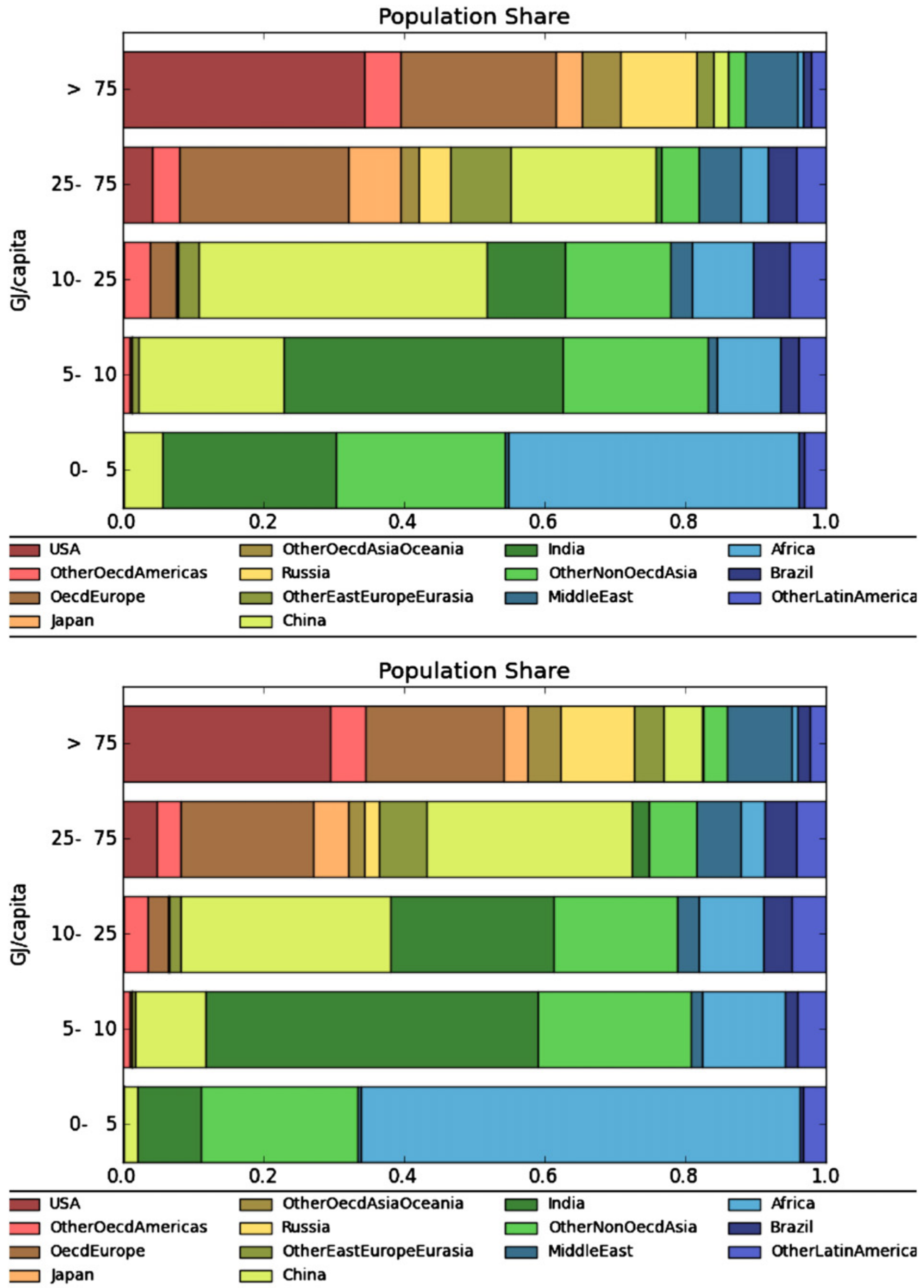

Fig. 2. Regional shares of population across the 5 energy consumption categories in 2009 (upper panel) and 2030 (lower panel).

have basic needs but lack productive uses. Table 2 summarizes the results of this energy poverty eradication program for the mostly affected regions, as well as globally. It indicates that globally the additional energy consumption of this poverty alleviation program would be slightly less than 20 EJ, or about 7% of total final energy consumption in 2030. The bulk of the additions would fall on Africa, whose aggregate final household energy consumption would need to exactly double with respect to the case without a poverty alleviation policy. Significant increases in demand – in the order of 20% – would also result in South and South-East Asia. This suggests that albeit the minor global impacts of energy poverty eradication, some regions would experience quite dramatic changes.

Our results indicate that the repercussions of a policy meant to eradicate energy poverty would be relatively small on global energy demand. Similar results have been suggested in other studies. For example, the International Energy Agency has simulated a universal access policy in 2030,[7] and has find that this would lead to an increase of global energy demand by only 1%. This is expected to require total investments in the order of 1 USD Trillion, or about 3% of the total energy-related infrastructure investment. Moreover, it has been shown that only a combination of policies that lowers costs for modern cooking fuels and stoves, along with more rapid electrification, can enable the realization of the energy poverty reduction goals (Pachauri et al., 2013).

[7] The IEA has focused on a policy which would allow to achieve universal electricity access, assuming a basic level of electricity for every person gaining access. Our policy allows for a higher threshold of minimum consumption (both basic and productive uses), and thus leads us to estimating slightly higher figures.

Table 2
The impacts of energy poverty eradication policy in 2030 on energy consumption, regionally and globally.

Region	Final HH energy consumption in a BAU (EJ)	Additional energy consumption for the poverty eradication policy (EJ)	Energy consumption increase over BAU (%)
World	254.4	18.9	7%
Africa	9.5	9.7	102%
India	14.8	3.4	23%
Other non OECD Asia	18.0	3.9	22%
China	38.1	0.87	2%
Other Latin America	8.3	0.66	8%
Brazil	7.3	0.18	2%

The additional energy demand can also be translated into additional CO_2 emissions depending on the carbon intensity of the energy mix. This is important if we want to assess the extent to which the energy poverty and the climate change agenda interact with each other. In order to do so, we assess different scenarios of carbon intensity of the energy mix, for a targeted energy poverty policy which linearly ramps up the energy consumption of the energy poor such that in 2030 the minimum per capita household energy consumption is 10 GJ/year. The purpose of this exercise is to estimate the mean and upper bound on the additional cumulative emissions generated until 2100. We assume that the additional energy has an intensity in the range 0.036 tCO_2/GJ [Low] to 0.112 tCO_2/GJ [High]. The 'Low' estimate uses renewables for generating electricity and natural gas as the clean fuel (cooking, heating, etc.) whereas the 'High' estimate uses coal for electricity and oil as fuel. We assume that, given the long life of energy infrastructure, the additional infrastructure will be in place for another 30 years (i.e. constant emissions until 2060). Finally, we make two different assumptions for the retirement of the additional energy infrastructure in the period 2060–2100: in the 'optimistic' case the additional infrastructure linearly ramps down to zero emissions in 2100. In the 'pessimistic' case, the additional emissions stay constant. Table 3 reports the estimated emissions and their breakdown in the three periods, as well as a quantification of the impacts of these emissions on global warming as measured by the increase in surface global mean temperature. The table shows that the cumulative emissions due to energy poverty eradication would be in the range of 44 to 183 $GtCO_2$, with the discrepancy mostly attributable to the use and retirement of the additional energy infrastructure in the long term. In terms of consequences for global warming, the induced temperature change would be very limited, below 0.13 °C in all cases with high probability. It is also instructive to compare this level of emissions to the carbon budget consistent with policies aimed at climate stabilization; climate stabilization policies compatible with the 2 °C objective entail cumulative emissions over the century in the range of 1500–2500 $GtCO_2$, and thus the emissions associated with the energy poverty policy would increase the mitigation effort by at most 7%. Carbon prices for a 2C climate policy (e.g. 450 ppm-eq) have been estimates at 12–120 $/$tCO_2$ in net present value, with a median of around 40$/$tCO_2$ Clarke et al. (2009); taking this last value the carbon costs of the energy eradication program would be at most in the order of 8–9 USD trillion (for the high scenario of 183 $GtCO_2$).

Finally, since our analysis has focused only on modern energy, we have not accounted for the additional implications of switching from traditional to modern means of energy. Moving cooking to LPG from biomass would increase fossil energy demand, but would displace biomass consumption. Recent work has quantified that this reduction is as much as 12–15 EJ Pachauri et al. (2013). Given that biomass is often harvested unsustainably, this reduction could lead to a reduction of biomass related emissions which would further lower the climate impact of the energy poverty program, in addition to generating welfare gains from air quality improvement.

6. Concluding remarks

Modern sources of energy like electricity and clean cooking fuels are the prerequisite of a life with a minimal standard of comfort and dignity. There is a tremendous imbalance in the access to and consumption of these energy sources today: the poorest 3 billion people suffer from debilitating energy poverty while the richest 1 billion consume an overwhelming fraction. Sub-Saharan Africa, South Asia and South East Asia are home to most of the world's energy poor. The projected growth under BAU will not lead to sufficient improvement in energy poverty eradication, especially in Africa. Countries like China will be successful in moving a significant number of people to higher energy consumption brackets. This paper proposes a simple model to quantify the number and global distribution of the energy poor, building on the data and methodologies developed to study income distribution. The model proposed in this paper is used to estimate the global distribution of energy consumption and its projected evolution in the next 30 years. It is useful for quantifying and mapping global imbalances. We show that a global energy poverty reduction policy aimed at providing 10 GJ energy per capita to the global energy poor would increase global energy demand by 7% in 2030; energy demand would increase substantially in some specific regions, most notably in Africa, where it would double. When accounting for the long lasting impacts of the needed energy infrastructure, we show that this policy would have a very small impact on climate change mitigation, even under scenarios where the additional energy infrastructure is carbon intensive. We estimate that the additional infrastructure will produce 44–183 $GtCO_2$ over the 21st century and contribute at most 0.13 °C warming. This impact is manageable when combined with mitigation and efficiency improvements in other fields, and the management of these emissions would not pose a serious threat to the achievement of climate protection goals, unless these are very stringent. The benefits to

Table 3
Estimated additional emissions and temperature rise from an energy poverty alleviation program.

	Low		High	
	Optimistic	Pessimistic	Optimistic	Pessimistic
2009–2030: Energy poverty alleviation emissions ($GtCO_2$)	8.0	8.0	24.9	24.9
2030–2060: Use of additional energy infrastructure ($GtCO_2$)	21.8	21.8	67.9	67.9
2060–2100: Retirement of additional infrastructure ($GtCO_2$)	14.6	29.1	45.3	90.6
2009–2100: Total emissions ($GtCO_2$)	44.4	58.9	138.1	183.4
Additional temperature increase (degree C): mean	0.02	0.028	0.066	0.088
Additional temperature increase (degree C): 10–90 percentile	[0.012–0.03]	[0.016–0.04]	[0.037–0.094]	[0.049–0.125]

human life and dignity of a successful energy poverty reduction will be immense.

We must remind the reader that the model has several limitations. The robustness of the income-energy elasticity is not without some variance, although the sensitivity analysis shown in Appendix A provides qualitatively similar results. The estimates focus on access to modern energy, considering traditional energy as essentially useless, and thus results need further investigation. Finally, the real question is whether energy poverty alleviation and pro-poor growth policies will lead to significantly faster rise in the growth of middle classes and their substantially higher consumption and associated emissions. Recent history shows that there is no clear answer to this question, different countries having had different growth trajectories from similar starting points.

Appendix A. Sensitivity analysis

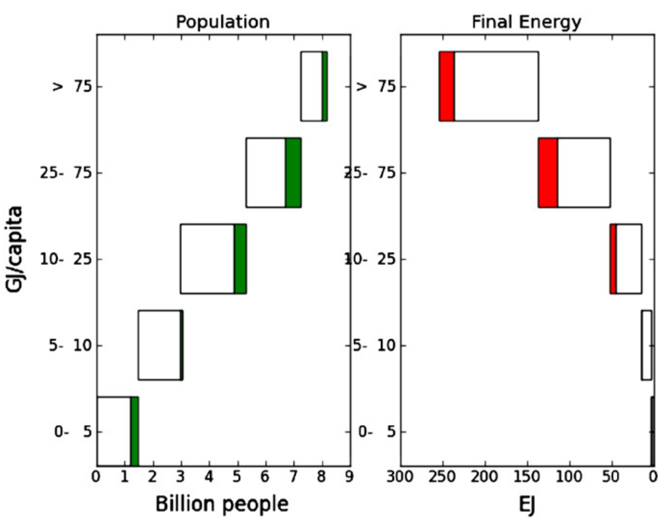

Fig. 3. Low elasticity. As in Fig. 1, but with an income elasticity of energy equal to 0.5 for all countries.

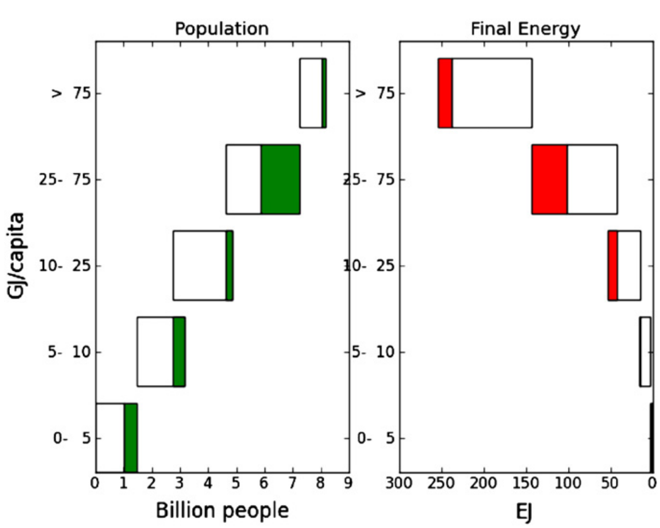

Fig. 4. High elasticity. As in Fig. 1, but with an income elasticity of energy equal to 1 for all countries.

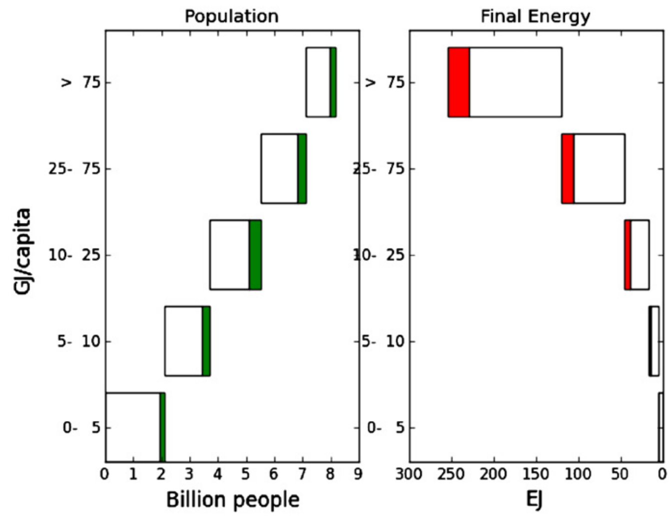

Fig. 5. Regional variation in elasticity. As in Fig. 1, but with an income elasticity of energy equal to 1 for developing countries (e.g. with today income below 12,000 USD per capita (PPP)) and 0.5 for industrialized countries.

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