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Energy and quality of life

Cesar Pasten*, Juan Carlos Santamarina[1]

School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive NW, Atlanta, GA 30332-0355, USA

HIGHLIGHTS

- Energy consumption is inherently coupled to quality of life and population growth.
- Limiting overconsumption can keep 2040 energy consumption at 2010 levels.
- Restricting population growth has a minor effect on future energy demand.
- Social inequality reduction increases quality of life with a minor energy use.
- Increasing energy-for-life efficiency can keep 2040 energy use at 2010 levels.

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ABSTRACT

Energy is required to sustain life. A human-centered analysis of the worldwide energy situation is conducted in terms of quality of life-related variables that are affected, but not directly determined, by energy consumption. Data since 1980 show a continuous global increase in both energy consumption and quality of life, and lower population growth in countries with higher quality of life. Based on these trends, we advance non-linear energy consumption predictions and identify various plausible scenarios to optimally steer future energy demands, in order to maximize quality of life. The scenarios consider the coupling between energy consumption rate per capita, quality of life, population growth, social inequality, and governments' energy-for-life efficiency. The results show the energy cost of increasing quality of life in the developing world, energy savings that can be realized by limiting overconsumption without impacting quality of life, and the role of governments on increasing energy-for-life efficiency and reducing social inequality.

1. Introduction

Energy is required to sustain and improve quality of life. The dramatic societal changes and the six-fold population growth since the industrial revolution have required vast amounts of energy provided mainly by coal and petroleum (Hall et al., 2003). In the near future, further population growth and improvements in quality of life will increase the demand for non-renewable fossil fuels and intensify the associated environmental implications (IPCC, 2007; Lee, 2011).

In the meantime, the high rate of fossil fuel consumption accelerates their depletion (Bentley et al., 2007—note: two-thirds of the world's oil-producing countries are already past their production peak), technological readiness and economic return on investment hinders the development of non-conventional fossil fuel sources (Arent et al., 2011; Resch et al., 2008), the hydroelectric capacity is almost saturated (EIA, 2010), renewed concerns affects investment in nuclear energy (Glaser, 2011), and renewables grow fast but starting from a small base (REN21, 2011). In this context, improvements in efficiency and conservation must remain important components in the global energy strategy (Herring, 2006).

Other aggravating conditions add further concerns to the present situation. The spatial mismatch between resource and demand strains international affairs (Colgan, 2010). Trade balance and technological differences imply disparities in energy and carbon dioxide embodied in global transactions (Machado et al., 2001; Peters and Hertwich, 2008). Finally, the contrast in the time scale between the political cycle (~4 years), industrial investments (~40 years), and natural processes (millennia) delays determined decision-making.

Abbreviations: QL, Quality of life index [–]; WA, Improved water access [–]; LE, Life expectancy at birth [years]; IM, Infant mortality rate [deaths/1000 live births]; MYS, Mean years of schooling [years]; EL, Electrification level [–]; GNI, Gross national income [US$/person]; ECR, Energy consumption rate per capita [kW/person]

* Corresponding author. Tel.: +1 404 385 0063; fax: +1 404 894 2281.
E-mail addresses: cpasten@gatech.edu (C. Pasten), jcs@gatech.edu (J.C. Santamarina).
[1] Tel.: +1 404 894 7605; fax: +1 404 894 2281.

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The purpose of this study is to anticipate energy needs and to explore alternative scenarios from a quality of life perspective. First, we identify the most meaningful quality of life-related indicators and combine them to define the simplest quality of life index *QL* that best predicts the energy consumption rate per capita. Then, we use the new index to trace global energy consumption trends and to explore the relationship between quality of life and population growth. Finally, we anticipate future energy demands based on current trends and explore the effects of various realizable scenarios.

2. New quality of life index in view of energy needs

Several indices, such as the human development index of the United Nations (UNDP, 2010), the human welfare index of Meadows and Randers (Meadows et al., 2004), and the quality of life index of the Economist Intelligence Unit (EIU, 2007) have been proposed to compare societies and to quantify their improvements. All these indices consider income, which inherently biases the indices to show a high correlation with energy consumption, as will be discussed later on.

2.1. Quality of life variables

An alternative quality of life indicator is explored herein in terms of quantifiable quality of life-related variables that are not directly determined by energy consumption. We place emphasis on variables that are available for most countries over several decades. Based on these considerations, we identify the following four variables:

- *Improved Water Access WA* [–]: Proportion of the population using improved drinking-water sources, such as public tap, tube well, and protected springs (UN, 2011b).
- *Life Expectancy at Birth LE* [years]: The number of years a newborn infant would live if the mortality patterns at the time of birth prevail throughout the individual's life (WB, 2011).
- *Infant Mortality Rate IM* [deaths/1000 live births]: The number of infants that die before reaching one year of age, per 1000 live births in a given year (WB, 2011).
- *Mean Years of Schooling MYS* [years]: Lifetime number of years of education received by individuals ages 25 and older (Barro and Lee, 2010; UN, 2011a; WB, 2011).
  Two additional variables, electrification level and income, are compared in this section. They are defined as follows:
- *Electrification Level EL* [–]: Proportion of the population with access to electricity (DM, 2011; Elvidge et al., 2011; IEA, 2010).
- *Gross National Income per Capita GNI* [US$/person]: Sum of value added by all resident producers in the economy divided by the mid-year population. It is expressed in purchasing power parity in US$ (UN, 2011a).

However, these two variables are not included in the definition of the new quality of life index because they would systematically bias the correlation between the index and the energy consumption: electrification, a critical infrastructure to quality of life, is inherently correlated with primary energy use, and income is the monetary dimension of energy.

Fig. 1 shows a plot of the selected variables for 118 countries versus the energy consumption rate per capita *ECR* [kW/person], which is computed as the annual rate of primary energy use divided by the country's population (EIA, 2011). Primary energy includes petroleum, natural gas, coal, hydroelectricity, and renewable energy (i.e., wind, solar, and geothermal). Embodied energy in food, the direct use of biomass, and other renewable energy sources, such as solar energy for heating, are not considered.

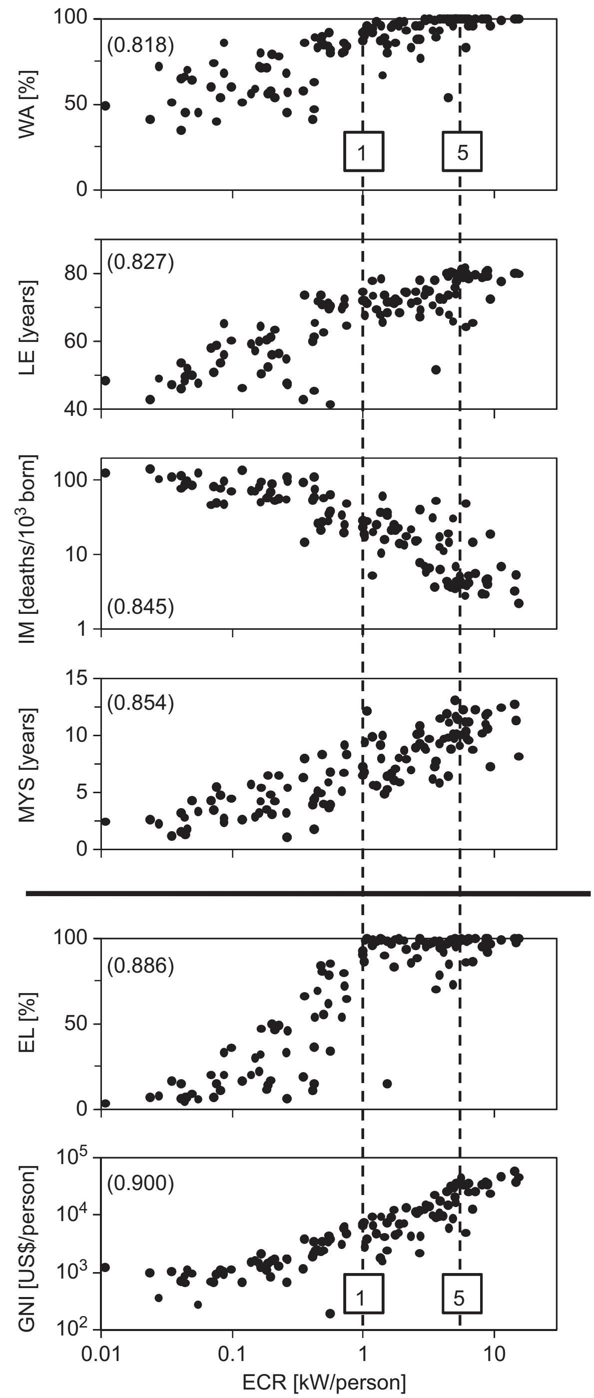

Fig. 1. Quality-of-life-related variables and energy consumption rate per capita *ECR*: Improved water access *WA*, life expectancy *LE*, infant mortality *IM*, mean years of schooling *MYS*, electrification level *EL*, and gross national income *GNI*. Correlation coefficient in parentheses (infant mortality and gross national income are considered in logarithmic scale). Note: Data for 118 countries with populations larger than four million in 2005 (data sources: Barro and Lee, 2010; DM, 2011; EIA, 2011; Elvidge et al., 2011; IEA, 2010; UN, 2011a, b; WB, 2011).

Although countries with high energy consumption rates collapse in the figure, the logarithmic scale helps us to differentiate countries with low consumption and highlights the three orders of magnitude difference between countries with low and high energy consumption. Water access, life expectancy, mean years of schooling, electrification level, and gross national income increase with the energy consumption rate, whereas infant mortality decreases. Indices are sorted by the correlation coefficient shown in parentheses; the range in infant mortality and gross national income exceeds two orders of magnitude, so the correlation coefficient is calculated with the logarithm of the indices.

Two threshold values can be identified in the figure. First, an energy consumption rate of 1 kW/person can ensure access to drinking water and electricity, a high life expectancy, and low infant mortality. Second, consumption in excess of ~5 kW/person is not needed to attain the highest values of the quality of life indicators. These energy thresholds reflect today's technology and will decrease with the development of new energy-oriented technology.

2.2. *Quality of life index*

Let's identify the quality of life index *QL* that both combines quality of life-related variables, *WA*, *LE*, *IM*, and *MYS*, and exhibits the strongest correlation with the measured energy consumption rate per capita. Since consumption ranges over more than three orders of magnitude between countries, the sought index is the best predictor of the logarithm of the energy consumption rate. Linear and factorial combinations are explored:

$$QL = \alpha \times WA + \beta \times \left(\frac{LE}{yrs}\right) + \gamma \times \log\left(\frac{IM}{deaths/1000born}\right) + \delta \times \left(\frac{MYS}{yrs}\right) + \varepsilon \quad (1)$$

$$QL = \left[WA \times \left(\frac{LE}{yrs}\right) \times \log\left(\frac{IM}{deaths/1000born}\right) \times \left(\frac{MYS}{yrs}\right)\right]^{1/4} + \varphi. \quad (2)$$

The constants α, β, γ, δ, ε, and φ are determined by error minimization (note: we considered L_1, L_2, and L_∞ norms; results presented here are based on the least squares L_2 norm).

Following Ockham's criterion, we seek to identify the smallest variable set without compromising predictability. The linear combination of life expectancy *LE* and mean years of schooling *MYS* correlates with the logarithm of the measured energy consumption rate per capita almost as highly as any other combination of the four variables (in part due to correlations among the variables). Due to simplicity and historical data availability, these two variables are adopted to define the new quality of life index

$$QL = 0.072 \left(\frac{LE}{yrs}\right) + 0.310 \left(\frac{MYS}{yrs}\right) - 2.16. \quad (3)$$

The coefficients are adopted such that the maximum quality of life index $QL_{max}=10$ corresponds to a life expectancy $LE_{max}=100$ years and mean years of schooling $MYS_{max}=16$ years, and the minimum quality of life index $QL_{min}=0$ corresponds to $LE_{min}=30$ years and $MYS_{min}=0$ years (note that this quality of life index can be computed for an individual or group). The best and worst life expectancy and education statistics can be used to estimate the maximum and minimum quality of life attained in 2010: $LE_{max}=83.2$ years (Japan) and $MYS_{max}=12.6$ years (Norway) give $QL_{max}=7.7$, whereas $LE_{min}=44.6$ years (Afghanistan) and $MYS_{min}=1.2$ years (Mozambique) combine to produce $QL_{min}=1.4$.

2.3. *Correlation between the quality of life index and energy consumption rate*

Fig. 2 shows the quality of life index plotted as a function of the logarithm of the energy consumption rate per capita. The *QL* index

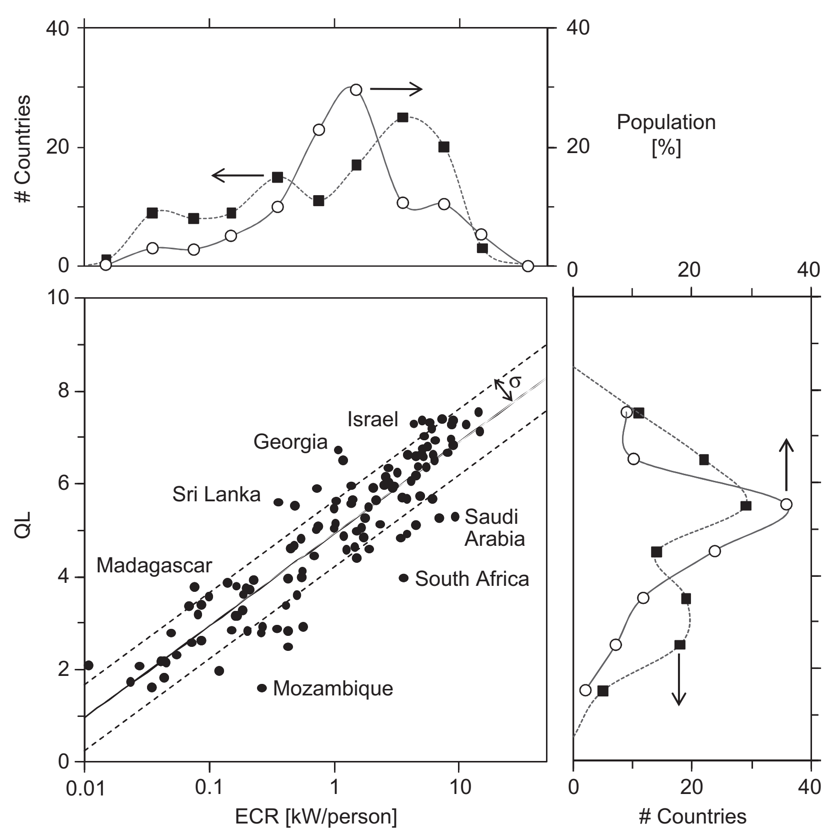

Fig. 2. Quality of life index *QL* and energy consumption rate per capita *ECR*. Data for 118 countries with populations larger than four million in 2005. The continuous line is the mean trend; dashed lines show the plus and minus one standard deviation trends. Note: Distance is defined as $d^2 = \Delta QL^2 + [\Delta\log(ECR\ /\ [\mathrm{kW/person}])]^2$.

has a correlation coefficient $cc=0.902$ with the logarithm of the 2005 energy consumption rate per capita in 118 countries with populations larger than four million. For a given consumption, Eq. (3) suggests that a 4.3 year increase in life expectancy requires the same increase in energy consumption as an additional year of schooling.

Histograms in the figure show two groups. The first group of 30 countries with low energy consumption rates between 0.03 and 0.3 kW/person corresponds mainly to African and Asian countries; their *QL* index ranges between 1.5 and 4.0. The second group of 62 countries between 1 and 11 kW/person includes Latin American countries in the lower end, and European and North American countries towards the upper end; their *QL* index ranges between 4.0 and 7.5.

Fig. 2 includes the mean plus-and-minus one standard deviation trends. Countries that plot below the mean minus one standard deviation exhibit particularly inefficient energy use from a quality of life perspective. This group includes high-energy-consumption countries, such as Saudi Arabia, Russia, Libya, Belarus, Iran, and South Africa, and low-energy-consumption countries, such as Zimbabwe, Yemen, Angola, and Mozambique. In contrast, countries that plot above the mean plus one standard deviation reflect their ability to attain high quality of life standards for a given energy consumption rate. This group includes Israel and the Czech Republic (both with $QL>7$), and Sri Lanka, the Philippines, Peru, Cuba, and Georgia (all with $ECR<1.2$ kW/person).

Currently, 15% of the world's population consumes more than 5 kW/person and accounts for 49% of the world's total energy consumption. This excess consumption above that needed to attain the highest levels of quality of life reflects prevailing lifestyles and cultural patterns. In contrast, 6% of the world's population lives under very precarious conditions and without basic services, consuming less than 100 W/person (equivalent to a healthy diet of 2000 kcal/day). These people rely on hunting, agriculture, and wood for fuel and construction, all of which are sustained by solar energy and natural processes.

3. Historical trends – analysis

The quality of life index computed with Eq. (3), using data available for several decades, allows us to assess global trends and to trace the evolution of selected countries. The mean trends for 1980 and 2010 plotted in Fig. 3 show a global increase in quality of life of about $\Delta QL=1.2$; this is the compounded effect of a 7 years increase in life expectancy and 2.5 years increase in mean years of schooling. Several countries have followed more decisive growth than the global trend. Complex trajectories in Fig. 3 typically reflect political conflicts and social turmoil experienced during this 30-year period. For example, the civil war in Rwanda from 1990 to 1994 corresponds to a sharp decrease in its *QL* index.

3.1. Energy efficient growth

The increase in the quality of life index ΔQL normalized by the change in energy consumption rate ΔECR [kW/person] is a measure of life-oriented energy efficient growth. Based on this concept, the efficiency angle α is defined as

$$\alpha=\tan^{-1}\left[\frac{\Delta QL}{\Delta ECR/(kW/pers)}\right]. \quad (4)$$

An increase in quality of life without an increase in energy consumption corresponds to $\alpha=90^{\circ}$. Countries with low efficiency angles use more energy per capita to attain similar improvements in quality of life. Fig. 4 shows the efficiency angle calculated using increments of the energy consumption rate and the quality of life index in the 30-year period from 1980 to 2010. Values of α are plotted versus the *QL* index and energy consumption rate in 2010. Countries with $\alpha>90^{\circ}$, such as Mozambique, the Democratic Republic of the Congo, Libya, Cuba, and the United States, have increased their quality of life while decreasing their energy consumption during these 30 years.

Mathematically, the linear trend in Fig. 3 $QL=a_{EC}+b_{EC}\log(ECR/[\text{kW/person}])$ can be used to compute the angle as $\alpha=\tan^{-1}(dQL/dECR)$; which is superimposed on Fig. 4b. Results show that the energy required to raise the quality of life increases with the energy consumption rate per capita. In other words, a small increase in energy use in countries with low energy consumption can result in a large increase in their *QL* index.

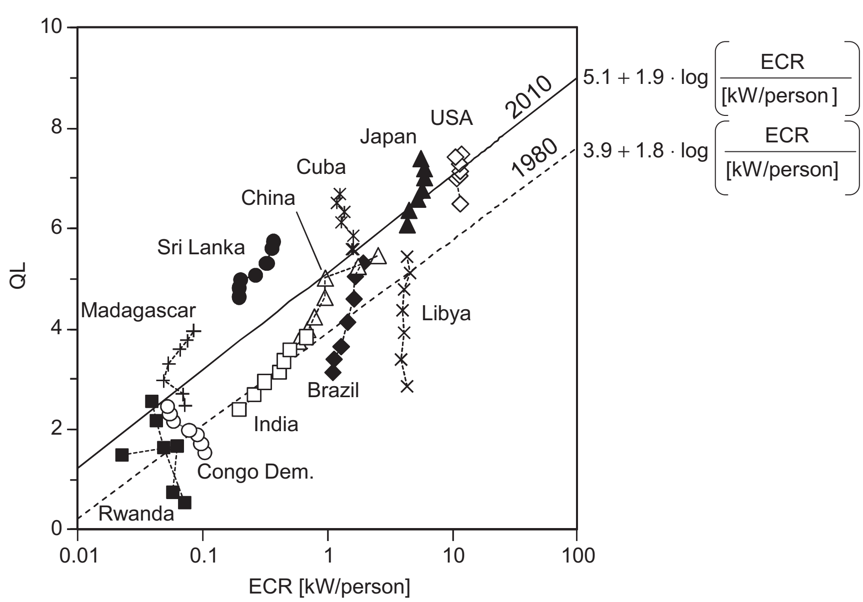

Fig. 3. Evolution of quality of life index *QL* and energy consumption rate per capita *ECR*. The evolution of selected countries from 1980 to 2010 is shown in five-year intervals. Lines show the mean trends in 1980 (calculated with 100 countries) and in 2010 (calculated with 119 countries).

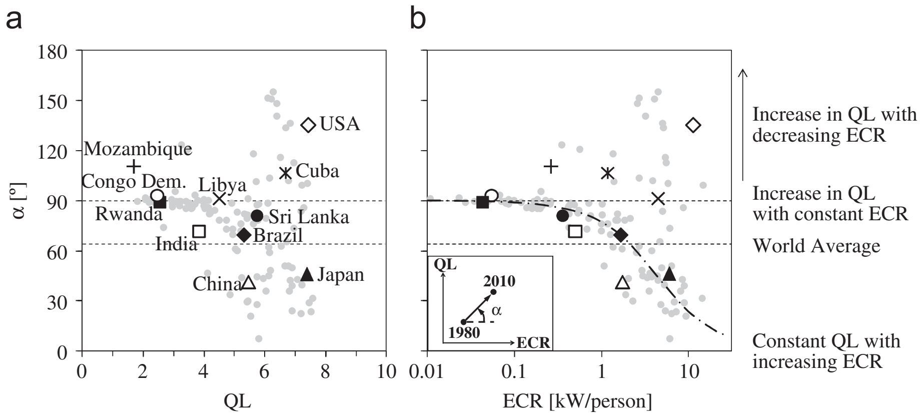

Fig. 4. Efficiency angle α versus (a) quality of life index QL and (b) energy consumption rate per capita ECR. The efficiency angle corresponds to the 30-year period between 1980 and 2010 (definition in the right pane insert). Values of the quality-of-life index and the energy consumption are for 2010. The 100 countries plotted have populations larger than four million in 2010. The dashed trend corresponds to $\alpha = \tan^{-1}(dQL/dECR)$ where $QL = a_{EC} + b_{EC} \log(ECR\ /\ [\text{kW/person}])$.

3.2. Population growth

Population growth rates calculated in five-year intervals PG_5 [%] are plotted against the quality of life index corresponding to the first year of the interval in Fig. 5. Results show that population growth rate is inversely correlated with the QL index adopted in this study [Eq. (3)],

$$PG_5 \approx 20 - 2.5\ QL. \tag{5}$$

In general, the evolution of the population growth rate in individual countries in the 1980–2010 period has followed the global trend (Fig. 5). For instance, Brazil, China, India, and Japan have experienced a steady decrease in population growth rate as the quality of life increased since 1980. Several countries with a low QL index, such as the Democratic Republic of the Congo, experienced instability during this period and exhibited an inconsistent population growth pattern. The inverse correlation between population growth and quality of life aggravates predictions of energy demands since a high increase in energy consumption is expected in the developing world. Countries that manage to improve their quality of life with a constant energy consumption rate per capita (i.e., $\alpha = 90^\circ$) will eventually lower their total energy consumption as their populations stabilize.

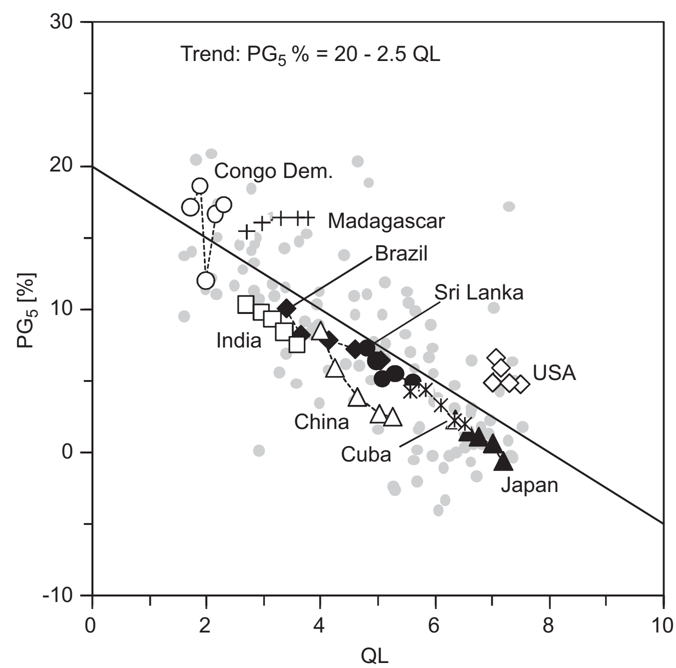

Fig. 5. Five-year population growth rate PG_5 and quality of life index QL. The evolution of selected countries from 1980 to 2010 is shown in five-year intervals. The corresponding quality-of-life index is the one at the beginning of the period. Dots represent 119 countries with populations larger than four million in the period 2005–2010. The line captures the global trend in the 30-year period from 1980 to 2010.

4. Scenarios: quality of life-centered energy consumption predictions

Predictions of energy consumption must consider the coupling between consumption, quality of life, and population growth. Given the time delay in data availability, we select the year 2010 as the base year.

A country's rate of energy consumption is the product between its population P and its energy consumption rate per capita ECR; the global energy consumption rate is computed as a summation for all countries

$$ECR_{global} = \sum_k ECR_k \times P_k. \tag{6}$$

For the base year 2010, the global energy consumption rate was $ECR_{global} = 17$ TW. Similarly, the global quality of life index is calculated as

$$QL_{global} = \frac{\sum_k QL_k \times P_k}{\sum_k P_k}. \tag{7}$$

The summation is extended to all countries where data is available to calculate the quality of life index QL_k. The global quality of life index in 2010 was $QL_{global} = 5.0$. Finally, 5-year changes in population growth rate ΔPG_5 [%] are related to changes in the quality of life index ΔQL (see Eq. (5) and Fig. 5—note: restrictions may apply):

$$\Delta PG_5 = -2.5 \times \Delta QL. \tag{8}$$

Several scenarios are explored to identify strategies that maximize global quality of life in terms of energy demands. The computation algorithms and assumptions for all scenarios are summarized in Table 1. Equations listed above and the additional constrains imposed in these scenarios combine to render non-linear predictions; in all cases, 30-year predictions are computed by updating all variables every five years.

Table 1
Algorithms for energy consumption scenarios.

Variable	Scenario 1 Limiting energy overspending	Scenario 2 Stimulating growth in the developing world	Scenario 3 Improving energy-for-life efficiency	Scenario 4 Restricting population growth
α	α_{curr} (a)	α_{curr} (a)	α_{curr} if $\alpha_{min} < \alpha_{curr} < 180^{\circ}$ α_{min} if $\alpha_{curr} \leq \alpha_{min}$	α_{curr}
ΔECR_5	$(ECR_{2010}-ECR_{1980})/6$	$(ECR_{2010}-ECR_{1980})/6$	$(ECR_{2010}-ECR_{1980})/6$	$(ECR_{2010}-ECR_{1980})/6$
ΔQL_5	$(QL_{2010}-QL_{1980})/6$	$(QL_{2010}-QL_{1980})/6$	$\Delta ECR_5 \cdot \tan\alpha$	$(QL_{2010}-QL_{1980})/6$
ECR_{j+1} (b)	$ECR_j+\Delta ECR_5$	$ECR_j+\Delta ECR_5$	$ECR_j+\Delta ECR_5$	$ECR_j+\Delta ECR_5$
Constraint at year 2040	$ECR_{2040} \leq ECR_{max}$	$EC_{2040} \geq ECR_{min}$ $QL_{2040} \geq QL(ECR_{min})$ (c)	Not applicable	Not applicable
QL_{j+1} (d)	$QL_j+\Delta QL_5$	$QL_j+\Delta QL_5$	$QL_j+\Delta QL_5$	$QL_j+\Delta QL_5$
PG_{j+1}	$PG_j-b_{PG}(QL_j-QL_{j-1})$ (e)	$PG_j-b_{PG}(QL_j-QL_{j-1})$	$PG_j-b_{PG}(QL_j-QL_{j-1})$	$PG_j-b_{PG}(QL_j-QL_{j-1}) \leq PG_{max}$
P_{j+1}	$P_j(1+PG_{j+1})$	$P_j(1+PG_{j+1})$	$P_j(1+PG_{j+1})$	$P_j(1+PG_{j+1})$

Notes:
(a) $\alpha_{curr}=\tan^{-1}[(QL_{2010}-QL_{1980})/(ECR_{2010}-ECR_{1980})]$.
(b) $ECR_{j+1} \geq 0.1$ kW/person in scenarios 1 and 3.
(c) $QL(ECR_{min})=a_{EC}+b_{EC}\log(ECR_{min})+2\sigma b_{EC}/(b^2+1)^{1/2}$.
a_{EC} is the intercept, b_{EC} is the slope, and σ is the standard deviation of the perpendicular distance to the mean $\log(ECR)-QL$ trend in the status-quo scenario for 2040.
(d) $QL_{max}=10$.
(e) $b_{PG}=2.5$ is the slope of the $QL-PG_5$ trend in Fig. 5.
(f) j to $j+1$ is a 5-year period.

4.1. Scenario 1: status quo

This scenario predicts the global energy consumption rate, based on historical increments of energy consumption rate per capita and the quality of life index. Since increments are very sensitive to short-term transients, both the change in energy consumption rate ΔECR_5 and the change in quality of life index ΔQL_5 are considered as the average of the five-year increments from 1980 to 2010. Extrapolation leads to unreasonable predictions for a few countries. Although such anomalous predictions do not affect the global result, we impose two limits: the maximum quality of life index is limited to $QL \leq 10$ and the minimum energy consumption rate is restricted to $ECR_{min} \geq 0.1$ kW/person.

Fig. 6 shows the historical evolution and predictions of global energy consumption rate, quality of life index, and population for the status-quo scenario. Predictions by the International Energy Agency (IEA, 2009), the US Energy Information Administration (EIA, 2010), the United Nations (UN, 2011c), and the US Census Bureau (USCB, 2011) are superimposed on the figure and are in close agreement with the values predicted under the status-quo scenario in this study. The global energy consumption rate increases to $ECR_{global}=25.5$ TW (50% increase), the associated global quality of life index increases to $QL_{global}=6.3$ (26% increase), and the population rises to $P_{global}=8.9$ billion (30% increase) in 30 years.

4.2. Scenario 2: limiting energy overspending

This scenario limits the maximum energy consumption rate per capita to ECR_{max} in high-consumption countries. As demonstrated in previous sections, the energy consumption rate can be reduced to $\sim$5 kW/person without affecting the quality of life index, and consequently the population growth rate. In this scenario, all countries change their energy consumption and quality of life index according to the status-quo scenario, but they are not allowed to exceed the selected ECR_{max} value in the 30-year horizon. Fig. 7 shows that the predicted global energy consumption rate in 2040 decreases sharply as ECR_{max} is lowered, and it could be similar to 2010 global consumption if ECR_{max} is limited to 3.7 kW/person in all countries. Given the assumptions in this scenario, the global quality of life index and the world population evolve as in the status-quo scenario.

4.3. Scenario 3: stimulating growth in the developing world

This scenario considers that the minimum energy consumption rate per capita in developing nations will increase to reach a target value of ECR_{min} in the 30-year horizon. If a country's energy consumption rate is lower than ECR_{min} by 2040, its consumption is set to ECR_{min}. In addition, its quality of life index is set to the value given by the status quo mean plus one standard deviation trend in 2040 at ECR_{min}. For all other countries, energy consumption and quality of life index change according to the status-quo scenario. Results in Fig. 7 show that raising the minimum energy consumption rate $ECR_{min}=1$ kW/person increases the global energy consumption rate by 7% and the global quality of life index by 11% above the status-quo scenario, whereas the world population is the same as in the status quo prediction.

4.4. Scenario 4: improving energy-for-life efficiency

This scenario imposes a minimum energy use efficiency from a quality of life standpoint, i.e., "energy-for-life efficiency." Countries develop as in the status-quo scenario only if their efficiency angles are larger than α_{min} [Eq. (4)]; otherwise, they are forced to evolve with α_{min}. The 5-year increment in energy consumption rate per capita ΔECR_5 is the same as in the status-quo scenario whereas the 5-year increment of the quality of life index ΔQL_5 is given by the efficiency angle and the consumption increment, $\Delta QL_5=\Delta ECR_5 \tan\alpha$. Fig. 7 shows that the global energy consumption rate decreases from the status quo value as the efficiency angle increases. Eventually, efficiencies larger than $\alpha=81^{\circ}$ lead to energy savings when compared to 2010 global consumption. The global quality of life index has a pronounced increase and the global population a drastic decrease with efficiency angles larger than $\alpha=50^{\circ}$. We note that 23 out of 110 countries considered in Fig. 4 had efficiencies lower than $\alpha=50^{\circ}$ in the 1980–2010 period.

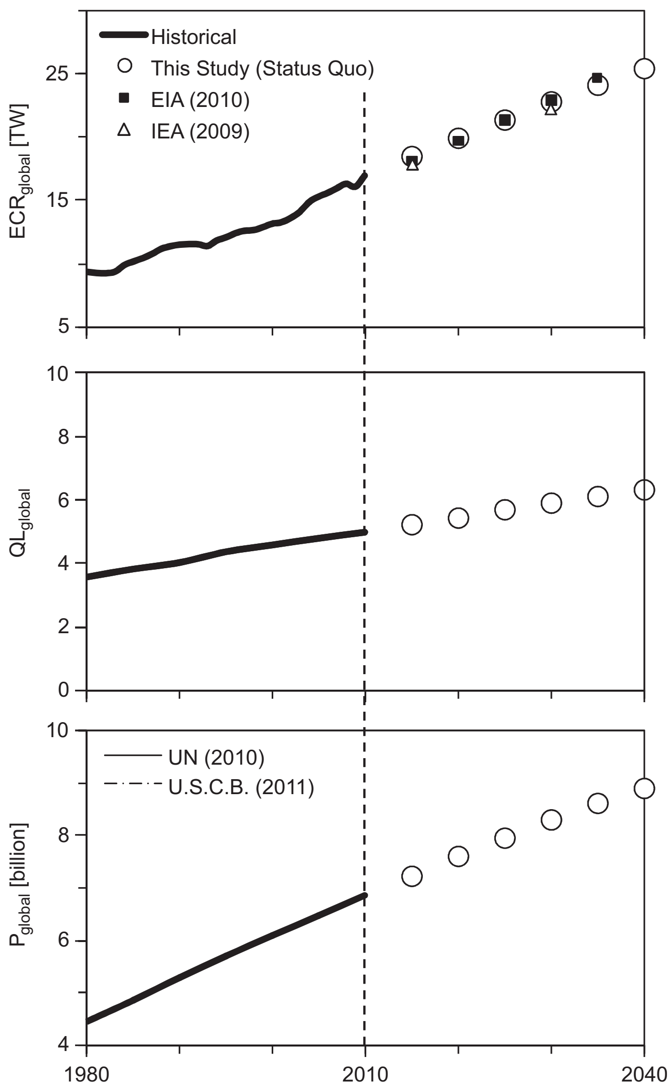

Fig. 6. Historical evolution and status-quo predictions (scenario 1) of the global energy consumption rate ECR_{global}, global quality of life index QL_{global}, and world population P_{global}. Historical energy consumption and world population data from the U.S. Energy Information Administration EIA (2011). Energy consumption projections by EIA (2010) and the International Energy Agency IEA (2009) are the reference scenarios in the International Energy Outlook 2010 and the World Energy Outlook 2009, respectively. The 2010 United Nations' projection UN (2011c) is scaled to coincide with the historical population in 2010.

4.5. *Scenario 5: restricting population growth*

This scenario restricts the maximum population growth rate in any 5-year period to a value PG_{5-max}: if the status-quo scenario predicts a population growth rate larger than PG_{5-max} in any 5-year interval between 2010 and 2040, the population growth rate for the period is set to PG_{5-max}. The energy consumption rate per capita and the quality of life index evolve as in the status-quo scenario, so only population growth affects the global energy consumption rate. This scenario predicts that the population in 2040 rises by 14% if the maximum population growth is set to $PG_{5-max}=4\%$ for all countries (for comparison, the status-quo scenario anticipates a 30% increase in population). The global energy consumption rate increases by 40%, and the global quality of life index increases slightly above the status-quo value to $QL_{global}=6.5$. Currently, 64% of the world's population lives in countries with population growth rates larger than $PG_5=4\%$ (79 out of 119 countries considered in Fig. 5).

4.6. *Scenario 6: combining energy and quality of life policies*

Multiple actions can be combined to optimize worldwide quality of life with minimal energy use. Consider the following set of combined strategies: the maximum energy consumption rate per capita is established at $ECR_{max}=5$ kW/person, the minimum consumption is raised to reach $ECR_{min}=1$ kW/person, the minimum efficiency is set to $\alpha_{min}=70^{\circ}$, and the maximum 5-year population growth rate is limited to $PG_{5-max}=10\%$. Thus, the global energy consumption rate in 2040 would increase by 14% with respect to 2010 consumption (status-quo: 50%), the global quality of life index would reach $QL_{global}=7.1$ (status-quo: $QL_{global}=6.3$), and the world population would be $P_{global}=8.1$ billion (status-quo: $P_{global}=8.9$ billion).

4.7. *Scenario 7: reducing social inequality*

Social inequality sustains internal tension, diminishes quality of life, and hinders development (Wilkinson, 2006). The Gini index is a measure of inequality: Gini=0 corresponds to perfect equality whereas Gini=100 corresponds to perfect inequality. Fig. 8 shows a plot of the Gini index versus the quality of life index defined in this study. Latin American countries exhibit marked inequality, i.e., a significantly higher Gini index compared to countries with a similar quality of life index. Disregarding Latin American countries, the general trend indicates that inequality decreases with an increase in quality of life.

In the absence of disaggregated national data, the global impact of limiting inequality cannot be completed. Nevertheless, the nature of the non-linear relationship between energy consumption rate per capita and quality of life index (Fig. 2) suggests that improvements in impoverished societies lowers social inequality, increases the overall quality of life, and has a minor effect on a nation's energy consumption. For example, combining trends in Figs. 2 and 4 allows us to predict that an increase in the average quality of life index $\Delta QL/QL_0=25\%$ requires a energy consumption rate increase $\Delta ECR/ECR_0=18\%$ at 0.1 kW/person, 29% at 1 kW/person, and 41% at 10 kW/person.

4.8. *Comments*

The two variables in the proposed quality of life index, life expectancy and mean years of schooling, correlate with other quality of life parameters. Therefore, improvements in the *QL* index will come together with improvements in all related indicators in most cases, including enhanced access to clean water, electrification, and income.

Scenarios analyzed in this study focus on quality of life and associated energy needs. They do not consider limitations in energy resources, the cost of energy and its implications, possible rates of infrastructure deployment, and potential restrictions on carbon dioxide emissions (Höök et al., 2010).

5. Discussion and conclusions

General observations: National averages of energy consumption per capita range in three orders of magnitude. Approximately 6% of the world population consumes less than 0.1 kW/person (i.e., the energy in a healthy diet), and 44% is below 1 kW/person (i.e., the energy level required to attain an adequate quality of life given today's technology). On the other hand, 15% of the world population consumes more than 5 kW/person (i.e., the energy required to attain the highest quality of life with today's technology).

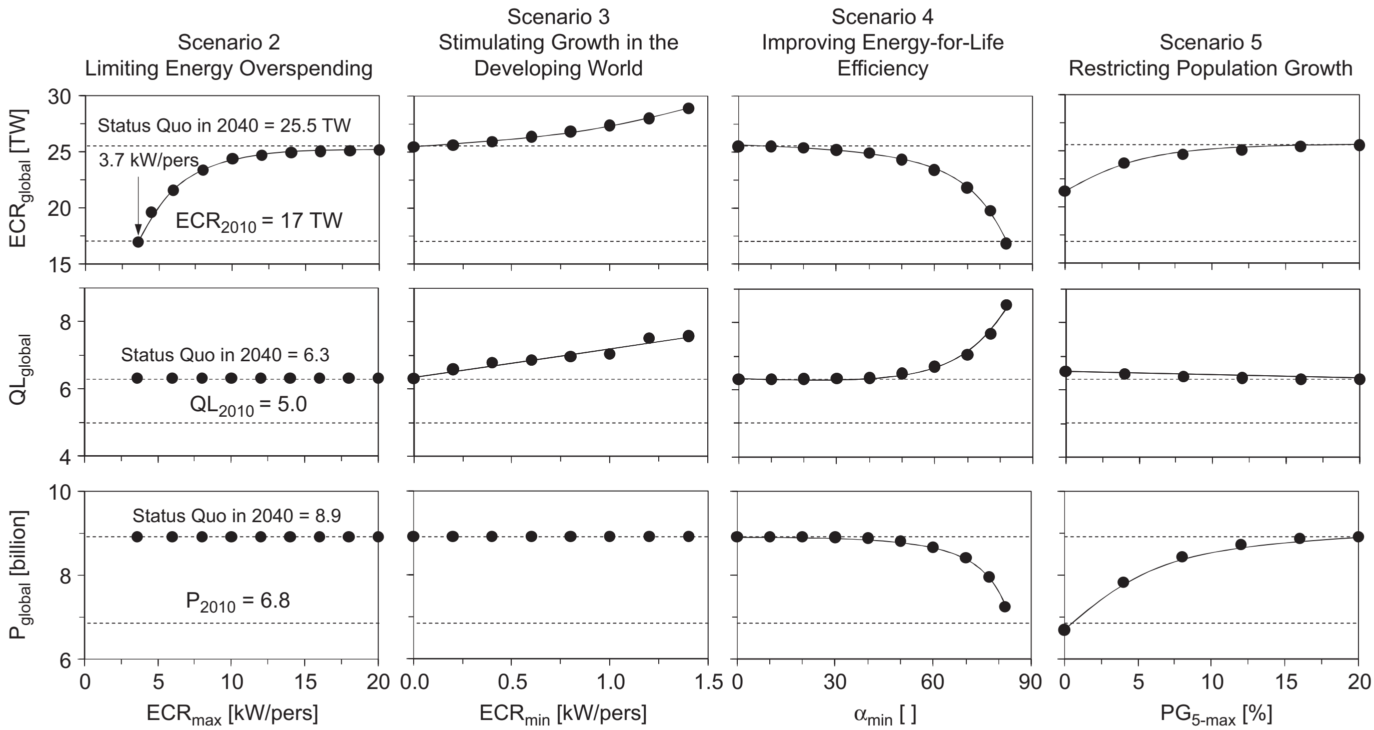

Fig. 7. Predicted global energy consumption rate ECR_{global}, global quality of life index QL_{global}, and world population P_{global} under various development scenarios in 2040.

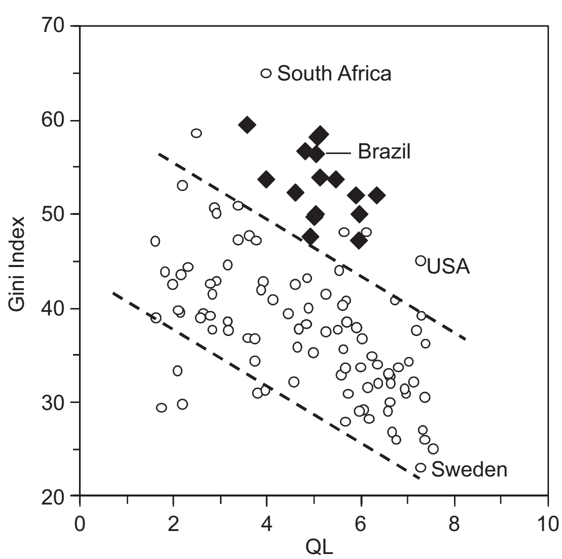

Fig. 8. Social inequality and quality of life. Gini index versus quality of life index. Data for countries with populations larger than four million in 2005. Diamonds represent Central and South American countries. Note: Gini index=0 is perfect equality, and Gini index=100 is perfect inequality. Data gathered from the World Bank (WB, 2011) and Central Intelligence Agency (CIA, 2011).

Future energy demands will reflect the coupling between energy consumption, quality of life, population growth, social inequality, and governments' energy-for-life efficiency. Following current trends, the status-quo scenario anticipates a global power consumption of 25.5 TW by the year 2040, which is a 50% increase from the 2010 level and an 8.5 TW increase in global demand in 30 years.

Developing countries—observations and policies: Growth in the developing world will cause a marked increase in global energy demand due to higher energy consumption rate per capita compounded with high values of current population growth rates.

Restricted population growth limits global energy use. Nevertheless, the impact of this single strategy on energy consumption is not significant unless the population growth rate in five year intervals is limited to $PG_{5-max}=5\%$ worldwide, which is similar to the current population growth rate in the USA.

Yet, significant improvements in quality of life can be attained with a limited impact on energy demands in all nations, particularly in developing countries. In fact, several countries (including Mozambique and Cuba) have successfully increased their quality of life with relatively low increases in energy consumption in the last decades. Furthermore, given the inverse correlation between quality of life and population growth, improvements in quality of life may lead to decreased energy consumption.

Stimulating growth in the developing world to attain a minimum energy consumption rate per capita of $ECR_{min}=1$ kW/person increases the global energy consumption by only 7% above the status-quo scenario and has a profound effect on global quality of life. To achieve this goal, emphasis should be placed on the implementation of available technology, the reduction in social inequality, and renewed government policies to enhance energy-for-life efficiency. The widespread use of technology for efficient knowledge delivery and for optimal use of resources, low-cost medicines, and portable medical systems are examples of recent developments that can be made readily available worldwide to improve quality of life with a virtually null increase in energy demand. Partnerships with developed countries and the private sector may facilitate the development and adoption of leapfrog technology and ensure financial support for energy plans.

Developed nations—observations and policies: Affluent societies in developed countries can readily reduce energy overconsumption. Energy consumption rates in excess of $\sim$5 kW/person do not lead to higher quality of life. Furthermore, limiting consumption to 3.7 kW/person would keep 2040 energy consumption at 2010 levels (note: it is anticipated that a consumption rate of 3.7 kW/person is achievable with today's technology with no negative impact on quality of life).

These energy conservation targets can be attained guided by education and motivated by taxation. However, what would individuals do with saved funds, or governments with excess tax collection? All expenditures imply energy consumption; thus, policy instruments must guide the use of saved funds to promote the development and adoption of clean, renewable energy, to correct energy market failures (e.g., not-accounted negative externality costs), and to overcome barriers in the adoption of energy-efficient technology.

Short and long-term plan: The implementation of policies properly targeted to developed and developing economies, can optimally steer future energy demands in order to maximize quality of life worldwide.

Short-term policies must recognize the current dependency on fossil fuels, their diminishing reserves, and climate implications. In this context, emphasis should be placed on increasing quality of life in the developing world and limiting overconsumption in developed nations. Savings should be invested to cause change towards a long-term solution based on unlimited, clean renewable energy and leap-frog technology required to support a high quality of life worldwide.

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