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Short communication

The 21st century population-energy-climate nexus

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HIGHLIGHTS

- World population growth, energy scarcity, and climate are interrelated issues.
- Non-renewable energy sources are projected to peak around mid-century.
- Renewable energy must provide 50+% of total energy by 2028 to maintain <2 °C warming goal.
- Renewable energy must provide 87+% of total energy by 2100 regardless of climate concerns.

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ABSTRACT

World population is projected to reach 10.9 billion by 2100, yet nearly one-fifth of the world's current 7.2 billion live without access to electricity. Though universal energy access is desirable, a significant reduction in fossil fuel usage is required before mid-century if global warming is to be limited to <2 °C. Here we quantify the changes in the global energy mix necessary to address population and climate change under two energy-use scenarios, finding that renewable energy production (9% in 2014) must comprise 87–94% of global energy consumption by 2100. Our study suggests >50% renewable energy needs to occur by 2028 in a <2 °C warming scenario, but not until 2054 in an unconstrained energy use scenario. Given the required rate and magnitude of this transition to renewable energy, it is unlikely that the <2 °C goal can be met. Focus should be placed on expanding renewable energy as quickly as possible in order to limit warming to 2.5–3 °C.

1. Introduction

Finding a beneficial solution to the interrelated problems of population growth, energy poverty, energy scarcity, and global warming is one of the great challenges of the 21st century. Global energy production is at the nexus of these problems. Nobel laureate Richard Smalley ranked energy as the greatest problem facing society and hypothesised that being able to supply sufficient quantities of energy is key to solving each of the other problems (Smalley, 2005). Global population has increased from 1.6 billion in 1900 to 7.2 billion today, while total global energy production has increased from 23 to 548 exajoules (EJ). As population is projected to increase to 10.9 billion (9.6–12.3 billion) by 2100 (Gerland et al., 2014), total energy demand will continue to rise as well. The World Bank's Sustainable Energy for All Initiative (SE4ALL) is a plan to provide the nearly 20% of the world's population that, as of 2010, did not have access to electricity or modern cooking fuels (Banerjee et al., 2013). As of 2013, the SE4ALL results have been positive, however increases in energy access have not kept pace with the growth in world population (Banerjee et al., 2013).

For the past 20 years policy-makers and scientists have argued that limiting global warming to 2 °C is necessary to prevent serious negative climate change consequences (Randalls, 2010). The non-renewable energy sources (NRES) comprise 91% (87% fossil fuels) of total energy used today and emitted an estimated 35.5 gigatonnes of carbon dioxide equivalent (Gt CO_2) in 2014 (BP, 2015). The fossil fuels and nuclear power are projected to peak in production by mid-century (e.g., Maggio and Cacciola, 2012; Mohr et al., 2015). Subsequent declining non-renewable production will require a rapid expansion in the renewable energy sources (RES) if either population and/or economic growth is to continue. This is especially important in striving for universal electricity access in the developing countries, vis-à-vis SE4ALL. Continued unconstrained use of the known fossil fuel reserves will lead to an unavoidable >2 °C warming (Pachauri et al., 2014).

On June 9, 2015 the G7 leaders agreed in principle on “decarbonising” the global economy by 2100. A climate constrained

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scenario limiting warming to $<2\,°C$, requires total CO_2 emissions to be less than 2900 Gt CO_2 from 1870 to 2100 (Pachauri et al., 2014). This in turn requires 50% or more of existing fossil fuel reserves to remain unused (McGlade and Ekins, 2015). If carbon emissions were to remain at the 2014 level indefinitely, total cumulative emissions since 1870 would surpass 2900 Gt CO_2 in the year 2038. What has been lacking to date when addressing these interrelated problems is a quantitative assessment of the growth in, and mix of, energy required through the 21st century. As carbon-intensive fuel sources constitute less and less of the global energy mix (either via economic and geologic peaking or as a result of climate and environmental concerns), renewable energy production will have to expand to meet the demand-production gap.

We aim to quantify the year-to-year changes in the global energy mix that are likely to result from A) business as usual fossil fuel consumption that is only economically and/or geologically limited and B) the constraint of fossil fuel energy usage necessary to achieve the $<2\,°C$ climate goal. The IPCC (2014) recently presented four Representative Concentration Pathways (RCP) for cumulative CO_2 emissions to 2100: RCP 2.6 (nominally 2900 Gt CO_2 and $<2\,°C$ warming), RCP 4.5 ($\sim$4500 Gt CO_2 and 2.5 °C), RCP 6.0 ($\sim$5300 Gt CO_2 and 3 °C) and RCP 8.5 ($\sim$7800 Gt CO_2 and 4.5 °C).

We address the issue of NRES usage to 2100 under an unconstrained fossil fuel scenario (UC) and climate constrained energy production scenario (CC). The unconstrained scenario assumes that the discovery, production and subsequent decline of NRES will follow a logistic curve in which peak production occurs when one-half of the reserve has been extracted (Hubbert, 1956). This scenario is not limited in any way by climate concerns and will provide an estimate of future CO_2 emissions should government leaders fail to reach a global agreement on limiting fossil fuel emissions. While the likelihood of major NRES discoveries is decreasing, this scenario assumes only what is considered to be economically viable at present, and that the energy return on investment (EROI) of current and/or undiscovered energy sources must be favourable enough for economically viable exploitation (Hall et al., 2009). Despite recent advances in tar sands recovery, tight oil, and shale gas, questions pertaining to long-term viability and ultimate recoverable resources remain (Murray and Hansen, 2013). We acknowledge that future technological advances may allow for the growth of the NRES used within our models. As such, this scenario represents a minimum estimate of future recoverable NRES. In addition, our statistics rely on industry-specific and/or national reporting of present and recent past reserves and consumption that can deviate from the actual numbers, as recently revealed about China underreporting their coal consumption (Buckley, 2015).

The climate constrained energy use scenario is based on limiting cumulative CO_2 emissions to 2900 Gt CO_2 from 1870 to 2100 and in turn global warming to $<2\,°C$. This goal was critically examined by McGlade and Ekins (2015). Our study is similar in that it also examines the amount of unburnable fossil fuels, but deviates in that on top of the means by which energy cannot be derived in the 21st century we quantify the additional RES production necessary to make up for the fossil fuels left unutilized, and the growth in world population.

Although RES potential is theoretically near-unlimited (de Vries et al., 2007; Marvel et al., 2013), we determine only the amount needed to meet total global energy demand in the two scenarios. Non-hydro, non-solid fuel RES was 2.4% of 2014 total energy production, nominally comprised of 50% wind,13% solar (primarily photovoltaic, or PV solar) and 37% other renewable energy sources. For the purposes of this study, the term 'solar' implies photovoltaic solar power. For our model scenarios we assume that the mix of non-hydro RES will be 60% wind, 25% solar and 15% biofuels (see Methods for rationale for these percentages). Our scenarios are used to calculate the rate of RES growth needed to offset the decline in the NRES and supply the additional energy needed to continue world population growth and per capita energy expansion in each of the UN's population scenarios (Gerland et al., 2014).

2. Data and methods

Our model scenarios are based on three main components. The first part of the model is the most recent UN population projections (Gerland et al., 2014). These projections include a median estimate (used in the model scenarios as presented in the main body of this paper) and high and low confidence intervals. We did not model population ourselves; rather, we used these projections as the basis of our model. The projections are provided in five year intervals from 2010–2100. We interpolated the year by year populations from these five year values. The dataset provided extends back to 1950. World population values from 1900–50 were from McEvedy and Jones (1978).

The second component of the model scenarios is energy. This includes production, consumption, and reserves data and logistic modelling. Several authors and agencies have estimated reserves (see Supplementary Table 1). We constructed historical energy production using the statistics found in (BP, 2015). These production values are widely used by researchers and extend back to 1965–81 depending on the energy source. We used the oil production values from ASPO (2006) for the years 1859–1965. Coal production before 1981 was extended back using Rutledge (2011). We used the data provided within the extended worksheet published by Laherrere (2004) to fill out natural gas production before 1970. Nuclear reserves were obtained from the World Nuclear Association (WNA, 2013) and historical production was available via BP (2015). Without reliable statistics available, hydropower was assumed to have scaled-up at a similar rate as it was growing from 1965–80. Considering the global-scale of energy production, nuclear and RES production were considered to be negligible before 1965 (0.24 and 0.05 EJ in 1965 respectively).

Combining the reported reserve estimates (BP, 2015) and the cumulative historical production of each NRES results in an estimate of each resource's ultimate recoverable resource (URR). The URR is an estimate of the total energy that can be extracted from each NRES before extraction of the resource is limited either geologically, economically, or technologically. It is not an estimate of the total energy content initially in place. Our URR estimate is in close agreement with the estimates derived by others (see Supplementary Table 1). Future production of the NRES was modelled using the normal logistic function as described in Hubbert (1956, 1982). The method and its variants are widely used for making projections of NRES energy production. The equation is as follows:

$$P = 2^{*}P_{pk}/(1+\cosh[b(t-t_{pk})])$$

wherein P is the production at time t, P_{pk} is the peak production value, b is a slope value equal to $4^{*}P_{pk}$/URR, and t_{pk} is the time of peak production. Peak production is assumed to occur at or around the point at which one half of the URR has been produced. We estimated this value and timing after extrapolating the trends in production of each source from 2000–14. The result of this method is a singular peaking of each NRES production and a subsequent decline approaching exhaustion into the future. Hydropower was projected using a simple growth trend from the 2014 production value of 36.9–52.5 EJ in 2100. The 2100 figure represents the IPCC estimate of global hydropower potential (Seyboth et al., 2011). We assume that this potential will be built out by 2100.

Our next step in the modelling was to examine the rate of

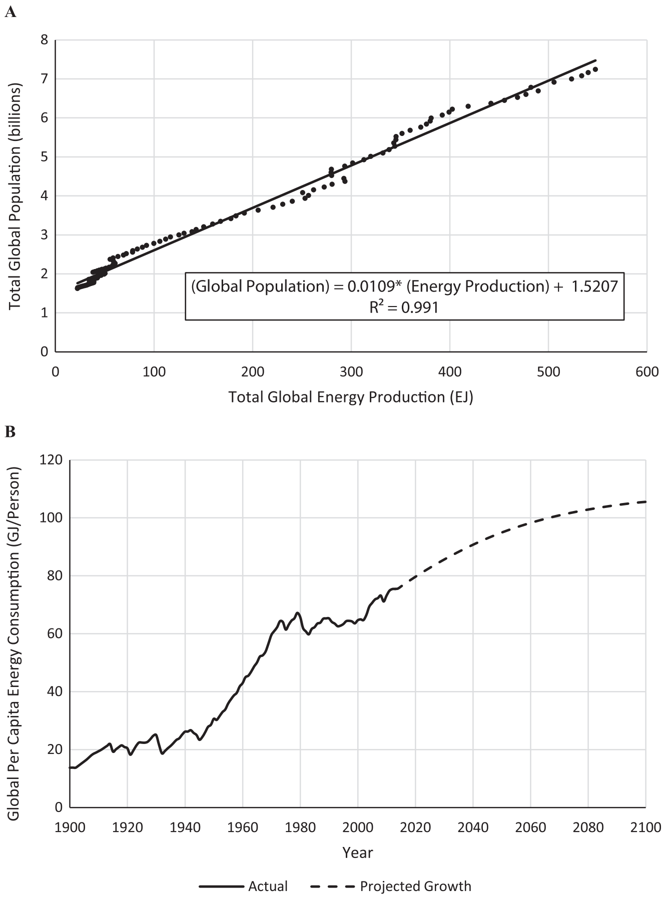

Fig. 1. Global energy and population. Data from (ASPO, 2006; BP, 2015; Gerland et al., 2014; Laherrere, 2004; McEvedy and Jones, 1978; Rutledge, 2011). (A) Correlation of historical energy production and world population, 1900–2014. Global energy does not include the solid fuel RES (i.e. wood and peat). (B) Per capita energy consumption with our extrapolation of projected growth to 2100.

energy consumption. Because our model is based on projected population growth, energy consumption must be measured on a per capita basis. Using historic energy production and population numbers (Fig. 1a), we calculate (1900–2014) and project (2015–2100) global per capita energy consumption (Fig. 1b). We calculated historical per capita energy consumption by dividing energy production by population. We assumed that the total energy production in each year was consumed in the same year. Strategic reserves and other energy storages were assumed to be of negligible value, and the solid RES (i.e. wood and peat) were not included.

To estimate the future trajectory of world average per capita energy consumption, we used the relationship of population growth (Gerland et al., 2014) and energy consumption (BP, 2015) over the period 2000–2014. We scaled the average annual growth of total global energy consumption (2.33%) relative to the average annual growth in global population (1.27%). We then applied the trend ratio (1.83) to the medium UN population scenario out to 2100 in order to determine our model's energy demand throughout the remainder of the century (Fig. 1b). Total energy demand was derived by multiplying global population by the per capita energy consumption projection for each year. The RES production for each year was determined by subtracting the NRES and hydropower production values from the total energy demand. This remainder was assigned to RES production.

In 2014, 50% of non-hydro RES was derived from wind and 13% from solar. The remaining production was derived from every other source (biomass, geothermal etc.) (BP, 2015). We simplified non-hydro renewable energy production to three sources: wind, solar, and algae biofuels. Liquid fuels currently constitute 18% of total global energy use (Caspeta et al., 2013). As such, algae biofuels were assigned 15% of total RES energy demand. The remaining 85% was divided between wind and solar energy. In 2014, wind energy production was approximately four times higher than solar production. The annual rate of growth since 2000 has been approximately 23% year for wind and 39% for solar. Considering both of these statistics, we assumed that solar would narrow the gap over time. Wind was assigned 60% and solar 25%.

We next scaled the three RES demand figures using 5 MW wind turbines for wind energy, square kilometres of solar panels for solar energy, and square kilometres of algae biofuel production facilities for algae biofuels. A 5 MW wind turbine operating at a capacity factor of 0.3 (EIA, 2016) produces approximately 47.3 terajoules (TJ) in one year.

$$5\ \text{MW} \times 8766\ \text{h} \times 0.3\ \text{capacity factor} = 13.149\ \text{GWh}$$

$$13.149\ \text{GW h} \times 3600\ \text{s} = 47.336\ \text{TJ/year}$$

Photovoltaic solar panels operating at 50% coverage and 10% conversion efficiency produce about 414 TJ/km^2 per year (Moriarty and Honnery, 2012). The most optimistic photobioreactor laboratory experiments for algae yield up to 58,700 litre of biofuel per hectare (186.2 TJ/km^2) (Chisti, 2007), theoretically making algae biofuels the most energy dense biofuel. However, scaling photobioreactors to large commercial-scale biofuel generation is impractical compared to open pond algae cultivation systems (Benemann, 2013). The most optimistic yield expected of the open pond process is closer to 25,000 litre of biofuel per hectare (Benemann, 2013), or approximately 79.3 TJ/km^2, the figure we use in our model.

To complete our assessment of future RES demand, we estimated how quickly the RES infrastructure will have to grow. Wind turbines and PV solar panels have a lifespan of approximately 20 years (Kubiszewski et al., 2010; Zweibel, 2010). We assumed that this lifespan applied to an algae growing facility as well. As such, our annualised installation figures for each of these three energy sources included a 5% replacement of the previous year's installed infrastructure. For each year of the model, we took the number of wind turbines that were required, subtracted the previous year's total, and then added 5% of the previous year's total. This figure represents our estimate of the number of 5 MW turbines equivalent that must be installed for each of the years within the model. The same approach applies to PV solar panel and algae facility areas.

The climate constrained scenario was built in the same way as described above. The addition of this climate constrained scenario first required an examination of carbon dioxide emissions within the model. This is the third main component of the model. Carbon dioxide emissions based on the standard global average conversion factors are estimated at 3.07 t per tonne of oil equivalent (TOE) for oil, 3.96 t/TOE for coal and 2.35 t/TOE for natural gas (BP, 2015). These numbers equal about 73, 94, and 26 megatonnes of CO_2 per EJ. The IPCC reports that as of 2010, a cumulative 1890 Gt CO_2 had been emitted via anthropogenic means (Pachauri et al., 2014). The unconstrained scenario resulted in about 4700 Gt CO_2 emitted by 2100. The IPCC suggests that this number cannot exceed 2900 Gt CO_2 in order to have a better than 50% chance of limiting global climate change to less than 2 °C.

Constructing the climate constrained scenario in accordance with the sub-2900 Gt CO_2 goal, the URR of oil, coal, and natural gas had to be lowered, and RES was forced to make up the difference in energy production between the unconstrained and the climate constrained scenarios. This type of fossil fuel limitation was described in McGlade and Ekins (2015). Their model was used as the starting point for limiting fossil fuels in the climate constrained scenario. We used logistic modelling, global ultimate recoverable reserves (URR), and global reserve estimates (BP, 2015), whereas McGlade and Ekins did not use URR estimates and summed present reserve estimates from individual countries. Our estimates of energy reserves are within 2% of those used by McGlade & Ekins (see Supplementary Table 1).

3. Results and discussion

To satisfy the emission limit, we find that 37% of oil, 54% of natural gas and 86% of coal reserves available for use in the unconstrained scenario need to remain unused in the climate constrained scenario. Individual energy production curves for both scenarios by source are presented in Fig. 2. Our model result for summed NRES and hydropower is shown in Fig. 3a. In the unconstrained energy use scenario NRES and hydropower production peak at 678 EJ by 2032 and decline to 152 EJ by 2100. We project global per capita energy consumption to increase from 76 gigajoules (GJ) today to 106 GJ in 2100, and world energy demand to increase from 548 EJ to 1146 EJ (Table 1). Independent of per capita energy change, total energy demand in 2100 varies by nearly 300 EJ based on the Gerland et al. (2014) population projections alone (Table 1).

Cutting carbon emissions in order to satisfy the conditions of the climate constrained scenario we find that non-hydro, non-nuclear NRES production needs to immediately begin to decline from 473 EJ to 6 EJ by 2100. In 2014 global non-hydro, non-solid fuel RES was comprised of 141,800 5 MW equivalent wind turbines, 4300 km^2 of solar panels (an area slightly smaller than Trinidad and Tobago) and algae biofuels production remains in the testing phase (Benemann, 2013; Chisti, 2007); thus current commercial production may be considered zero. In 2014 all sources of

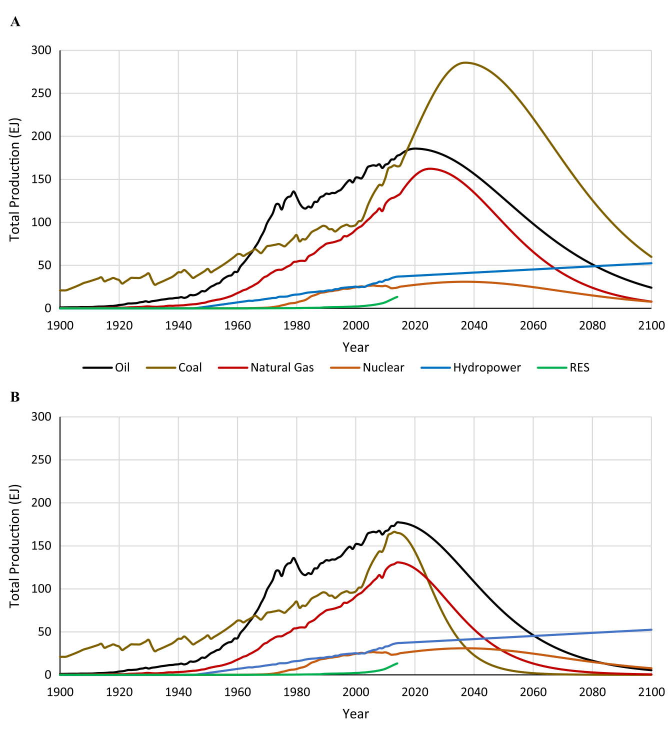

Fig. 2. Energy production by source, 1900–2100. (A) Unconstrained scenario based on 2000–2014 production trends and logistic model. Results in line with independently derived projections from (Höök et al., 2010; Mediavilla et al., 2013; Mohr and Evans, 2009; Mohr et al., 2015). (B) Climate constrained logistic scenario in which all three fossil fuel sources peak immediately to keep cumulative anthropogenic CO_2 emissions to <2900 Gt by 2100. All data compiled from (ASPO, 2006; BP, 2015; Laherrere, 2004; Rutledge, 2011; Seyboth et al., 2011; WNA, 2013).

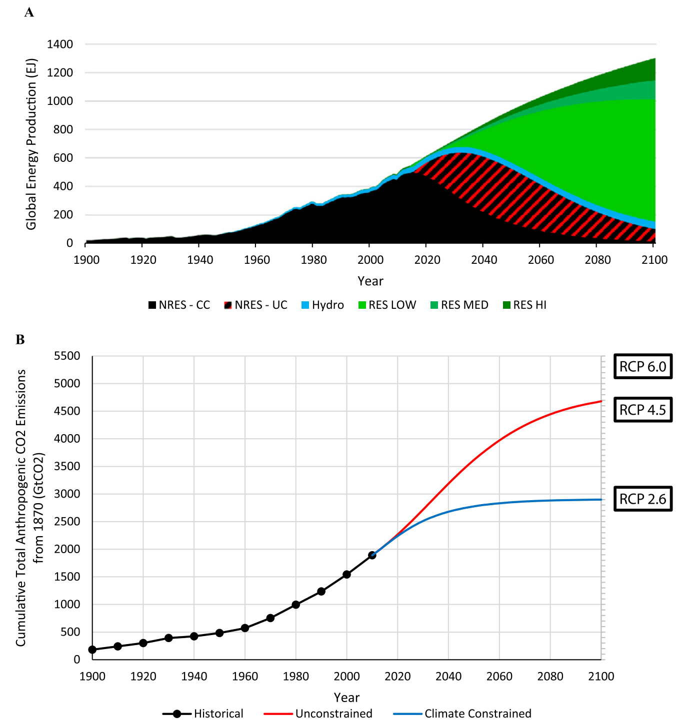

Fig. 3. Model results of energy production, mixture and carbon dioxide emissions. (A) Energy production mixture, 1900–2100. Includes results of unconstrained and climate constrained model scenarios. Results for three population projections (HI, MED, LOW = High, Median, and Low projections) included (Gerland et al., 2014). NRES = non-renewable energy sources (oil, coal, natural gas, nuclear). Red hatched area represents NRES production in unconstrained scenario and RES production in the climate constrained scenario. (B) Cumulative anthropogenic carbon dioxide emissions since 1870 from our climate constrained and unconstrained energy use scenarios. The IPCC AR5 (Pachauri et al., 2014) suggests that in order to have a better-than-even chance of avoiding a global average warming of 2 °C, CO_2 emissions should remain below 2900 Gt (RCP 2.6). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

biofuel production were equivalent to 37,500 km^2 of algae biofuels production (approximately the area of Bhutan).

The cumulative carbon emission trajectories from 1900 to 2100 for our two model scenarios are shown in Fig. 3b. The climate constrained model scenario restricts cumulative CO_2 emissions to 2900 Gt, whereas the unconstrained energy use model scenario maximises NRES use within the constraints of our logistic modelling. Here we find a cumulative emission of 4700 Gt CO_2, a value between RCP 4.5 and RCP 6.0. Although RCP 8.5 is theoretically possible if all probable and possible fossil fuel reserves are burned, it is an unrealistic scenario given estimates of fossil fuel URRs of geologically and economically extractable reserves.

The 2100 energy demand that cannot be met via NRES and hydropower must be made up in RES production (Table 2). For the unconstrained energy use scenario 87% of total energy in 2100 is derived from RES. This is a 75-fold increase from the 2014 level and would require the equivalent of 12.6 million 5 MW wind turbines, 600,000 km^2 of solar panels (similar to the area of Ukraine) and 1.9 million km^2 of algae production facilities (approximately the area of Sudan). In the climate constrained scenario 94% of total energy in 2100 is RES. This is an 81-fold increase from the 2014 level and would comprise the equivalent of 13.7 million 5 MW wind turbines, 652,000 km^2 of solar panels and 2.04 million km^2 of algae production facilities.

Assuming a 20 year lifespan (Kubiszewski et al., 2010), over 700,000 5 MW equivalent wind turbines will need to be installed under either scenario in the year 2099 alone (Fig. 4b). That is equivalent to adding the entire 2014 production of wind turbines

Table 1
World population, energy production, and renewable energy source (RES) requirements; 2014, 2028, 2054, 2100. Based on energy production in our unconstrained (UC) and climate constrained (CC) scenarios. Gerland et al. (2014) median, high, and low population projections. Mid-century dates provided based on 50/50 RES/NRES production ratio in climate constrained scenario (2028) and the unconstrained scenario (2054). World population measured in billions. Energy production figures (±1) measured in exajoules.

	2014	**2028**			**2054**			**2100**		
		UC	**CC**	***CC-UC***	**UC**	**CC**	***CC-UC***	**UC**	**CC**	***CC-UC***
Population	7.2	8.3	8.3	*0*	9.7	9.7	*0*	10.9	10.9	*0*
Oil	177	181	152	*−28*	116	61	*−55*	24	6	*−18*
Coal	165	259	82	*−177*	248	4	*−243*	60	0	*−60*
Natural Gas	131	161	98	*−63*	85	21	*−64*	8	1	*−7*
Nuclear	24	30	30	*0*	27	27	*0*	8	8	*0*
Hydropower	37	39	39	*0*	44	44	*0*	53	53	*0*
RES	13	30	299	*268*	417	780	*362*	994	1079	*86*
Total	548	700	700	*0*	937	937	*0*	1146	1146	*0*
Wind	7	18	179	*161*	250	468	*218*	596	647	*51*
Solar	2	8	75	*67*	104	195	*91*	248	270	*22*
Algae[a]	3	5	45	*40*	63	117	*54*	149	162	*13*
Gerland et al. (2014) **High population projection**										
Population	7.2	8.4	8.4	*0*	10.2	10.2	*0*	12.3	12.3	*0*
RES	13	40	308	*268*	459	821	*362*	1150	1236	*86*
Total	548	710	710	*0*	979	979	*0*	1302	1302	*0*
Wind	7	24	185	*161*	275	493	*218*	690	742	*52*
Solar	2	10	77	*67*	115	205	*90*	288	309	*21*
Algae[a]	3	6	46	*40*	69	123	*54*	173	185	*12*
Gerland et al. (2014) **Low population projection**										
Population	7.2	8.2	8.2	*0*	9.3	9.3	*0*	9.6	9.6	*0*
RES	13	20	289	*268*	378	740	*362*	861	947	*86*
Total	548	690	690	*0*	898	898	*0*	1013	1013	*0*
Wind	7	12	173	*161*	227	444	*217*	517	568	*51*
Solar	2	5	72	*67*	95	185	*90*	215	237	*22*
Algae[a]	3	3	43	*40*	57	111	*54*	129	142	*13*

[a] The 2014 algae production value includes all biofuels production as per BP (2015).

Table 2
Renewable energy source (RES) infrastructure requirements; 2014, 2028, 2054, 2100. Based on energy production in our unconstrained (UC) scenario and climate constrained (CC) scenario. Gerland et al. (2014) medium population projection. Wind energy production is measured in terms of 5 MW wind turbines equivalent (47.3 terajoules/year). Solar energy production (414 terajoules/km^2/year) and Algae biofuel production (79.3 terajoules/km^2/year) are measured in terms of area.

	2014	**2028**			**2054**			**2100**		
	Actual	UC	CC	CC-UC	UC	CC	CC-UC	UC	CC	CC-UC
Wind (5 MW)	141,800	385,900	3,784,400	3,398,500	5,288,600	9,883,100	4,594,500	12,592,900	13,678,800	1,085,800
Solar (km^2)	4300	18,400	180,300	161,900	252,000	470,800	218,900	599,900	651,700	51,700
Algae (km^2)[a]	37,500	57,600	564,800	507,200	789,400	1,475,100	685,700	1,879,600	2,041,600	162,100

[a] The 2014 algae production value includes all biofuels production as per BP (2015).

(~13,150 five MW equivalents) every seven days in 2099. In the shorter term, 485,000 and 94,000 5 MW wind turbines will need to be installed in the climate constrained and the unconstrained energy use scenarios respectively in 2028 alone. That is a 37-fold and 7-fold expansion in the annual installation rate in only thirteen years.

Despite increasingly energy efficient vehicles, appliances, and consumer electronics throughout the developed world, rebound effects (Sorrell, 2009) and global economic development (Wolfram et al., 2012) have led to overall growth in global per capita energy consumption. China (90 GJ/person) and India (21 GJ/person) account for 37% of the world's population, yet currently use very little energy per capita compared to the European Union (7% of world population, 133 GJ/person) or the United States (4% of world population, 299 GJ/person) (Supplementary Table 2). The 2014 global average is 76 GJ/person; yet, rates of individual countries span three orders of magnitude. Since 2000, overall EU and US per capita energy consumption has declined 12%, while China and India increased 174% and 77%, respectively. Over that same time, global per capita energy consumption increased 18%. Even if the consumption in the EU and US continues to decline, rapid economic growth (and projects such as SE4ALL) within the more populous developing world is likely to offset any decline in per capita energy consumption within the developed countries.

4. Conclusion and policy implications

The ability of the world to continue to support population and consumption growth is dependent upon a timely transition to an increasingly RES world. Our model results indicate that, with or without climate considerations, RES will comprise 87–94% of total energy demand by the end of the century. Despite the similar RES requirement in 2100 under both scenarios, the trajectories from 2015 to 2100 are quite different (Fig. 4a). The growth in RES plus hydropower in the unconstrained energy use scenario has a longer shallower ramp up during much of the 21st century and does not reach 50% of total energy until 2054. In contrast, the climate constrained scenario requires an immediate and rapid expansion of RES, reaching 50% of total energy by 2028. In essence, the transition from NRES to RES is a "pay me now, or pay me later" scenario. The benefits associated with allowing the world a slower

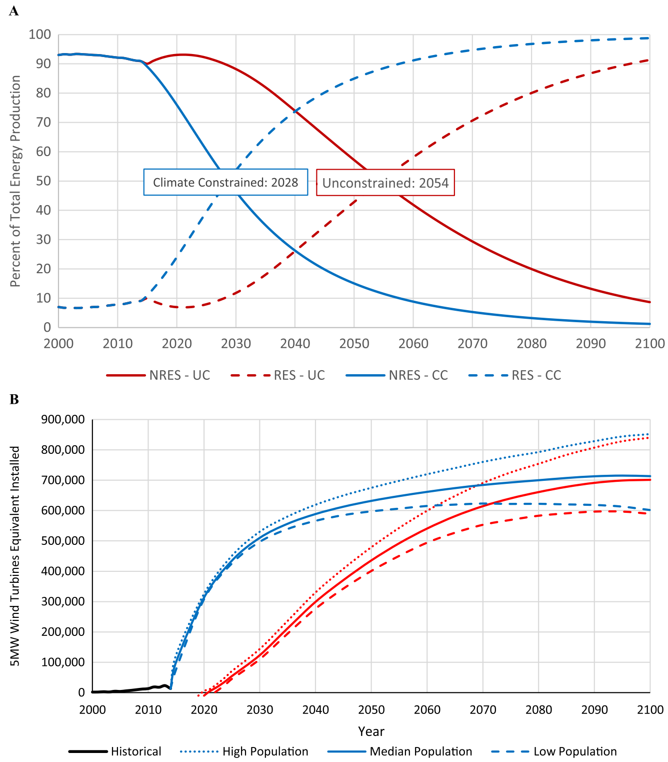

Fig. 4. Renewable energy requirements throughout the 21st century. (A) Comparison of NRES & RES energy mix, 2000–2100. Unconstrained (UC) scenario and Climate Constrained (CC) scenario with approximate dates at which 50/50 energy mix is projected. UC scenario projects a 50/50 mix by 2054 and CC scenario projects 2028. For this figure RES includes hydropower. (B) Annual 5 MW wind turbines equivalent installations per year, 2000–2100. Colour indicates energy scenario (UC – Red, CC-Blue) and line type indicates high, median and low population projection (Gerland et al., 2014). Solar panel and algae production facility area follow the same curve but on different scales. To convert to km^2 PV solar panel area, multiply 5 MW wind turbines equivalent by 0.114. To convert to km^2 algae production area, multiply 5 MW wind turbines equivalent by 0.597. Note: in the unconstrained scenario RES is theoretically unnecessary before 2020–25, whereas the immediate peaking of oil, coal, and natural gas in the climate constrained scenario results in a large up-front installation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transition come at the cost of global warming (i.e. >4700 Gt CO_2), whereas the benefits of avoiding serious climate change repercussions would require a large up-front cost and likely be a detriment to the goal of providing universal access to electricity.

On paper any form of scaling is simply a matter of numbers. In reality it could prove a monumental task to develop RES to support world population projections. EROI is a particularly important factor to consider in the transition to RES. Though the EROI of RES technologies has been increasing, there are theoretical limits (Atlason and Unnthorsson, 2014). The scaling of the RES infrastructure to our model output requirements would require the use of increasingly marginal lands and lower grade material inputs, leading to an overall lower EROI (e.g., Fizaine and Court, 2015; Moriarty and Honnery, 2012). Additionally, the transition to RES will require material resources (e.g. steel, copper and rare earth metals) whose per unit energy cost is significantly higher than for NRES (Vidal et al., 2013). Lower EROI fuels quickly reduce the share of net energy available for societal use (Murphy and Hall, 2010) and as less energy is available to societies, it is speculated that there will have to be a reprioritization of societal energetic needs (Lambert et al., 2014).

Coal, oil, and natural gas each took 35+ years to increase from 5% to 25% of total global energy production (Smil, 2014). A comparable transition to a renewable energy infrastructure will take decades, not years (Davis et al., 2010; Hirsch et al., 2005; Smil, 2014), time that is not available for a <2 °C scenario. The energy invested in creating the RES infrastructure takes a period of time before these sources become net energy producers (i.e., energy payback time). For example, it is estimated that there is a 1–4 year energy payback time for PV solar panels (Bhandari et al., 2015) and between 1–3 months for smaller (0.3–0.5 MW) wind turbines (Uddin and Kumar, 2014). We have not explicitly included the energy or material required to construct the RES infrastructure, though this is an important avenue for future research. However, doing so here would exacerbate the already high RES installation rates in our model.

Our analyses of NRES decline, population, and per capita energy consumption increase suggest that RCP 8.5 is unlikely to occur in the unconstrained energy use scenario, and RCP 2.6 appears equally unachievable in the climate constrained scenario, a conclusion in agreement with the qualitative assessment of others (Sanford et al., 2014; Victor and Kennel, 2014). Trying to achieve <2 °C warming (i.e. RCP 2.6 scenario) will require renewable energy to expand to $>50\%$ of total global energy by 2028, a 37-fold increase in the annual rate of supplying renewable energy in only 13 years. Our results further suggest that the "ambitious" end-of-century decarbonisation goals set by the G7 leaders will be achieved due to economic and geologic fossil fuel limitations within even the unconstrained scenario in which little-to-no proactive commitment to decarbonise is required.

The results of our study lead us to recommend that 1) the population-energy-climate nexus is not an either/or route for policymakers, rather 2) global efforts should focus on implementing adaptation responses to climate change under the IPCC RCP 4.5 and 6.0 scenarios, and 3) significant rapid RES expansion should be undertaken well before mid-century.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2016.02.044.

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