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A Solar Transition is Possible

By Peter D. Schwartzman & David W. Schwartzman

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Contents

Introduction	6
Our Modeling Approach	6
Results and Discussion	9
How much energy does humanity really need?	12
Conclusion	12
References	13
Appendix	15

Introduction

Arguably no challenge is more serious for the world's future than bringing about a rapid decarbonation of the energy infrastructure with the possibility of preventing the onset of catastrophic climate change. With a mathematical model we demonstrate that this transition is technically plausible using modest inputs of existing fossil fuel reserves in the creation of a global solar power infrastructure even with existing solar technologies such as wind turbines. In addition, this global power capacity can likewise provide energy consumption per person levels for all of humanity consistent with high human development requirements.

An energy infrastructure that depends largely on renewables appears inevitable as easily mined fossil fuels will be exhausted.^{1,2} Given the potential for catastrophic climate change and the inherently negative environmental externalities of non-renewable forms of energy production, we must find ways to transition to renewables as soon as possible. Studies of this potential transition have pointed to the possibility of a swift shift from fossil fuels to renewables, using existing technologies, while providing sufficient long-term energy needs for all humanity.^{3,4,5,6} Smil's⁷ and Kramer and Haigh's⁸ pessimism with respect to the timing of this change stems from a preoccupation with the history of major energy shifts but in our view fails to consider the power of exponential growth in R&D investments to usher in more rapid change. We submit that the massive economic investments to propel this switch are available if spending priorities are changed.^{5,9,10}

Current world's power production is ~16.5 terawatts (TW) resulting in the consumption of 522 EJ of energy annually; electrical production (from central producers) amounts to only 13% of this.^{11, a} By 2030 global energy consumption is projected to rise 39% to 724 EJ.¹² Theoretically, the amount of available renewable power far exceeds current human uses, by a factor of well over one thousand.⁴ Discounting inaccessible zones (i.e., open seas, high mountains), available wind power is 40-85 TW¹³ and solar power is ~580 TW.³ Current production however is extremely low with a mere 0.02 TW (wind) and 0.008 TW (solar).³ Thus, if we can tap into just a fraction of available renewable energy (RE), we can easily displace the need for fossil fuels and nuclear power completely. Therefore, technically-speaking, our species will not run out of available energy into the far future. Furthermore, greenhouse gas and many toxic air emissions can also be greatly diminished, potentially averting climate catastrophes as well as and substantially reducing social and environmental externalities of fossil-fuel byproducts.⁶ Fortu-

nately, the utilization of this energy should not significantly contribute to climate change, in particular, by tapping into wind as a source of energy.^{14,15,16, b}

Building the renewable infrastructure to sustain future energy needs will require dedicated effort and use of existing non-renewable energy sources. Jacobson and Delucchi³ make the case that this goal can be accomplished as early as 2030 with a mixture of new wind, solar photovoltaic (PV), and hydroelectric power plants. Sovacool and Watts⁵ argue that no technical limitations exist to converting the entire electrical grid (in both the United States and New Zealand, the two countries they examine) to one based completely on renewable sources. Fthenakis *et al.*¹⁷ argue that the U.S. can supply 69% of its electrical (and 35% of total energy) needs by 2050 using solar energy alone, given expected technological improvements in PV, concentrated solar power (CSP) and compressed air electrical storage (CAES). With these optimistic studies in mind, here we model the creation of new RE infrastructure as a function of a fraction of annual fossil fuel consumption in order to determine the fossil fuel inputs that may be necessary to make this transition as well as the importance of other contributing variables.

Our Modeling Approach

Our model defines f_{FF} as the fraction of the *present* global fossil fuel power capacity, P_{FF} used to produce new renewable power in the form of wind and other solar resources. We focus exclusively on wind and solar resources as these have been shown to be sufficient and have now undergone life-cycle analyses permitting further study. Additionally, the model commits a fraction of RE production to developing new renewable power infrastructure—representing this fraction by f . Integrating these two production streams continuously over time, we can determine how much new renewable power has been generated.

In order to model the level of renewable power produced, two additional parameters must be included: (1) the expected usable lifespan of any RE source (represented by L); and, (2) the amount of usable RE that will be created (over the source's lifespan) for every unit of energy used to build and maintain its infrastructure (we represent this magnifier term by M , also known as, EROI, or "energy return over energy invested"). (Note that the ratio (M/L) multiplied by instantaneous energy invested equals the instantaneous renewable power capacity created.) In this parameterization, we assume as a first approximation that all energy invested is homogeneous (e.g., input as electricity) and that all such

^a Reported numbers are for 2007. The total power is calculated by dividing the energy consumed by the number of seconds in a year.

^b Keith *et al.*¹³ and Roy and Traiteur¹⁴ suggest that the net climate impacts of a 4 TW extraction of global wind power will not be appreciable.

energy invested goes into the creation and siting of new renewable power capacity. (Since we are appropriating so little fossil-fuel, this assumption is valid. If more fossil fuel was required, we would need to consider the forms of energy produced with this fossil-fuel. Most PV and wind power stations will produce electricity as well.) As a consequence, we subsume the energy needed for maintenance and demolition of obsolete renewable capacity in the growing power capacity of the renewable infrastructure. We combine these terms to project future renewable power capacity at some time t , and represent it by P_{RE} . With all the relevant parameters thus accounted for, the change in P_{RE} as a function of time can be written as:

$$(1) d(P_{RE})/dt = [(M/L)(f)(P_{RE})] + [(M/L)(f_{FF})(P_{FF})];$$

This differential equation's solution is:

$$(2) P_{RE} = (f)^{-1}(f_{FF})(P_{FF})[e^{[(f)(M/L)(t)]} - 1]$$

Equation (2) provides a very useful predictor of the amount of renewable power generation during its lifespan. When we go to future times where $t > L$, we have to account for lost capacity due to gradual breakdown of deteriorating renewables (that were built when $0 < t < L$). This lost capacity, P_{REL} , goes as the solution above (i.e., the breakdown of renewables occurs at approximately the same rate as the creation of their infrastructure):

$$(3) P_{REL} = (f)^{-1}(f_{FF})(P_{FF})[e^{[(f)(M/L)(t-L)]} - 1]$$

From this term, we can easily determine its rate of change by taking the derivative:

$$(4) d(P_{REL})/dt = (f_{FF})(P_{FF})(M/L)[e^{[(f)(M/L)(t-L)]}]$$

Adding this to the differential equation for P_{RE} , eq. (1), leads to a new equation for the rate of creation of P_{RE} (for years L to $2L$):

$$(5) d(P_{RE})/dt = [(f)(M/L)(P_{RE})] + [(f_{FF})(P_{FF})(M/L)][1 - e^{[(f)(M/L)(t-L)]}]$$

where P_{RE} (at $t = L$) = $(f)^{-1}(f_{FF})(P_{FF})[e^{(fM)} - 1]$, the initial condition for the new time period.

Solving this equation leads to:

$$(6) P_{RE} = (fL)^{-1}(f_{FF})(P_{FF})[(f)(M)(L)e^{[(f)(M/L)(t)-(f)(M)]} + (L)e^{[(f)(M/L)(t)]} - (f)(M)(t)e^{[(f)(M/L)(t)-(f)(M)]} - L]$$

This equation, at $t = 2L$, provides the renewable power capacity after two full cycles of RE lifetimes.

Now, if fossil fuel use were to be ended at $t = L$, then equation (5), the change in renewable power capacity from $t=L$ to $2L$, reduces to:

$$(7) d(P_{RE})/dt = (f)(M/L)(P_{RE}) - (f_{FF})(P_{FF})(M/L)(e^{[(f)(M/L)(t-L)]})$$

This has a solution of:

$$(8) P_{RE} = [(f)(M)(L) + (L)(e^{(f)(M)}) - (f)(M)(t) - L] [(fL)^{-1}(f_{FF})(P_{FF})e^{[(f)(M/L)(t-L)]}]$$

These equations, in particular, (2) paired with (5) and (2) paired with (8), allow us to figure the dependence of P_{RE} on many empirical and/or society-directed variables.

The above model for renewable power capacity creation produces results that are heavily dependent on assumed parameters. These parameters have measured or empirically-derived values found in the literature or otherwise chosen. In the case of chosen values, we make reasonable assumptions concerning plausible inputs of fossil fuel and existing renewable power capacity to make new renewable power capacity. With these inputs, the model allows for reliable predictions about the magnitude of renewable power capacity in the future.

The scientific literature abounds with estimates for the parameters utilized in the model. Incorporating robust values for them is essential if the model is going to be realistic and productive. Let's now examine each parameter:

P_{FF} is given by ~14 TW, the global fossil-fuel power capacity.¹¹ Since this represents 86.4% of all power produced (the bulk of the rest being nuclear and hydropower), it provides an ample source for the creation of new renewable infrastructure; note: not all of this power is of course currently converted into electricity. Thus, our model does not use, and therefore doesn't depend on, nuclear power and currently existing renewable power, the latter of which currently accounts for ~8% of the energy consumed today (almost all of which is in the form of electricity).

In this first approximation modeling we simply vary f_{FF} to get a dedicated input of fossil fuel energy to create new renewable power capacity. Thus, for an assumed f_{FF} the energy in from fossil fuels is constant over the time period chosen, since P_{FF} is the present power capacity. It is a simple matter then to equate our model results to a scenario where f_{FF} steadily increases to a value of 1 while P_{FF} declines to the assumed value of $f_{FF} \times P_{FF}$ at the end of the assumed total

period of P_{RE} creation with lifetime equal to L , i.e., $(f_{FF} \times P_{FF})$ remaining constant, with fossil fuel capacity being progressively replaced by renewable capacity.

The lifespan of RE infrastructure, L , depends on the form of RE and the specific technology utilized. For wind turbines, lifespans of 20 years are generally reported.^{18,19} This is consistent with values offered by companies—National Wind reports 20-30 years,²⁰ VSB énergies nouvelles reports 20 years,²¹ and Wind Solutions Ltd. claims (a minimum) 25 years on all its turbines (including its largest—1.5 MW).²² With regard to photovoltaics (PV), typical modules last 20-30 years^{23,24,25} and a life-cycle assessment of concentrated solar plants (CSP) found lifespans of up to 40 years.²⁶ Most solar panel manufacturers provide 10-20 years warranties for their product; Wind Solutions Ltd. even offers a 35 year warranty.²² For the purposes of our model, we use $L = 20$ years as a reasonable and conservative value.

The magnifier term, M , is the ratio of the energy produced by a renewable source to the energy consumed in its creation and operation (commonly known as EROI). The choice of M provides the most influential variable in our model. As with L , M also varies with energy source, technology used, and scale of operation. A wind farm with a total capacity of 75 MW (in 1.5–1.65 MW turbines) was found to have an M in the range of 28.3-39.7 with larger turbines generally having values at the higher end.¹⁸ Two smaller wind farms (5-9 MW with 500 kW turbines) in Denmark were found to have M values of 51.3 (onshore) and 76.9 (offshore) (computed from energy payback times derived by Schleisner¹⁹). Lund,²⁷ synthesizing three analyses including Schleisner's,¹⁹ reported M values of 18 (offshore) and 34 (onshore) for wind farms consistent with a value of 18 reported by Kubiszewski *et al.*²⁸ A recent analysis of wind turbine life cycle energy concluded that previous estimates of EROI underestimated the energy inputs in their creation.²⁹ This study inferred EROI values of 21 and 23 for a small (850 kW) and large (3.0 MW) scale wind turbine respectively (assuming 20 year lifetimes). Further, maintenance and part replacement energy inputs were found to be 7.6% and 8.6% of the total energy inputs, respectively, demonstrating that most energy goes into the creation and siting of the turbines. For assumed lifetimes of 30 years, the EROI values went up to 32 and 35 respectively.

For photovoltaic plants, Alesma³⁰ estimated M values between 7-10. Lund,²⁷ synthesizing five analyses, reported a range of 6-9 for M values for photovoltaic technologies while Battisti and Corrado³¹ obtain a value of 6.8. More recent studies indicate that “state of the art” PV modules in U.S. and Germany have M values between 25-38 (calculated using the lifetimes and energy payback times provided).^{17,32} For comparison, non-renewables have M values in the range

0.7-7.0—0.7-2.9 for oil-fired plants, 2.5-5.1 for conventional coal-fired plants, and 3.5-7.0 for Coal Gasification/Combined Cycle (CGCC).¹⁷ Murphy and Hall's³³ review of EROI provides much larger values for non-renewables (from 10-80) but these values appear to be abnormally high because they only factor in energy requirements at the point (or boundary) of the oil well or mine-mouth.^{34,35,36,37} Given that the future energy grid will contain a mix of wind and solar, we consider M values in the range 10-40 reasonable for our model (a 50/50 mix of wind and PV farms would have an M value between 12-57 based on the reported figures). This selected range for M appears even more justified, since values of M are trending upward (due to technological advancement) for renewables.³³

The fraction of existing fossil-fuel derived power redirected to build new renewable power infrastructure, f_{FF} , is a variable chosen to vary from 1-10% in our model. While higher fractions are imaginable, we conservatively expect that no more than 10% of existing fossil fuel energy will be directed to build the renewable power capacity. As we'll see, one doesn't need to redirect a greater fraction to produce a sufficient amount of renewable power capacity. Currently, non-hydroelectric renewable power capacity produced each year is 1.0% of current fossil fuel use,⁴ a near doubling from the proportion of 0.52% fifteen years earlier. This increase suggests that f_{FF} has effectively averaged below 0.05% per year in the past 15 years. Sawin and Moomaw⁹ note that the “renewable share of additional global power generation (excluding large hydropower) jumped from 5 percent in 2003 to 23 percent in 2008, and this ratio is significantly greater in many individual countries.” Evidence of an increasing f_{FF} input can also be inferred from new wind power capacity added in 2009 (a total of 37.5 GW).³⁸

Assuming an EROI of 20, a lifetime of 20 years and a capacity factor of 35% for this new wind power capacity, we compute an estimated $f_{FF} = 0.1\%$ for 2009, evidence of an accelerating investment. Nevertheless, despite recent developments, the transition to renewables currently underway still lacks the intensity that will allow it to drive the replacement of fossil fuels in a few decades.

The fraction of new RE derived power redirected to build additional renewable power, f , is chosen to vary from 1-50% in our model. At the lower end of the scale, the model is heavily dependent on fossil fuels whereas, at the higher end, available renewable power becomes virtually independent of fossil fuels in a short period of time (due to the power of exponential growth). Once enough P_{RE} is available, lower f values are expected to sustain the system indefinitely.

There is a legitimate issue of whether the “embodied energy” in labor and other factors of production in the global

economy are accounted for in our model. We submit that this embodied energy is already taken into account in the growth of solar power replacing and then surpassing the existing global power capacity in our transition, with all of the following factors tending to decrease its requirements: (a) a steady decline of fossil fuel consumption with a likely higher second law efficiency using renewable energy; (b) increased energy efficiency especially in the global North; and, (c) an exponentially increasing total global power capacity with much higher EROI solar energy technologies (our conservative “best case” showing a doubling of present capacity in 25 years with complete replacement by solar ($M = 20$, $f = 10\%$, $f_{FF} = 2\%$). A comparison of our current fossil fuel “energy in” to our anticipated solar “energy in,” as defined by the EROI concept, further convinces us that future embodied energy is already addressed in our model. Today, we estimate that ~7-8% of total fossil fuel consumption goes as “energy in,” assuming a conservative EROI of petroleum (i.e., 10) and coal (i.e., 50) (using the 2007 estimates of ~68% fossil fuel energy generated by petroleum (oil and natural gas), and ~32% from coal), neglecting the ~15% of total energy consumption derived from other sources such as nuclear power and renewable. Note that the percentage of required energy going in to make more power capacity is roughly constant in our modeled transition, with our conservative “best case” scenario requiring 10% of renewable energy and 2% of present capacity used to continuously create renewable capacity. In the early stages of transition, with only modest levels of renewable capacity in place, roughly 10% of existing fossil fuel capacity is used, close to the present percentage, while in the later stages the same percentage of what is now dominantly renewable capacity is used. We conclude that the embodied energy factor is more than adequately addressed especially in a world of increased energy efficiency.

Results and Discussion

Two models were run, one that uses fossil fuels and newly created renewable power for building RE capacity over two generations (~40 years) of renewable infrastructure (Run I), and one that cuts out the fossil fuel after the first generation (Run II). Concerning Run I, Fig. 1 depicts how the R^* ,^c the ratio of future renewable power capacity (P_{RE}) to existing fossil fuel power generation (P_{FF}), varies as a function of M , the magnifier term, for very conservative values of f_{FF} (1%) and f (10%); note the y-axis is logarithmic and scaled to show when P_{RE} is comparable with existing fossil fuels (P_{FF})—when $R^* \approx 1$. For $M=10$, P_{RE} doesn’t match P_{FF} by the end of the forty year period. However, for $M=20$, P_{FF} begins to surpass P_{RE} in about 24 years and much earlier for higher M values (ones representative of modern wind farms). For $M=30$ and 40, note that P_{RE} becomes more than ten times P_{FF} in this rather short time frame.

Fig. 2 represents R^* as a function of different values of f_{FF} , once again for reasonable values of M (20), L (20 yrs) and f (10%). While the bottom curve (same curve as shown in Fig. 1) exhibits a final P_{RE} of ~4 times P_{FF} , increasing f_{FF} a few percent can boost the final P_{RE} substantially. Fig. 3, depicting similar R^* values for both Run I and II, establishes the relatively small impact of removing P_{FF} after the first 20 years (i.e., first generation of RE infrastructure) indicating that twenty years of small fossil fuel contributions to the renewable transition will be all that is required.

Fig. 4, presenting R^* for both Run I and II, assuming $f_{FF} = 1\%$, and different values of f , indicates that f levels of 5% or less do not provide enough input to make P_{RE} surpass P_{FF} over the forty year period. Yet, since $f = 10\%$ definitely does, this serves as the first-order threshold for the creation of a self-sustaining RE system.

Figure 1: Future Renewable Energy Capacity with Different Energy Return Over Investments (M) ($L=20$ yrs, $f=10\%$, $f_{FF}=1\%$)

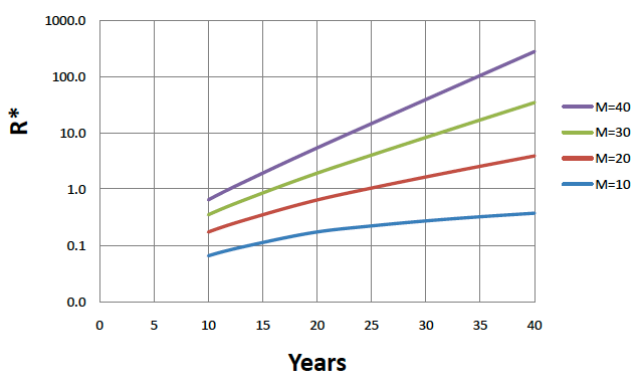
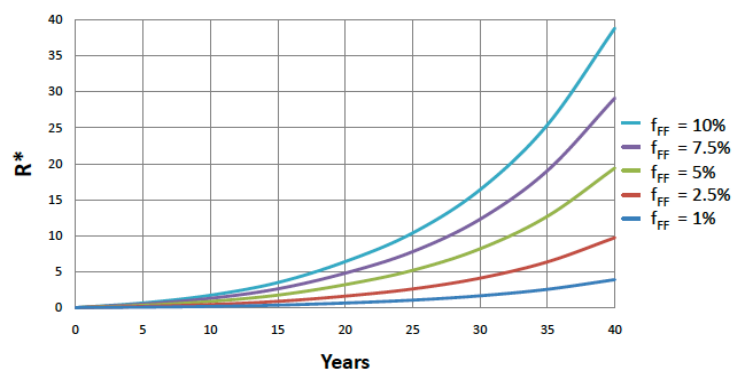


Figure 2: Future Renewable Energy Capacity with Different Fractions of Annual Fossil Fuel Contributions (1% - 10%) ($M=20$, $L=20$ yrs, $f=10\%$)



^c $R^* > 1$ indicates more RE production in the future than current fossil fuel production.

Figure 3: Future Renewable Energy Capacity with Different Fractions of Annual Fossil Fuel Contributions (1%-5%), with and without (WO) FF after $t=20$ yrs ($M=20$, $L=20$ yrs, $f=10\%$)

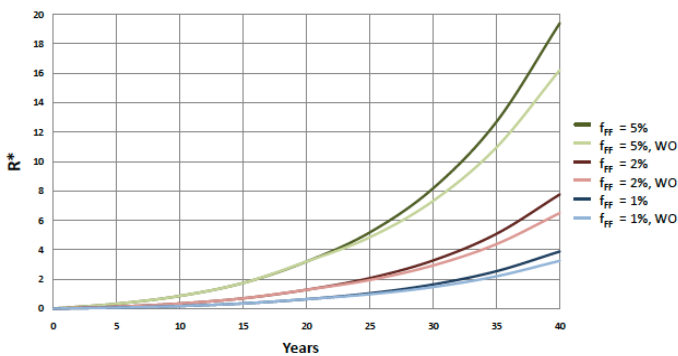
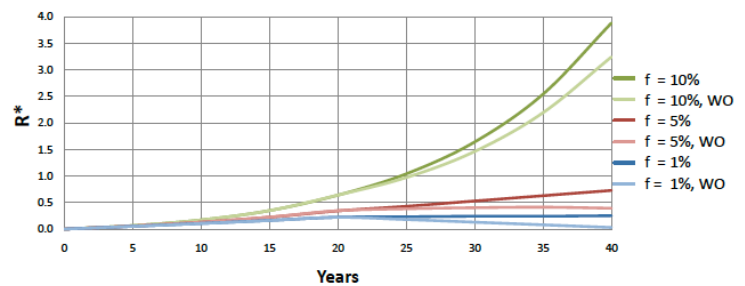


Figure 4: Future Renewable Energy Capacity with Different Fractions of Annual Renewable Energy Contributions (1%-10%), with and without (WO) FF after $t=20$ yrs ($M=20$, $L=20$ yrs, $f_{FF}=1\%$)



Based on the output of our model, as displayed in Figs. 1-4, we come to the following conclusions. With very little input of fossil fuels (just 1% of current consumption annually), we can create a RE infrastructure with wind farms and photovoltaic panels that will be able to power the entire world energy system in no more than forty years, and in many scenarios, with modestly greater inputs, fossil fuels become superfluous in only twenty years. This infrastructure will be self-sustaining with only 10% of RE capacity being used to regenerate it (while 5% of RE to regenerate new RE isn't sufficient to benefit from exponential impacts on time scales relevant this half-century). And again, this all can be done with merely 40% of the present annual consumption of global fossil fuel spread out over the entire period.

These conclusions are based not on future technological discoveries but rather on conservative values for lifespan and EROI from existing and currently operating wind and solar technologies. Therefore, other "solutions" to future energy needs, such as nuclear power or CGCC, are not necessary, and ultimately distractions from a RE transition. Sawin and Moomaw⁹ similarly find renewables to be more than adequate to our near future energy needs. Additionally, our findings suggest an effective path to carbon neutrality because of the low carbon emissions entailed in the creation of a global solar power infrastructure.

The critical subtext for this modeling approach is of course reducing the contribution of future fossil fuel consumption to carbon emissions driving global warming. In this paper, we do not attempt explicit modeling of trends in carbon emission reduction implied by a shift from fossil fuel to a RE infrastructure. Nor have we included the implementation of aggressive energy conservation technologies which would make possible even faster reduction in carbon emissions derived from fossil fuel consumption, as well as freeing up fossil fuel energy required for the solar transition, especially in its early stages. And it is precisely in its earliest stages, as a

component of radical reduction carbon emissions program, that very aggressive energy conservation should be implemented particularly in the United States and other industrial countries with proliferate waste of energy use. The most vigorous growth of renewable capacity should occur in the global South, where most of humanity is now suffering the impact of energy poverty, having a low energy consumption level per person.^{39,40}

An aggressive energy conservation program in the United States could potentially reduce oil consumption by more than 50% by 2025 with technological innovations in transportation, buildings and industry.⁴¹ A reduction of 25% to 35% of primary energy use in industrial countries may be achievable over the next 20 years while still maintaining the quality of life.⁴² Nevertheless, it is obvious that radical reduction, indeed the virtual elimination of anthropogenic carbon emissions, is a direct outcome of the complete conversion of energy sources to renewables in just a few decades in the most aggressive cases. We submit that solarizing the energy sources for the transportation sector is achievable with rapid and complete conversion to solar-generated electricity for rail, mass transit and electric cars (plus the production of truly renewable hydrocarbon fuels in this time frame).⁴³ Finally, we are persuaded that the elimination of fossil fuel energy in the agricultural sector could likewise be achieved with sustainable agriculture including agroecologies (for the optimist case see Ref. 44).

As optimistic as our findings seem, it would be misleading if we didn't mention some of the potential roadblocks. We observe **four** potential obstacles to this transition. Firstly, we note that world governments do not seem sufficiently motivated to support a timely overhaul of the global fossil-fuel based economy nor the creation of one that will be cleaner and more secure. In particular, the U.S. government projects that renewables will only account for 14% of the world's total energy mix in 2035, with a minimum of 75%

coming from fossil-fuels.¹¹ We submit that sufficient political will and determination can overcome this resistance, just as in earlier eras when the stakes were set high enough—e.g., retooling the American automobile infrastructure for World War II armaments and racing to land a human on the moon. Secondly, there may be limitations in the materials readily available and necessary to build all the new wind turbines and other solar technologies that will be needed. Jacobson and Delucchi³ conclude that the challenge of adequate supply of concrete and steel (for turbines and their platforms) is not insurmountable, particularly because both materials are nearly fully recyclable. However, they highlight the potential unavailability of rare-earth metals (for turbine gearboxes, PV cells, and batteries for an electric car fleet). Thirdly, given that the best solar and wind regions don't often overlap and are not distributed equally, a concern arises surrounding how energy will be made available at all the points where it will be needed. This is commonly referred to as the baseload challenge facing solar power. Jacobson and Delucchi³ argue that this is handled by having a smart balance of renewable resources, using geothermal as base supply wind at night, solar during the day, and hydropower at peak hours of need. Zwiebel *et al.*⁴ demonstrate that a new direct-current (DC) distribution network, as a means for moving solar-generated electricity around the country, is achievable and economically feasible. Kempton *et al.*⁴⁵ show that "wind power output could be stabilized" by situating offshore wind generators in specific configurations based on meteorological data. It should be noted that baseload backup, indeed the very creation of a global solar power infrastructure, will continue to be dependent on the existing energy base, especially fossil fuels (preferably petroleum because of its lower carbon emissions per energy output), until a global smart grid and solar infrastructure is fully in place. The grid development necessary to absorb expected increases in renewable electricity production will undoubtedly reduce EROI values a bit. However, since CSP electrical infrastructure adds only a \$0.01-\$0.02 per kwh, additional transmission lines will not be that energy demanding to construct (see Refs. 47-48 for some of the latest information on the storage issues involved with expanded PV energy sources).⁴⁶

Fourthly, if the EROI of petroleum, particularly that of end uses, continues to decline in the period we model for a full transition to solar power, i.e., the next few decades, this outcome would severely lessen the viability of using this fuel for this transition. This scenario would be a likely result of the world already reaching the state of "Peak Oil", i.e., the maximum global production of petroleum has already occurred with inevitable decline of its availability and, consequently, its EROI, in the future. Smil^{1,49} has critiqued this argument by pointing out the wide variety of estimates of the remain-

ing reserves of recoverable conventional oil, with those of the U.S. Geological Survey being nearly twice that of estimates made by peak oil "catastrophists" (his terminology). Of course, we agree that sooner or later (perhaps in the next decade or so) the peak in production of fossil fuels, starting with petroleum, will be inevitable, if business as usual continues in face of the mounting threat of climate change. However, for several reasons, we don't think a reduction of fossil fuels production will necessarily make a significant difference in our ability to make the necessary transition, assuming we don't wait another several decades to jump start it.

First of all, in our model of solar transition, as solar capacity reaches and eventually overtakes in 20-30 years the overall power capacity derived from the present energy regime (see Figure 3), the demand for petroleum in our global economy will significantly decrease, and this drop in demand coupled with technological innovation will most likely stabilize, or even increase the EROI of mined petroleum, as the most easily extractable—i.e., most profitable fields—get priority. In this scenario we are assuming that the deliberate phase out of petroleum will be faster than one driven by the exhaustion of current reserves of recoverable conventional petroleum. Moreover, even assuming the EROI of petroleum will decline in the later years of this transition, this factor would have progressively less impact on the economy, since only 1-2% of the present fossil fuel capacity is needed per year for solar transition—a mere fraction of the solar power capacity produced at the end of the "carbon" era. Notice the relatively minor impact on R* of keeping this fossil fuel input beyond twenty years (see Figure 3).

Petroleum/gasoline demand should significantly decrease as well when mass transit and electrified transport become realities based on both environmental and economic imperatives. Hence, aggressive energy conservation in the first few decades of this solar transition will free up additional petroleum of the highest available EROI levels even for pessimistic estimates of recoverable reserves.

We emphasize the use of petroleum for solar transition because of coal's greater greenhouse emission per unit of energy production ratio (this ratio compared to refined oil and natural gas is 25 to 19 to 14, respectively).⁵⁰ For this reason, in the early phases of solar transition the rapid termination of coal use is likely imperative to increase the chances of avoiding catastrophic climate change (e.g., see Ref. 51). Nevertheless, if EROI of petroleum decreases late in solar transition our model is open to a return to a modest use of coal to complete this transition, given coal's much larger reserves than petroleum⁴⁹ and a much higher EROI over the past 50 years of 80.^{33,52} For example, assuming a more conservative

EROI value for coal of 50, petroleum's EROI would have to decrease to 1.5 for coal supplying the same available energy to have a lower carbon emission than petroleum.

A few recent studies have come to quite different conclusions about the likelihood/potential for a swift shift to an energy system dominated by renewables. Galiana and Green⁵³ argue that only a technology revolution can meet future energy needs while also limiting global temperatures. Kramer and Haigh⁸ maintain that empirical laws will restrict how quickly new energy technologies can be brought to fruition. We do not find these arguments compelling because in our view they are unjustifiably pessimistic regarding the potentialities of existing technologies of wind and solar and are too restrictive with respect to the potential capital resources assumed to be available to make the swift transition necessary. Further, even in the economics discourse, we find arguments that complete elimination of carbon emissions by mid-century is achievable with 1 to 3% of world GDP per year dedicated to creation of renewable power capacity and carbon sequestration.⁵⁴

Nevertheless, projected "business as usual" investments into solar power would likely be far too small to achieve full solarization in the time period of a few decades.^{55,56} Thus, following the incisive analysis of Brown,⁵⁷ we are persuaded that the demilitarization of the global economy would free up the resources required for the renewable transition in the time scale necessary to avoid climate catastrophe. It is difficult to imagine real climate security without peace. The promotion of a global transition to a solar power infrastructure will likely facilitate progress towards this goal.

How much energy does humanity really need?

Can solar power provide it?

Assuming a minimum of 3.5 kilowatt per capita necessary for a world standard high human development index (hdi), with life expectancy alone being arguably the most robust single measure of quality of life,⁴⁹ the present world population of 6.8 billion people would require a minimum global power capacity of 23.8 TW (1.5 times the present capacity) to provide this hdi to everyone living on our planet. Our conservative "best case" generates a doubling of present capacity in 25 years with complete replacement by solar ($M = 20$, $f = 10\%$, $f_{ff} = 2\%$). This would provide a minimum energy supply corresponding to 3.5 kilowatt per capital for 9 billion people, with a power capacity of 32 TW.

Hence, while the U.S. and several other countries, with wasteful excess per capita consumption, surely need to reduce their energy consumption, most of the Global South requires a significant increase to achieve "state of the art/science" quality of life. But a shift to wind and solar-generated electricity as an energy source could reduce the required power level by roughly 30% once a global system is created, given the greater 2nd law efficiency of solar versus fossil fuels.³ Achieving high hdi for all people using this greater 2nd law efficiency translates into a present global solar power requirement of 16.7 TW or 5% higher than the present power capacity.

A shift to solar power would likely increase quality of life for the same level of present energy consumption by reducing/eliminating the negative externalities of fossil fuels and nuclear power/weapons production (e.g., the impact of air and water pollution on health). On the other hand, in the transition to a fully global solar power infrastructure, additional energy will likely be required to clean up the "mess" left by the historic dependency on fossil fuels and nuclear power and to repair the physical infrastructure as well as sequester carbon dioxide from the atmosphere to achieve a safe level of less than 350 ppm.⁵¹ Future progress in increased energy efficiency, such as dematerialization of information technology, will likely reduce the required minimum per capita consumption.

Based on these considerations, we conclude that the creation of a global solar power capacity adequate to providing everyone a high human development index is achievable within several decades using present renewable technology.

Conclusion

We submit that the models provided here present a compelling case that the road to a sustainable future lies in concerted efforts to move from fossil fuels to renewable wind and solar energy sources. This transition can occur in two or three decades and requires very little fossil fuel (on the order of one half of a year's present global consumption) and no revolutionary technological innovations. Since our model uses conservative estimates, the true renewable potential that is available to our society may be even more optimistic than we show. The primary anticipated obstacles to implementing this transition are non-technical, including lack of political will and economic prioritization. Nevertheless, this transition in the time scale of a few decades is imperative for global climate security.⁵¹

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Author Contributions

Both authors collaborated on all aspects of this paper, while Peter Schwartzman programmed the model calculations with the assistance of Mathematica.

Conflicts of interest

The authors declare no conflicts of interest.

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Appendix

Explore our Model with a Calculator

Model Calculator is found at: <http://www.solarutopia.org>

This calculator establishes the future ratio (R^*) of the world's Renewable Power Capacity (RPC) to current world Fossil Fuel Power Capacity (FFPC), where renewable is coming only from wind and solar (e.g., PV and CSP) energy systems and where nuclear power is deliberately left out (as it is inherently the most dangerous form of energy and it is absolutely not necessary as a component of the new energy infrastructure that all the world's people will need in the future). $R^* = 1$ means that $RPC=FFPC$, and $R^* > 1$ indicates that RPC has surpassed FFPC. (Note: RPC reflects the actual power available, not just what is installed, i.e., "potential").

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Corrections & Clarifications to “A Solar Transition is Possible” (*IPRD*, March 2011)

(p. 6, left column, line 29) change “Current world’s power” to “Current *world* power”

(p. 6, footer, footnote b) change numbers on two referenced articles: “Keith et al.¹⁴ and Roy and Traiteur¹⁵ suggest that the net climate impacts of a 4 TW extraction of global wind power will not be appreciable.”

(p. 7, right column, line 27) change “fossil-fuel power *capacity*” to “fossil-fuel power *production*”

(p. 9, left column, line 13) add additional “)” after “2%)”

(p. 9, left column, line 30) add italicized words to “roughly 10% of existing fossil fuel capacity is used *as energy in*”

(p. 12, left column, line 39) add italicized words to “the present world population of 6.8 billion people would require a minimum global *delivered* power capacity of 23.8 TW (*1.4 times the present delivery*)”

(p. 12, left column, line 45) change “power *capacity* of 32 TW.” to “power *delivered* of 32 TW.”

(p. 12, right column, line 9) correct sentence, adding italicized words as replacements, “Achieving high hdi for all people using this greater 2nd law efficiency translates into a present global solar power requirement of 16.7 TW or *1.2%* higher than the present power *delivered*.”