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Supplementary

Threshold Electricity Consumption Enables Multiple Sustainable Development Goals

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1. Data sources

Human Development Index data are from the United Nations Development Programme as part of the Human Development Report published each years. Data for both the overall index as well as for the individual components are available at http://hdr.undp.org/en/content/human-development-index-hdi. For the present work, chosen years for the HDI are matched to the years for which energy data are available, usually 2014. Data for other indicators are taken from the World Bank database of World Development Indicators (WDI) that can be found at https://data.worldbank.org/indicator and from the US Energy Information Administration (https://www.eia.gov) Specific indicators used here are:

Indicator name	Indicator code	Figure
Electric power consumption, population	https://www.eia.gov/beta/international/data/browser/	1-3
Electric power consumption (kWh per capita)	EG.USE.ELEC.KH.PC	4, S5-S11
GDP per capita, PPP (constant 2011 international $)	NY.GDP.PCAP.PP.KD	S8, S12
Maternal mortality ratio (modeled estimate, per 100,000 live births)	SH.STA.MMRT	1, S1
Mortality rate, under-5 (per 1,000 live births)	SH.DYN.MORT	3, S3
Mortality rate, neonatal (per 1,000 live births)	SH.DYN.NMRT	2, S2
Human Development Index (HDI)	http://hdr.undp.org/en/indicators/137506	S4, S5, S6
Mean years of schooling	http://hdr.undp.org/en/indicators/103006	S7

Gross national income (GNI) per capita	http://hdr.undp.org/en/indicators/141706	
Life expectancy at birth	http://hdr.undp.org/en/indicators/69206	S9
Final energy use [GJ]	IEA Energy Balances [1]	S4
Food security index	http://foodsecurityindex.eiu.com/	S10
Improved sanitation facilities (% of population with access)	SH.STA.ACSN	S11
Population, total	SP.POP.TOTL	4

Population data, both current and projected increases, are taken from the United Nations World Population Prospects 2015 update, POP/DB/WPP/Rev.2015/POP/F01-1.

The WDI database does not include per capita electricity consumption for many African countries and other LDCs, or for many Small Island Developing States. For more complete coverage, data from the United States Energy Information Administration (https://www.eia.gov/) were used. In a few cases, to fill in gaps and cross-check data, the United Nations Environment Programme *Atlas of Africa Energy Resources* was used [2].

2. Threshold fits and statistics for SDG3-related targets

The following three figures repeat those in Figs. 1 – 3 in the main text, but include as well tables of least-squares fit parameters and uncertainties for each of the SDG3 targets as well as the original data plotted on linear scales

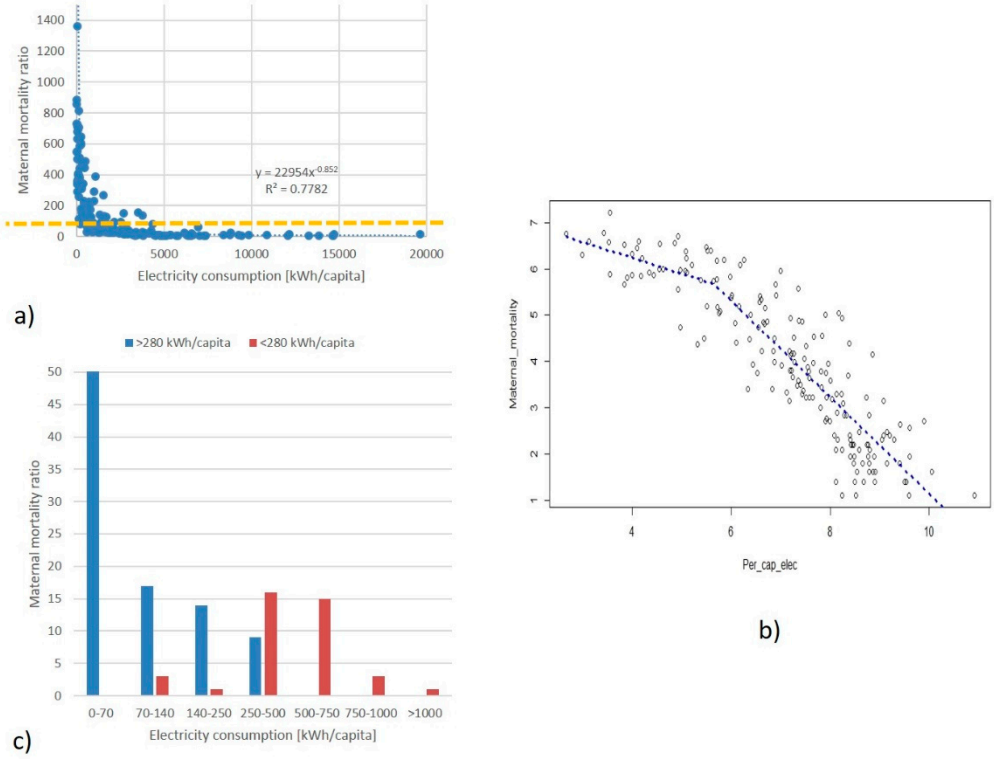

Figure S1 Maternal mortality rate vs per capita electricity consumption, **a**) linear scale, with the horizontal dashed line representing the SDG3 target; **b**) logarithmic scale for each with single

breakpoint fit result; **c**) histogram based on the breakpoint value and the SDG3 target. Data also shown in main text, Figure 1.

In the Box below, raw output from the R package "segmented" is shown for the fit to logarithmic data of maternal mortality rate and per capita electricity consumption.

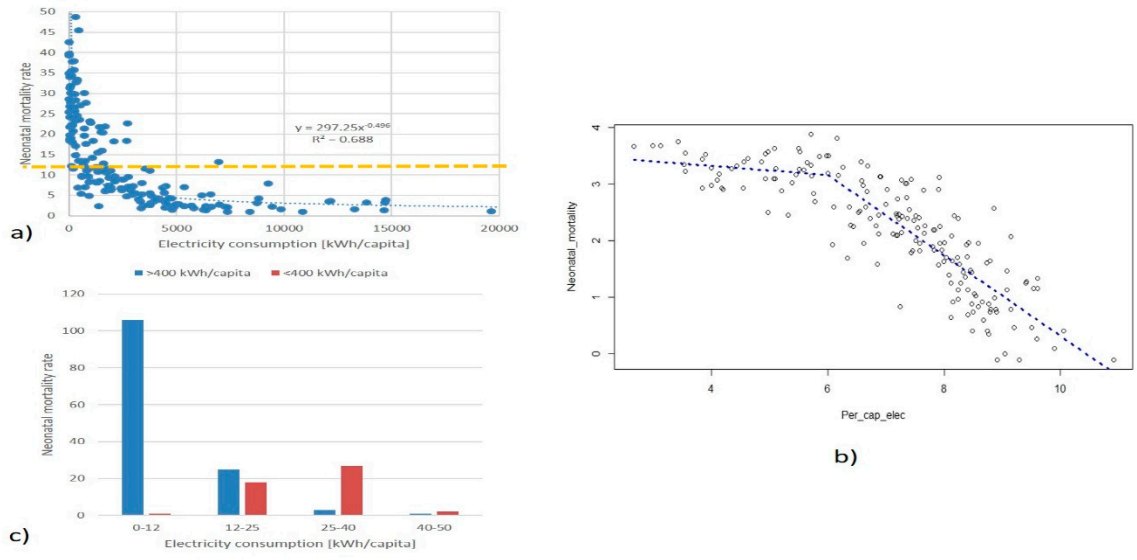

Figure S2 -Neonatal mortality rate vs per capita electricity consumption, **a**) linear scale, with the horizontal dashed line representing the SDG3 target; **b**) logarithmic scale for each with single

breakpoint fit result; **c**) histogram based on the breakpoint value and the SDG3 target. Data also shown in main text, Figure 2.

In the Box below, raw output from the R package "segmented" is shown for the fit to logarithmic data of neonatal mortality rate and per capita electricity consumption.

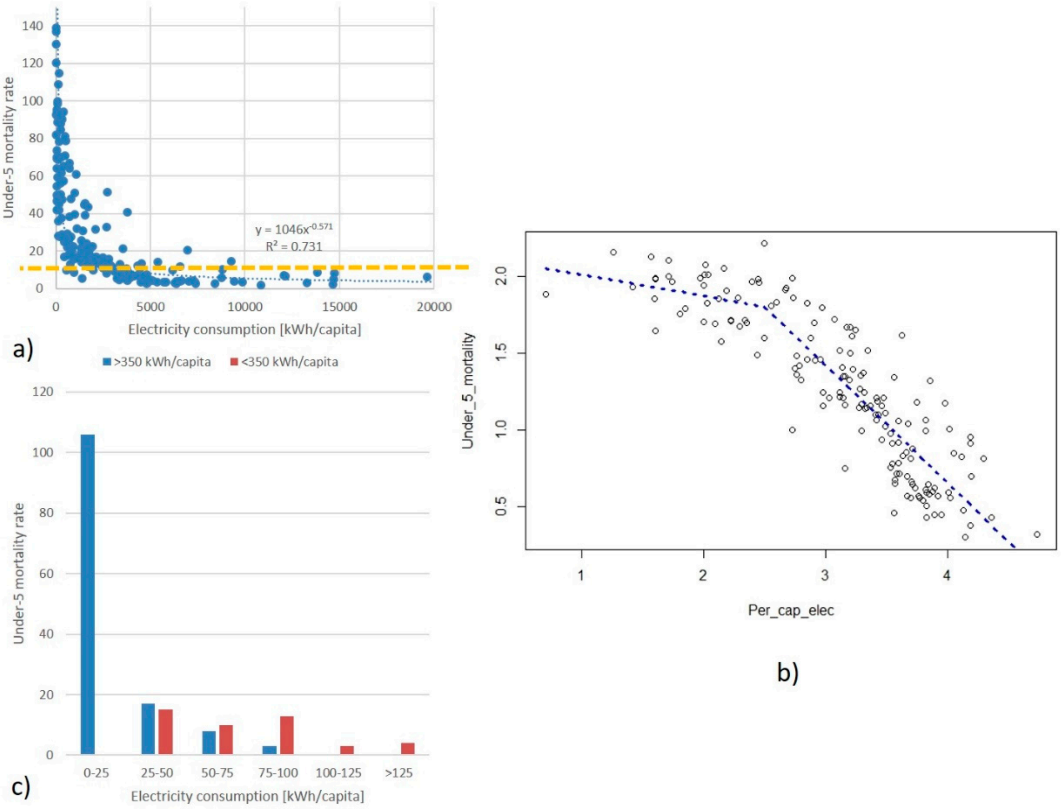

Figure S3 - Under-5 child mortality rate vs per capita electricity consumption, **a**) linear scale, with the horizontal dashed line representing the SDG3 target; **b**) logarithmic scale for each with single breakpoint fit result; **c**) histogram based on the breakpoint value and the SDG3 target. Data also shown in main text, Figure 3.

In the Box below, raw output from the R package "segmented" is shown for the fit to logarithmic data of under-five mortality rate and per capita electricity consumption.

3. Energy Consumption and Human Development

The Human Development Index (HDI) is one measure of average quality of life for a country [3].Expressed on a scale between 0 and 1, the HDI is a composite index of economic wealth, education, and health indicators. A plot of HDI values vs. final energy consumption per person [1] as shown in Figure S4 results in a characteristic trend toward higher levels of HDI with greater energy consumption, at least for lower levels of HDI. Beyond a certain level (greater than an HDI of about 0.8), however, increased energy consumption does not correlate with an increase in well-being. The diamonds in Figure S4 represent a snapshot of HDI values in the year 2014 for 139 countries for which both HDI and final energy data were available. The United Nations Development Programme considered ranges of human development (2014): <0.55, low (12% of world population); 0.55-0.70, medium (37%); 0.70-0.80, high (31%); >0.80, very high (20%)

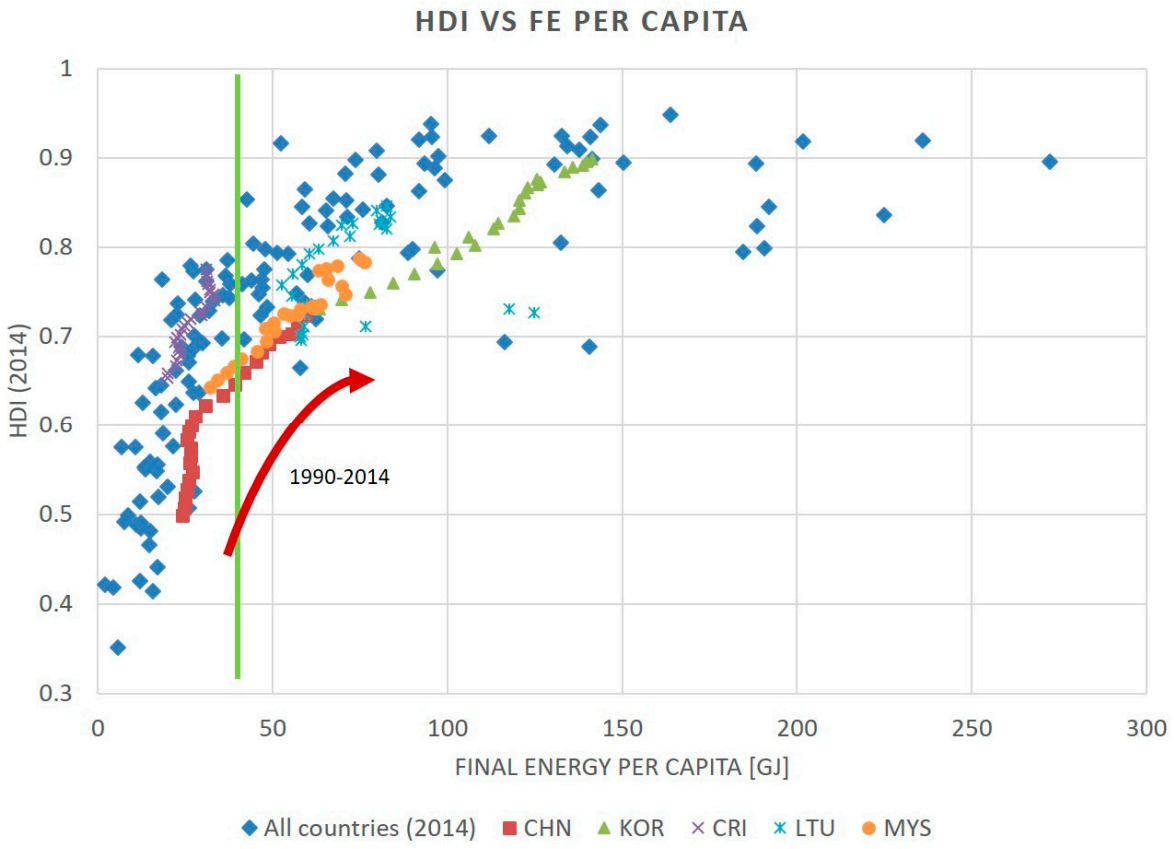

Figure 4. - Human Development Index as a function of per capita final (i.e. useful) energy. The diamonds are a snapshot of all countries with available data in the year 2014. The other series are for selected individual countries for each year from 1990to 2014. Sources of data: UN Development Programme, http://hdr.undp.org/en/content/human-development-index-hdi and International Energy Agency, http://wds.iea.org/wds/ReportFolders/ReportFolders.aspx?CS_referer=&CS_ChosenLang=en and World Bank, World Data Indicators, http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators#.

The low-energy, low-HDI end of the scale is most crucial in what follows. There is no country at a "very high" level of HDI (above 0.8) that does not have an average availability of final energy of at least 40 GJ per person per year. (In the US, final energy consumption is approximately 200GJ.) Conversely, countries with average final energy consumption of less than 40 GJ/capita, representing about half the world's population, have not been able to achieve "high" or "very high" HDI. Furthermore, we can look at these data to see how several individual countries develop over time (represented schematically by the curved line for all countries), and find that to-date, they follow a path that moves through stages represented by the snapshot of countries today, tracking from the lower left toward the upper right of the plot.

4. HDI and electricity consumption

The relationship between the Human Development Index (HDI) and per capita electricity consumption is shown in Figure S5. Panel S5a show data for 172 countries, representing about 97% of the world's population for which data on both HDI (vertical axis) and per capita electricity consumption (kWh per person per year, horizontal axis) are available for the year 2014. Wealthy countries, as represented by the Organization for Economic Cooperation and Development (OECD) have per capita annual electricity consumption of >5000 kWh, with an average of over 8000

kWh/person/year, with the United States at more than 12,000kWh/person/year (average value including all sectors of the economy). Looking more closely at lower-consuming countries, as in Figure S5b, it appears from the data that achieving a per capita electrification of about 2000 kWh would be correlated with raising the development index into the range of about 0.7, which the United Nations Development Program classifies as "High Human Development." Looking even further (Figure S5c), countries with less than 1000 kWh average per capita electricity consumption, representing 42% of the world's country populations, uniformly have HDI <0.7, with many of these countries being in Sub-Saharan Africa. It is these countries that are the focus of this paper.

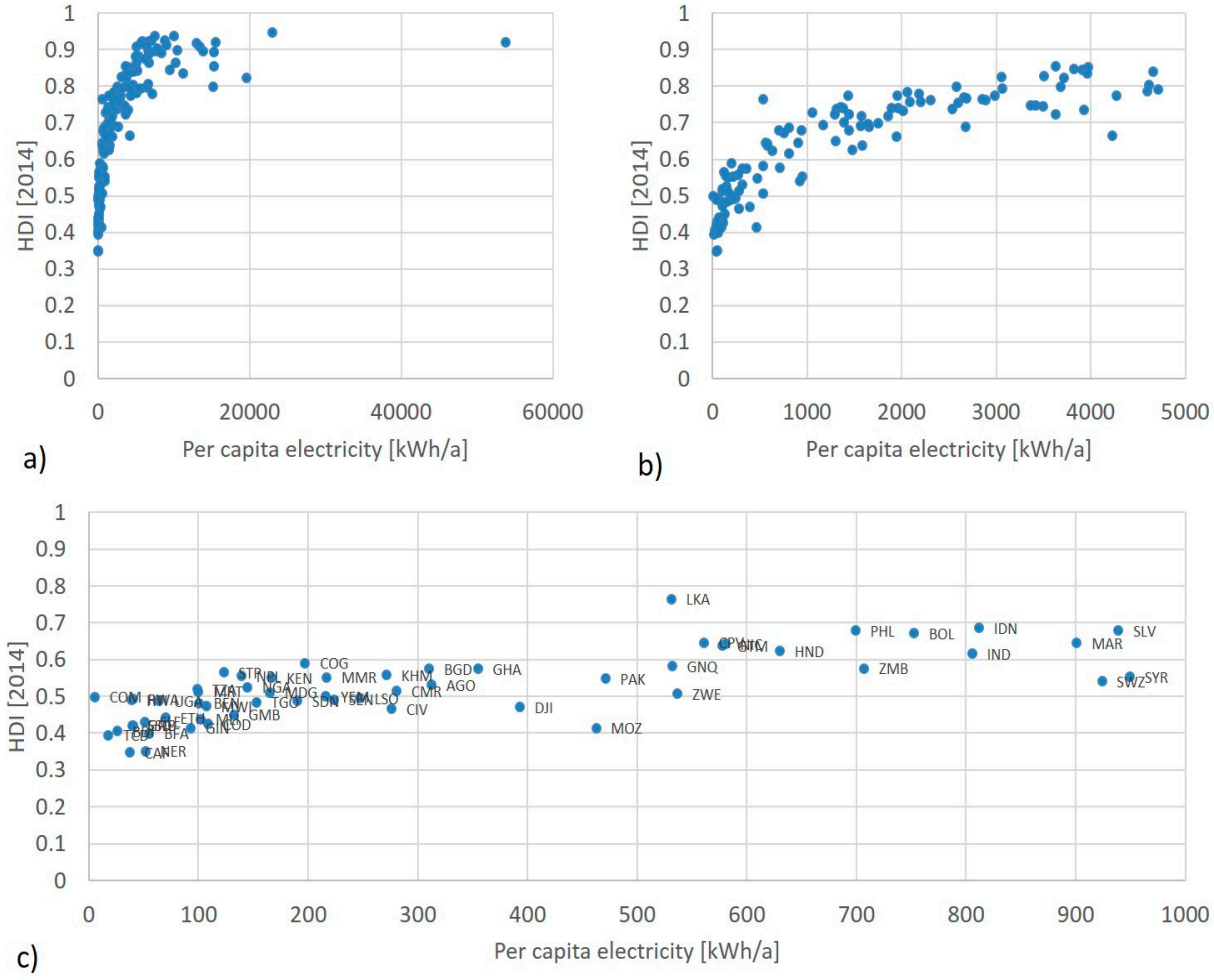

Figure 5. - Human Development Index as a function of per capita electricity consumption. ach point represents one country with data from 2014. Source: World Development Indicators, http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators# and http://hdr.undp.org/en/content/human-development-index-hdi.

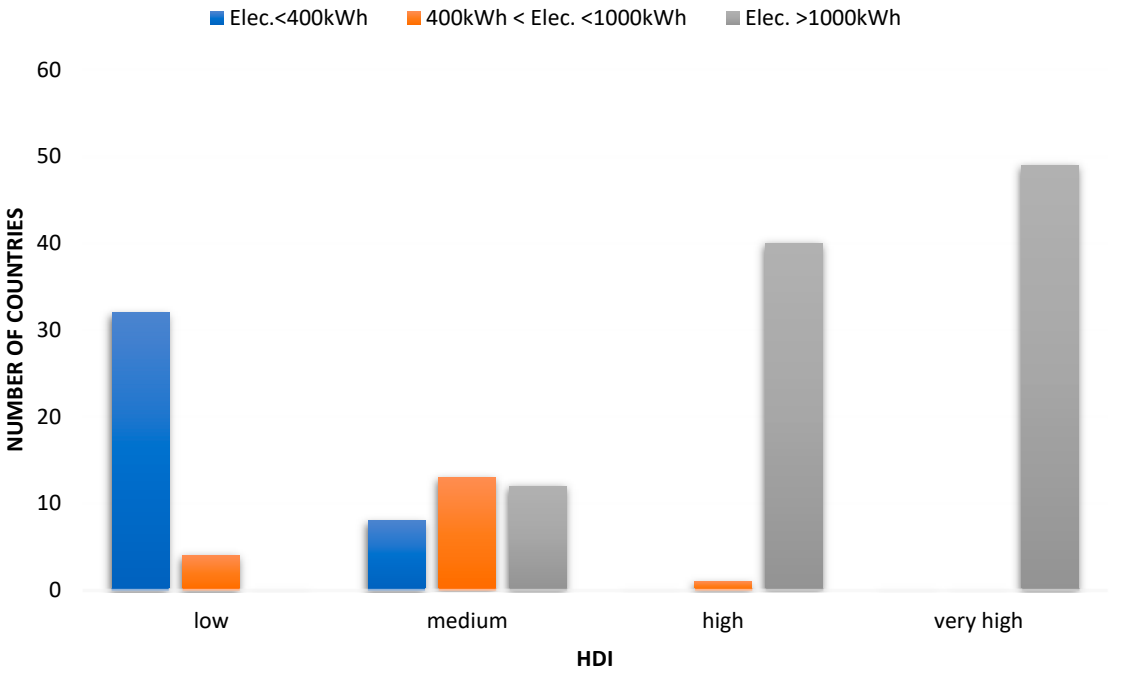

Figure 6. - Histogram of data for HDI, sorted according to electricity consumption per capita.

Figure S6 shows a histogram of countries as a function of HDI level and sorted as to per capita electricity consumption. With only one exception (Sri Lanka) no country meets the standard of "High" or "Very high" development with less than 1000kWh per capita country-average electricity consumption. Only 20% of those countries that rise above the "Low" Human Development category have electricity consumption of less than 400 kWh per capita.

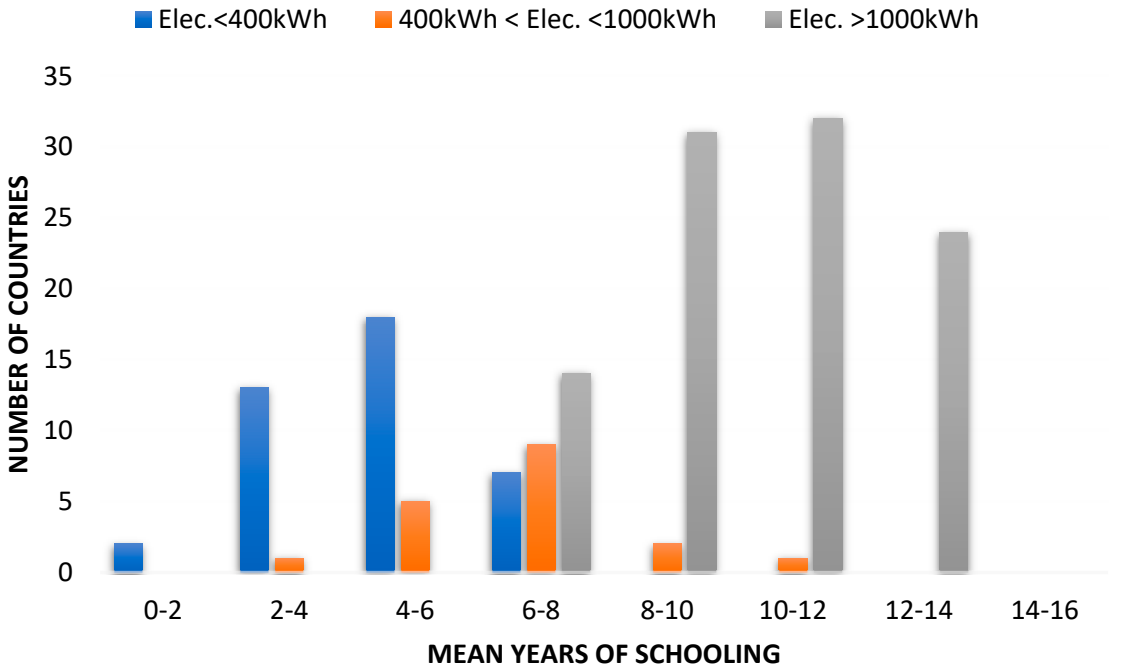

Figure 7. - Mean years of schooling for different electricity consumption ranges. Groups of countries are those with <400kWh per capita average annual consumption, those with between 400 kWh and 1000 kWh per capita, and those with >1000kWh. Data from UNDP, http://hdr.undp.org/en/data

One component of the HDI is mean years of schooling, with access to education also addressed by SDG4, to "ensure inclusive and quality education for all and promote lifelong learning" [4], with targets involving universal access, literacy and numeracy, and appropriate facilities. Figure S7 shows histograms for mean years of schooling [3], with different country groups divided by per capita electricity consumption [5]. There is a strong separation, with countries having lower electricity consumption very unlikely to have more than early secondary school education levels on average. In contrast, countries with greater than 1000kWh of per capita average annual electricity consumption *are very unlikely to average less than nearly eight years of schooling.*

Two components of the HDI are income (GNI per capita) and life expectancy at birth, in addition to the mean years of schooling discussed in the main text. Figure S8 is a histogram of the different electricity-consumption groups, each divided into bins corresponding to different per capita incomes. Of countries with per capita GNI corresponding to less than $10/day, 80% have average per capita electricity consumption under 400kWh/year. Conversely, of those countries with per capita GNI greater than $5/day, only 15% have <1000kWh/year electricity consumption. The GNI measure also corresponds to an augmented version of SDG1, to "end poverty in all its forms, everywhere" [4].

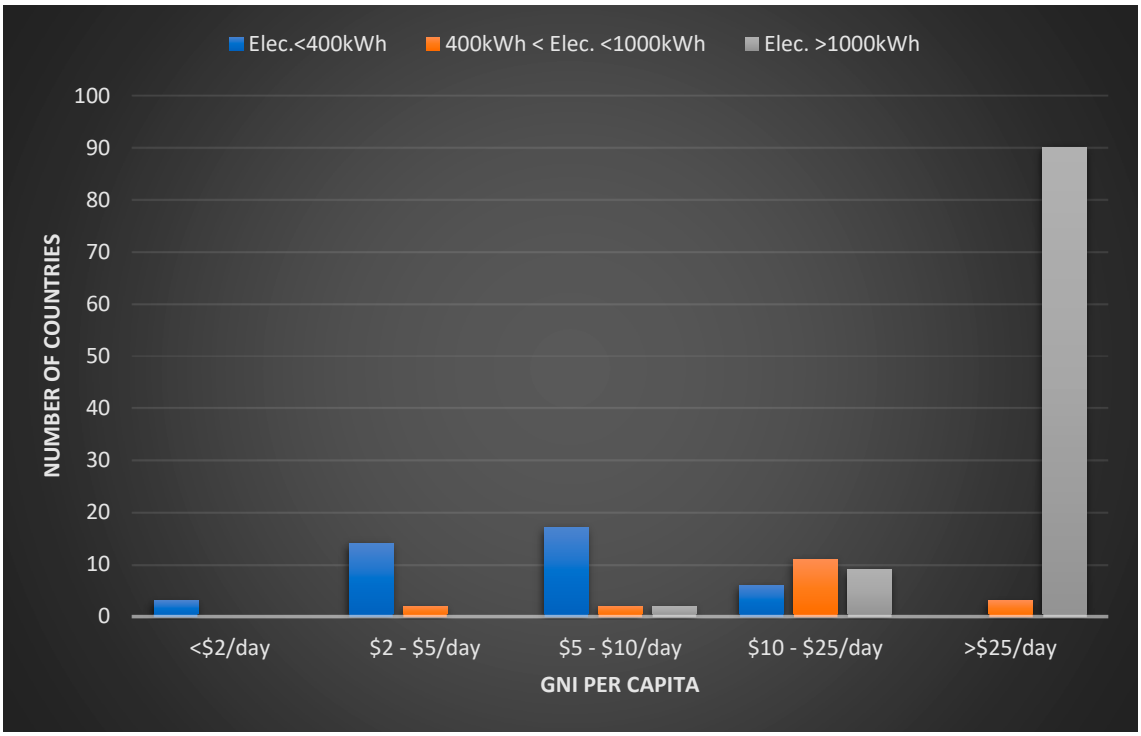

Figure 8. - Per capita GNI (Gross National Income) for different electricity consumption groups. Countries are grouped by how much electricity is consumed on average per capita per year, either <400kWh, between 400 kWh and 1000 kWh, or >1000kWh. Data from UNDP, http://hdr.undp.org/en/data.

In Figure S9 the world is again divided into countries that have, on average, consumption to either less than or more than 1000kWh/person/year, with the former category further sub-divided into those with less than the 400 kWh per capita used as marker in the main text, and those with between 400 kWh and 1000 kWh. Average life expectancy at birth is between 70-85 years for those with higher electricity consumption. If a country has consumption of less than 1000kWh of electricity per person, it is highly likely that the average life expectancy at birth is less than 70 years. This

division again links the idea of energy consumption to SDG3, "Ensure healthy lives and promote well-being for all at all ages."

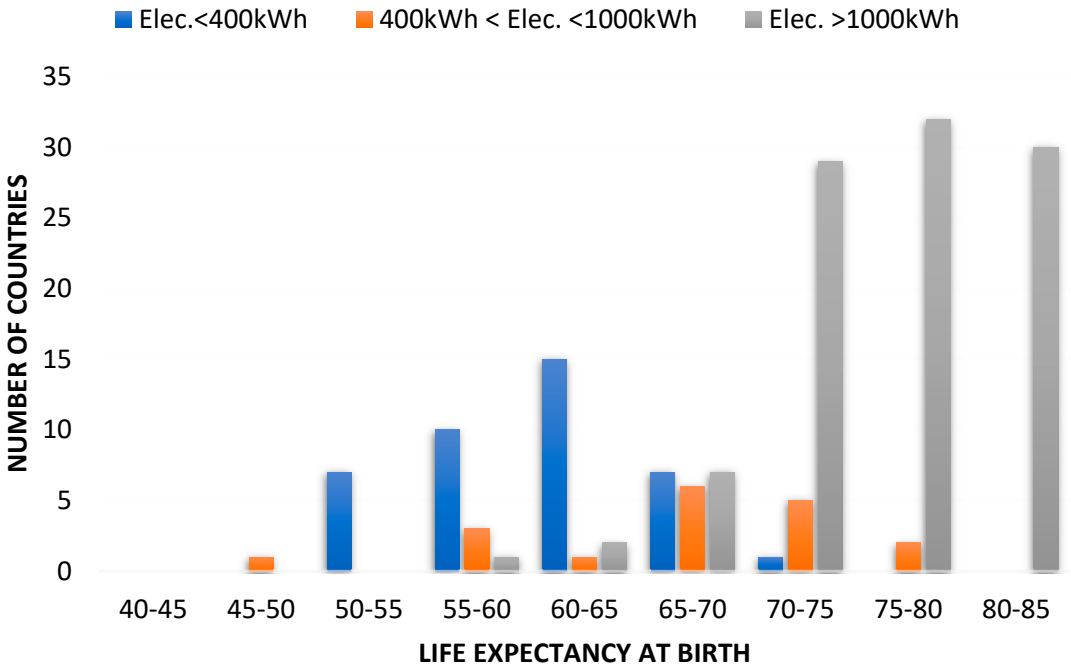

Figure 9. - Histogram of the number of countries with different ranges of life expectancy at birth. Countries are grouped by how much electricity is consumed on average per capita per year. The groups are a) <400kWh; b) between 400 kWh and 1000 kWh; and c) >1000kWh. Data from UNDP, http://hdr.undp.org/en/data.

Countries with average per capita electricity consumption of less than 400kWh per year have uniformly poor human development indicators, and are not meeting SDG targets. As discussed in the main text, this can be expressed on the other hand by stating, from the same data, that there is almost no country with average electricity consumption of 1000kWh per capita that has an average number of years of education less than eight, or life expectancy at birth of less than 70 years. For reference, this is the level of electricity use in the US in about 1950, as well as the life expectancy, and would correlate to average educational attainment at that time as well.

5. Electricity consumption thresholds for further SDG targets

As another, SDG2 calls for the world to "End hunger, achieve food security and improved nutrition and promote sustainable agriculture," with targets to "By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round" and "By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons." Expressing these targets in terms of the Global Food Security Index[1] an aggregate index on a scale of 0-100, with components of availability, affordability and quality, the familiar pattern from other development indicators appears.

[1] http://foodsecurityindex.eiu.com/

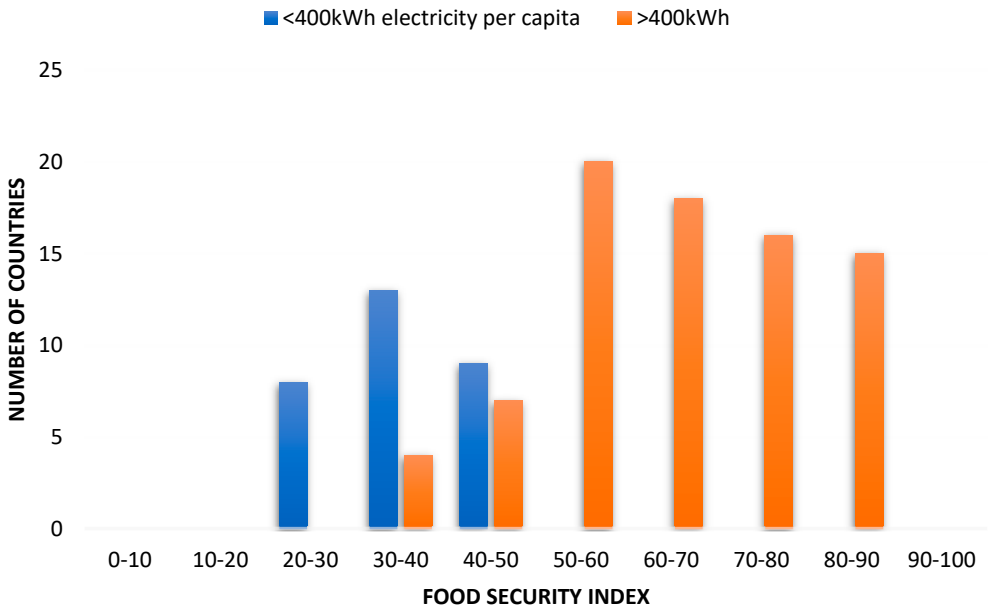

Figure 10. - Global Food Security index for 44 countries (blue bars) with <400 kWh per capita annual electricity consumption, and 67 countries (orange bars) those with >400 kWh per capita electricity consumption. Data from *http://foodsecurityindex.eiu.com/*.

We see in Figure S10 that those countries with less than 400kWh per capita electricity consumption are likely to be classified as having low food security, whereas those countries with higher per capita electricity consumption are very unlikely to have a low food security index (under 50).

Returning to the indicators in terms of the breakpoint fits found earlier, if 400kWh per capita is taken as a measure, then we find that no country with less than this level of consumption achieves a food security index value of >50.

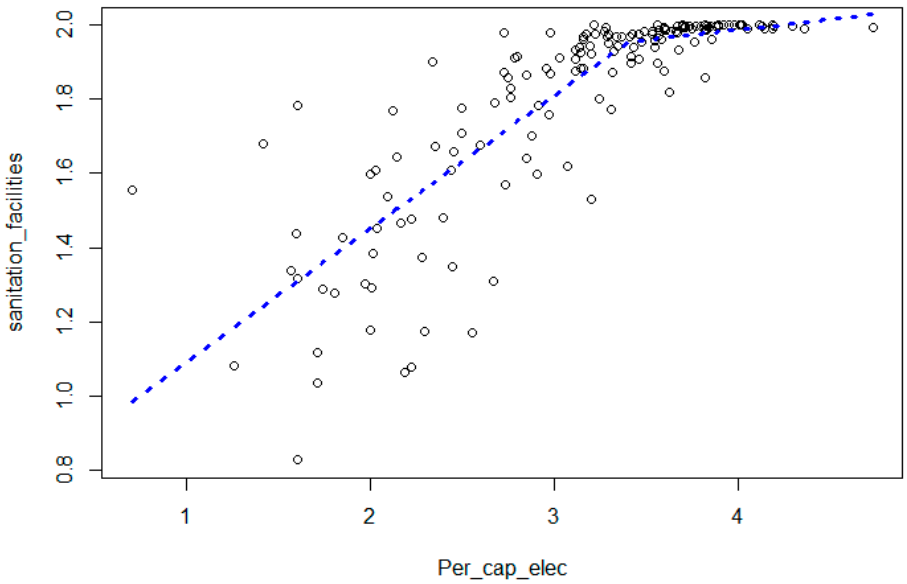

Figure 11. - Access to sanitation facilities (with a maximum of unity; here on a log scale) as a function of per capita electricity consumption.

Another example that works a bit differently is that of access to sanitation facilities. There is a threshold with a continuous increase in access until all have access. The breakpoint is at about 2500 kWh/capita (+920, -630 kWh) as shown in Figure S11.

6. Breakpoint analysis dependent on chosen variable?

One possible objection to this analysis is that we have chosen electricity consumption as the independent variable, but could have chosen other variables. In other words, energy consumption is just a proxy for "wealth" or GDP/capita. In fact, the two are closely related, as shown in Figure S12. But interestingly, the threshold behavior is not as evident as a function of GDP as it is in terms of electricity consumption, as shown in the following figure. In all figures, the axes are logarithmic

At least in this sense it may be possible to draw the conclusion that it truly is energy consumption that is a key to achieving these (and possibly other) SDGs, and not just increase in wealth. A next step is to then look more closely at the literature to find out exactly what are the key determinants for improved health outcomes as discussed in the above outline.

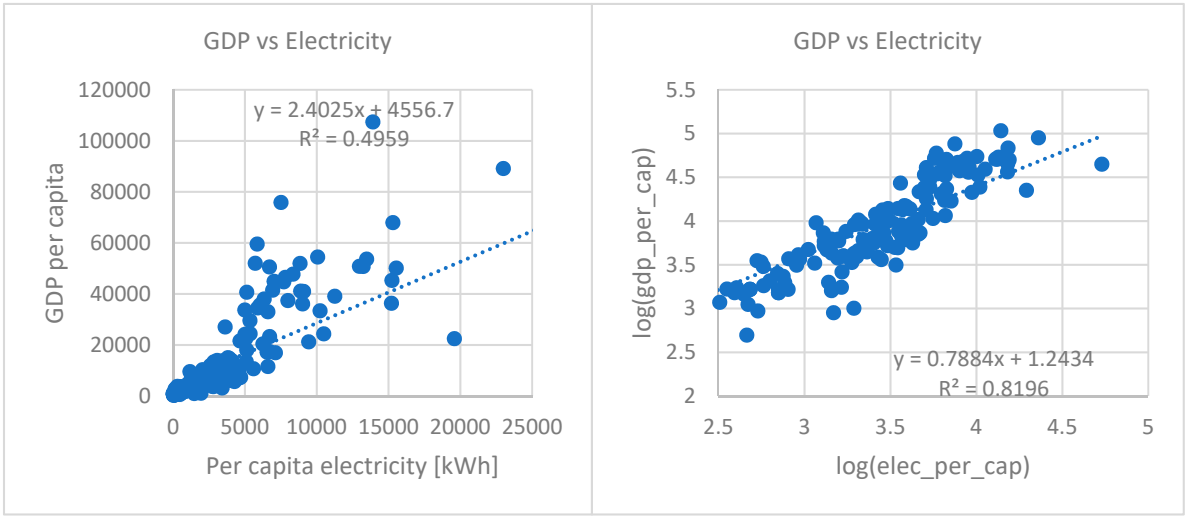

Figure 12. - Plots of GDP vs electricity consumption per capita.

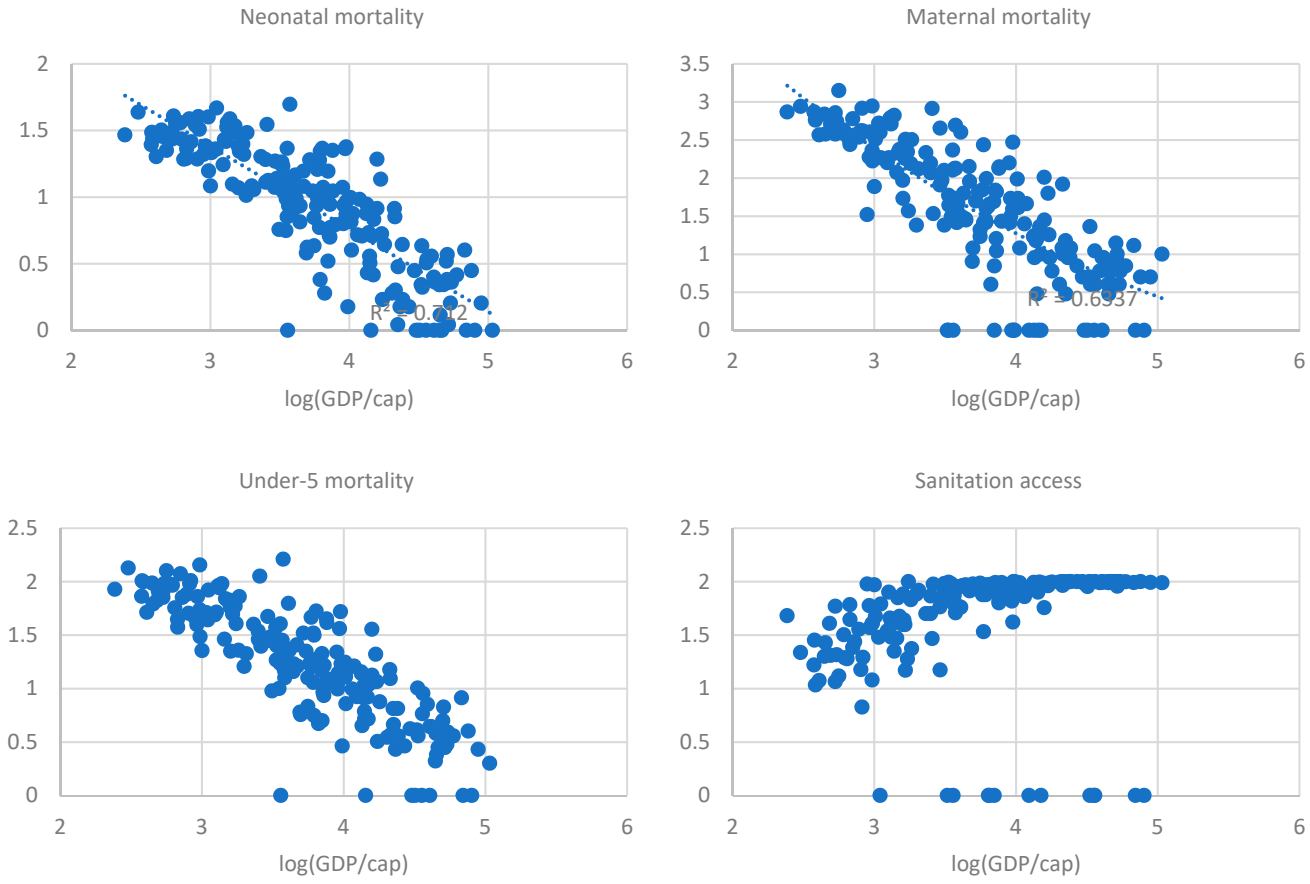

Figure 13. – SDG3 components for which breakpoints were identified as a function of per capita electricity consumption, now looking at the connection to GDP per capita. Each plot is for all countries in one year, with logarithms of the indicator values plotted vs. log of GDP per capita.

The hypothesis of a breakpoint vs. a simple linear relationship can be tested for the three mortality data sets described in the main text. For neonatal mortality, the breakpoint fit does find that to be a possibility, with slopes of -0.16±0.20 with 95% CI -0.55 to 0.27, and -0.68±0.04 with 95% CI -0.75 to -0.60; these intervals do not quite overlap. The plot is shown in Figure S13. The adjusted R^2

values for the two different fits are very similar, 0.75 and 0.76 for linear and breakpoint fits, respectively. In the case of under-5 mortality and maternal mortality, the results are less clear. For the former, the slopes of the breakpoint fit strongly overlap in 95% CI and the R^2 values are equal for linear and breakpoint fits. For maternal mortality, the breakpoint found be the least-squares fitting is unphysical, resulting in an increase in mortality at the highest incomes; R^2 values are the same for both types of fitting as well. At least as a first estimate, parsimony would dictate not using a more elaborate fitting procedure when a simpler one gives the same goodness of fit and adds no physical information.

References

1. IEA, "World Energy Balances," International Energy Agency, Paris, 2016. Available Online: https://www.iea.org/statistics/balances/ (accessed on 11 July 2019)
2. UNEP, *Atlas of Africa energy resources*. Nairobi, Kenya: United Nations Environment Programme, 2017. Available Online: https://www.icafrica.org/fileadmin/documents/Publications/Africa_Energy_Atlas.pdf(accessed on 11 July 2019)
3. UNDP, Ed., *Human development for everyone*. New York, NY: United Nations Development Programme, 2016. Available Online: http://hdr.undp.org/sites/default/files/2016_human_development_report.pdf (accessed on 11 July 2019)
4. UN General Assembly, *Transforming our world: the 2030 Agenda for Sustainable Development*. 2015. Available Online: https://www.un.org/development/desa/dspd/2015/08/transforming-our-world-the-2030-agenda-for-sustainable-development/ (accessed on 11 July 2019)
5. World Bank, "World Development Indicators," *World Development Indicators*, 2017. Available Online: https://data.worldbank.org/data-catalog/world-development-indicators. (accessed on 11 July 2019)