Clean Technologies and Environmental Policy (2019) 21:1517–1533
https://doi.org/10.1007/s10098-019-01739-4

PERSPECTIVE

Renewable energy and sustainability

P. Ray[1,2]

Received: 6 May 2019 / Accepted: 23 July 2019 / Published online: 9 August 2019

Abstract

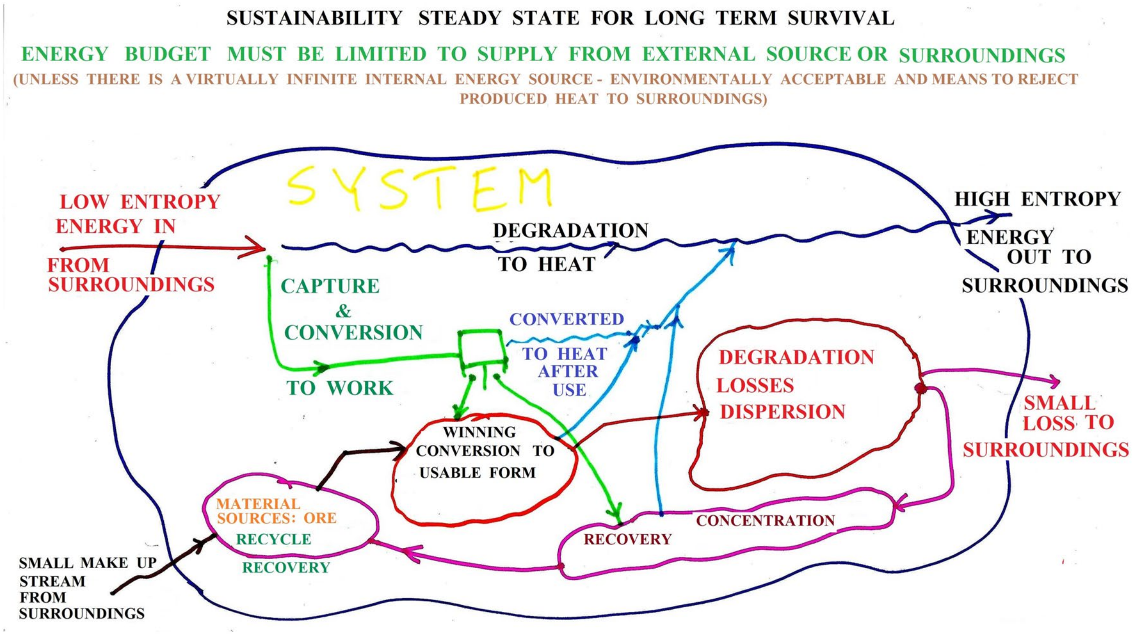
Renewable energy and sustainable development are widely discussed and highly debated topics. The current and majority opinion is that for sustainable development renewable energy is a necessity and plenty of it is available, which can be harvested economically and in environment friendly way. There are also dissenters who feel strongly that fossil fuels are far from exhausted, can be used with clean technologies, which are already developed, while technical problems for renewable energy are far from solved and they are very often more damaging to the environment and society than envisaged. The phenomena of global warming and carbon dioxide build-up are also inseparably entangled with sustainability and energy. Most analyses take a short-term view, hardly ever beyond 2050 or 2100. We certainly expect the society to survive and remain viable well beyond these dates and therefore need to explore what such long-term sustainability may imply. So it seems appropriate to consider a much longer time span and in order to keep the discussion from becoming speculative, certain restrictions need to be imposed. Therefore, a concept of sustainability steady state is proposed. Rough analysis presented here based on data that are commonly accepted, and mass and energy conservation principle with second law, seem to indicate that irrespective of correlation between carbon dioxide build-up and global warming, renewable energy, specifically direct solar energy will have to be adopted. This will of course have to be aided by judicious amount of indirect solar energy like wind energy and particularly bio-energy. Renewable sources, while having orders of magnitude greater energy content than human society may use up, are not particularly easy to harness, allowing only a small part to be finally harvestable. There are tough technical, environmental and societal problems, all quite significant, that have to be solved and restrictions on its transmission and location of usage have to be followed. It will also require development of "wasteless technology" and recovery and recycle of materials, particularly those which are difficult to win from natural sources and may be in short supply. Thus, in the long run, "renewable energy" will become inevitable, but even this will require a great deal of effort and planning and will not come easy.

✉ P. Ray
praycuce@rediffmail.com

[1] RKM Vidyamandira, Belur Math, Howrah 711202, India

[2] University of Calcutta, Kolkata, India

Graphical abstract



Keywords Renewable energy · Sustainability steady state · Recycle and recovery

Introduction

Renewable energy and sustainability are two inseparable, widely discussed and fashionable topics. Current majority opinion is that the path of development followed by the human society, particularly since the industrial revolution, is likely to lead to disasters or very uncomfortable situations for future generations, and hence, there is need for "sustainable development", and consequently need for renewable energy. But there is also a strong dissenting opinion that such fears are unfounded and consequently there is no need for "renewable energy", at least not in next few decades. Also harvesting and using renewable sources of energy require technologies still to be invented, and will be uneconomic.[1] The major points of criticism about renewable energy are as follows:

- It is not necessary, fossil fuels and nuclear energy will last a long time.
- Not enough of harvestable renewable energy, it is too dilute.
- Except for hydropower, all renewable energy sources are fickle or intermittent, and require storage, a problem that has not been solved.
- They may be too costly or uneconomic to harvest.
- Not really environment friendly as claimed.

Currently, major sources of energy are fossil fuels. These are not renewable, and hence will get exhausted. However, new reserves are also being discovered and improved technologies are making production possible even from older fields. The 2P (Proven and Probable) reserves for oil have kept up with depletion due to production (BP Energy outlook 2018, 2019). However, it is difficult to predict whether these will be able to keep up with an increase in demand though some like Gold (1999) feel that hydrocarbon content of earth is many orders of magnitude greater than we presume. In addition, there are apprehensions that continued use may cause a significant change in world climate.

The United Nations has officially taken note of the need for equitable and sustainable development, and the member nations have, after wide ranging discussions, proposed and accepted the Goals and Targets of the 2030 UN agenda on Sustainable Development in 2015. There are 17 goals and 169 targets, and goal 7 is specifically for Affordable and Clean Energy. It proposes shift to renewables, cleanup of fossil fuel-based power and increase in efficiency of energy usage.

---

[1] Clack et al. (2017), Kleidon (2012), Rosenbloom (2004), Batts (2017), Silverman (2008), Geiger et al. (2008), Isenberg et al. (2013), Halkema (2006), Jacobson et al. (2015, 2017), Johnson (2013), Moalem (2016), Kunzig (2015), Gregory (2017), IRENA (2018).

Incidentally, almost all projections seem to be limited to 2050 or at most 2100, and presented for several types of assumed growth rate, but without any explicit linking with the increase in world population and increase in standard of living or "well being".

While planning for a "sustainable society", limiting vision to 2050 or 2100 does not seem logical. It is unlikely that the world population or per capita consumption will stabilize by that time. Sustainability will imply provision for adequate and continued supply of energy and other material needs, without major or unwanted changes in the environment even at a stage when the population and its consumption stabilizes and not just during the transition.

In article 27 of chapter 1 of the "Report of the World Commission on Environment and Development: Our Common Future", commonly known as Brundtland Commission report, the following sentence occurs: "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs". This is considered to be the definition of sustainable development. The Commission also "believes that widespread poverty is no longer inevitable. Poverty is not only an evil in itself, but sustainable development requires meeting the basic needs of all and extending to all the opportunity to fulfil their aspirations for a better life. A world in which poverty is endemic will always be prone to ecological and other catastrophes". And it advocates equitable distribution of wealth and necessary development of world political system. It also notes that "energy has been used in an unsustainable manner" (Brundtland 1987).

Development or even existence at the present level of standard of living requires energy. As long as energy is obtained from unreplenished sources, future generations will have less and less amount available, eventually compromising some future generation.

Extraction of useful energy from any source requires expenditure of some energy. When the ratio of useful energy extracted to energy required to extract falls to unity, the source becomes exhausted. Many of the current energy sources may become exhausted in this sense, before all the fuel is extracted.

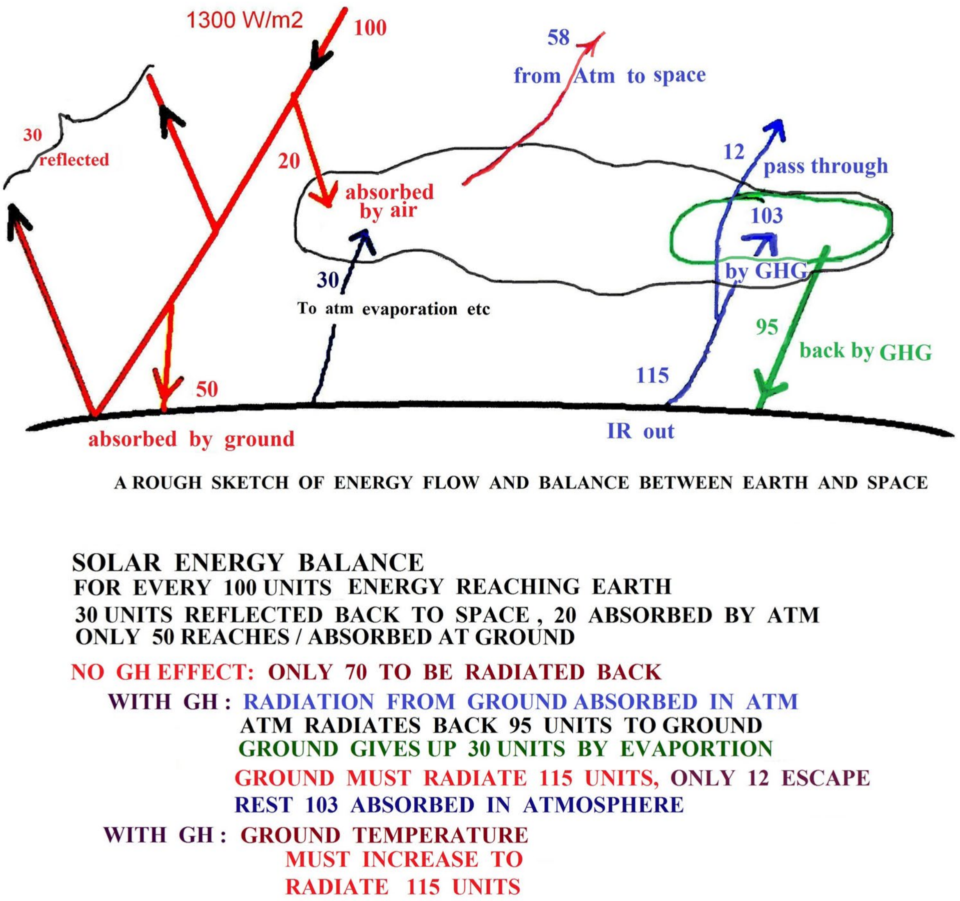
Two features of the definition of sustainable development should be noted. One is "future generations"—raising the question how far into the future—hundred years, ten thousand years or a million years. Answers to sustainability will differ significantly on the scales of future we envisage.

The second feature is "meeting the needs"—what exactly these needs are—are they defined now, and what is the scope for changes.

Steady states

In thermodynamics, there is a concept known as the steady state. Any system kept for a sufficiently long time, according to classical thermodynamics, attains a steady state; it may be an equilibrium state, where there will be no changes in properties and no fluxes in the system, or there may be continuous fluxes of both matter and energy through the system, there being no accumulation or depletion and no change in properties. Such a state is "sustainable", that is, it will remain as such for any length of time providing the same characteristics or environment. This is not the concept of "sustainable development"—for a human society, where there have to be continuous changes yet keeping some essence of the surroundings and environment and facilities unchanging. We may conceive a human society occupying a region of space, which is closed or nearly closed in thermodynamic sense, as sustainable if it remains "steady", that is, does not die down or explode. Such stability will be attained when the necessary materials and energy available remain more or less constant or steady. There can be changes subject to a few restrictions. Since the system is considered to be closed or nearly closed, this concept implies that all materials must be recycled or transformed into useful forms, and not allowed to transform into nonrecoverable or nonrecyclable state or keep on getting permanently consumed or fixed. This also implies a more or less stable population. There can only be energy flux through this region of space, with low entropy energy flowing in and same amount of high entropy energy flowing out without any substantial accumulation or depletion of total energy content. This also means that the energy inventory and distribution should remain such that several important parameters like the temperature, atmospheric pressure and composition will remain within currently considered "comfort zone". There may thus be the concept of a "sustainability steady state", a human society enclosed in a virtually closed space without substantial input or output of matter, with a steady flux of energy passing through it, without material waste formation. It does not however exclude change with time, as a thermodynamic steady state does. It however means no substantial loss or gain of materials or "excessive" changes in energy content. This will also imply a steady or constant population or a very slowly changing population, a constant flux of energy from surrounding through the system, no input or output of matter, and an environment—atmospheric conditions, biosphere and geosphere, remaining within comfortable ranges, and not producing a situation that causes the system parameters to run uncontrollably away from the comfort region.

Sustainability steady state is therefore quite different from thermodynamic steady state though there are certain similarities.



SOLAR ENERGY BALANCE
FOR EVERY 100 UNITS ENERGY REACHING EARTH
30 UNITS REFLECTED BACK TO SPACE , 20 ABSORBED BY ATM
ONLY 50 REACHES / ABSORBED AT GROUND
NO GH EFFECT: ONLY 70 TO BE RADIATED BACK
WITH GH : RADIATION FROM GROUND ABSORBED IN ATM
ATM RADIATES BACK 95 UNITS TO GROUND
GROUND GIVES UP 30 UNITS BY EVAPORTION
GROUND MUST RADIATE 115 UNITS, ONLY 12 ESCAPE
REST 103 ABSORBED IN ATMOSPHERE
WITH GH : GROUND TEMPERATURE
MUST INCREASE TO
RADIATE 115 UNITS

Fig. 1 Energy exchange at earth surface

This will also exclude a large number of technological concepts which at present can only be considered very remote if not complete speculation—for example asteroid mining for bulk metals, sea floor cities and farming.

It can be argued that this will be a useless exercise since it is impossible to predict the technological developments that far in future. However certain universal concepts and laws will still be applicable, for example, conservation of mass and energy will remain valid; conversion to useful forms of energy through initial conversion to heat will always be subject to second law limitations. This analysis will remain subject to such constraints only.

Nature seems to push ecosystems towards states similar to sustainability steady state. We may therefore get some idea of what such a steady state implies from some natural ecosystems. At the ocean bed, close to the plate upwelling lines, there are many hydrothermal vents, pouring out hot and sometimes supercritical mineral-rich water. Almost all such regions support ecosystems consisting of chemotrophic bacteria to large worms which may grow up to several feet in length.[2] This system is physically restricted to a small area surrounding the hot vent, where temperature is high enough. The area of the system does not change much, and there is a stream of energy and material through the system. So this is not a closed system, but material and energy do not accumulate in this region. The creatures maintain a sort of steady state, obtain their energy and material requirements from the entering streams, and allow the degraded energy and material excreta to be carried away with the streams leaving the region. Some of these ecosystems seem to have survived for millions of years. They are not unchanging—evolution is quite active, but the system as a whole is in a sort of steady state, neither dying out nor exploding and spreading out without limit. Some aspects of this "steady state" will be discussed later. For the world system inhabited by the human species, the system has to be closed as there is not much scope of any substantial material flow through the system. Being virtually closed, the material requirements must be met by almost total recycle.

---

[2] Woods hole Oceanographic Institution (2019), Zierenberg et al. (2000).

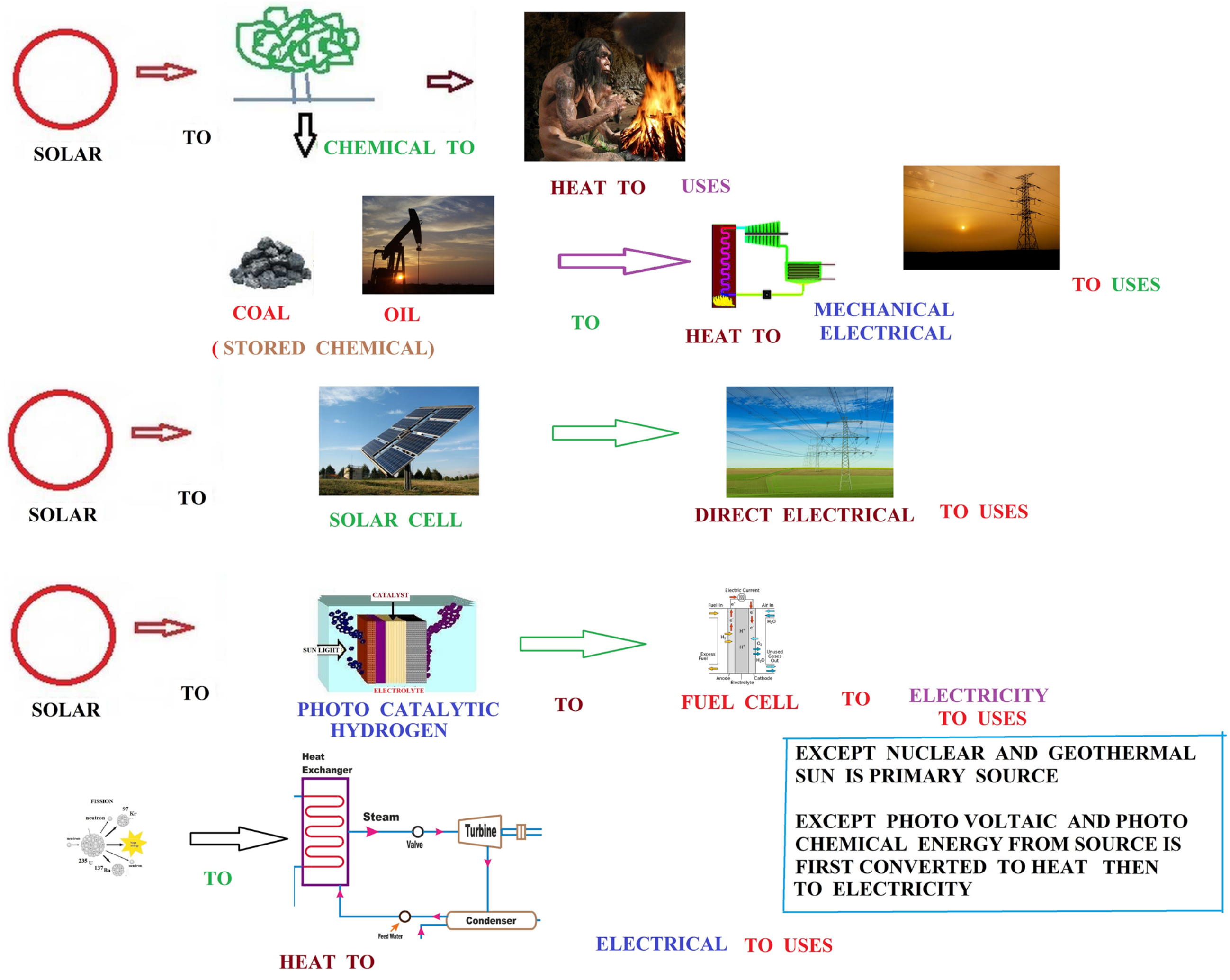


Fig. 2 Energy: original, source, collection and conversion

Some basic data

Figures 1 and 2 and Tables 1 and 2 show some basic data and concepts.

In Fig. 1, the basic energy exchange between earth's surface and sun and space is shown. Geothermal flows and tidal energy inputs have not been considered in this figure. In the absence of greenhouse gases in the atmosphere, the surface would have to radiate out 70 units of energy, but with GHG, the amount increases to 115 units. This requires a heating up of the surface. Use of Stefan–Boltzmann fourth power law shows that this will require an increase in temperature by 33 C almost exactly matching the greenhouse effect on earth. This match however is probably fortuitous but it does illustrate the greenhouse effect.

Table 1 shows a comparison between the planets of the inner solar system. It shows very specifically that carbon dioxide can produce a strong greenhouse effect, as it has done in case of Venus and Mars, but is not the main greenhouse gas on Earth (ACS 2016). It however can act as a trigger and cause a large effect. Carbon dioxide is also known to increase the acidity of the oceans with other environmental consequences. One should also note that the surface of Venus, receives less solar radiation than the surface of Earth yet it has a much higher temperature due to greenhouse effect. Role of CO_2 in greenhouse effect and consequent global warming and climate change have been widely discussed in the literature.[3]

In Table 2, we take a look at the primary energy consumption and population in this millennium for the whole world and for a representative advanced country, the USA. The population and per capita energy consumption of the

---

[3] IPCC (2007), Arrhenius and Holden (1897), Anderson et al. (2016), Callendar (1938).

Table 1 Planet parameters

	Venus	Earth	Mars
Solar constant (kW/m^2)	2.54	1.3	0.56
Diameter in km	12,104	12,740	6780
Area intercepting solar radiation (km^2)	1.15×10^8	1.27×10^{08}	3.61×10^7
Total surface area (km^2)	4.60×10^8	5.1×10^{08}	1.44×10^{08}
Albedo	0.75	0.3	0.25
Total power received (10^{15} kW)	292.29	165.72	20.22
Power received after albedo correction in (10^{15} kW)	73.07	116.00	15.16
Average power per unit surface of globe (W/m^2)	158.75	227.5	105
Radiation equilibrium temperature (C)	−43	−21	−66
Actual average surface temp (°C)	465	15	−55
Warming (°C)	508	36	11
Surface P bar	90	1	0.006
Atmosphere composition			
CO_2	96.50%	0.004%	95.30%
N_2	1%	78%	2.50%
Ar	1%	1%	1.50%
O_2	0.00%	21%	2.50%
H_2O	20–30 ppm	0–4%	0–0.1%
CO_2 partial mm Hg	66,010	0.288	4.33

Table 2 World population and energy requirement current and expected

	World			USA	
	2000	2017	Stabilized	2000	2017
Primary energy (J/y)	4.20×10^{20}	5.85×10^{20}	4.73×10^{21}	9.51×10^{19}	8.99×10^{19}
Population	6.14×10^{09}	7.55×10^{09}	1.50×10^{10}	2.82×10^{08}	3.05×10^{08}
Total power (W)	1.33×10^{13}	1.86×10^{13}	1.50×10^{14}	3.02×10^{12}	2.85×10^{12}
Per capita power (W)	2.17×10^{03}	2.46×10^{03}	1.00×10^{04}	1.07×10^{04}	9.35×10^{03}

USA seems to have stabilized, and the stabilized world figures are based on the ad hoc assumption that world population will stabilize at around 15 billion, and per capita energy consumption will be about the same as in the USA today that is approximately 10 kW. The data are from IEA (2017) and Worldometers.info (2019). This implies that provision of power at this rate—nearly 150 TW—may be necessary to maintain the sustainability steady state. The world population, particularly the level at which it will stabilize, is probably the most important factor, which can only be guessed at this time.

Figure 2 shows routes used for extraction of energy that are in use or been developed. It may be noted that usually energy is released as heat, which is converted into other forms using some heat engine or may be used directly as heat. Estimates of stabilized world population have been made using data from UN reports (UNDESA 2004, 2017), which show that under high growth condition, approximate population in 2150 will be about 15 billion. Even though medium growth predictions seem to indicate population stabilization by 2080 to 2100 at levels of 10 to 12 billion, “high growth” population at 2150 was taken arbitrarily. Energy production and usage data are available from many different sources, and these generally match.[4]

Table 2 shows population and per capita primary energy consumption and expected ones at population stabilized state. The US energy consumption seems to have stabilized even decreased slightly on per capita basis.

Energy sources

The various renewable energy sources and the estimated capacities of these sources are given in Table 3 (Kleijn and van der Voet 2010). A comparison of these sources with non-renewable sources is vividly shown in a figure by Perez and Perez that is reproduced here as Fig. 3 (Perez and Perez 2009, 2015). The total amount of energy that

---

[4] World Energy Council (2013), OECD (1999), FAO (2008), BP Energy outlook (2018, 2019), Owusu and Asumadu-Sarkodie (2016).

Table 3 Energy sources as multipliers of expected consumption

	Power in Watts	Multiplier for 2050 energy use in MF scenario (1.28×10^{21} J) MF: market first	Multiplier for stable population at US standard of consumption (4.42×10^{21} J)
Solar			
Solar energy reaching earth land surface	2.60×10^{16}	642	185
Collectable in Sahara desert with current PV efficiency (10%)	2.1×10^{14}	5	1.44
Wind			
Total kinetic energy in the earth atmosphere	3.5×10^{15}	86	24.78
Total in bottom 100 m	1.3×10^{15}	31	8.93
Maximum practically realizable	5.7×10^{12}	0.14	4.03×10^{-2}
Technical potential	1.5×10^{13}	0.37	1.07×10^{-1}
Hydro			
On basis of precipitation on land	1.0×10^{13}	0.2	5.76×10^{-02}
Principally available	1.2×10^{12}	3.00×10^{-02}	8.64×10^{-03}
Realistic reserve hydro	6.3×10^{11}	1.50×10^{-02}	4.32×10^{-03}
Tidal			
Total tidal energy	3.0×10^{12}	7.40×10^{-02}	2.13×10^{-02}
Tidal world potential at best sites	1.2×10^{11}	3.00×10^{-03}	8.64×10^{-04}
Wave			
Total wave energy	1.1×10^{11}	2.80×10^{-03}	8.07×10^{-04}
Geothermal			
Total stored in the earth (J)	4.00×10^{30}	3.10×10^{09}	8.93×10^{08}
Total heat outflow	3.00×10^{13}	0.7	2.02×10^{-01}

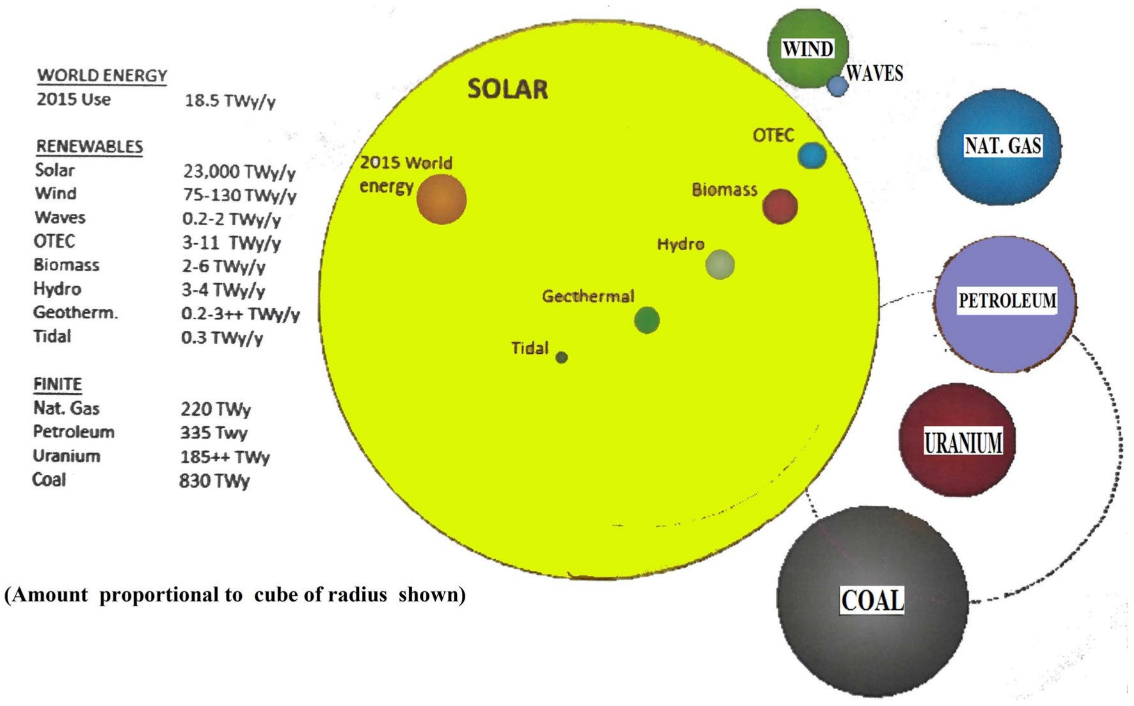


Fig. 3 Energy availability and requirement. Reproduced from Perez and Perez (2015)

can be provided by exhaustible sources is also shown for comparison. The amounts indicated for exhaustible sources are probably not accurate, but possibly not by orders of magnitude.

The multiplier in Table 3 indicates the ratio of estimated energy provided by the source and the estimated requirement at 2050 or after population stabilization. The figure for geothermal energy is the number of years this source could supply at the estimated rates of consumption. The estimates clearly indicate that except for direct solar energy conversion, other indirect renewable energy routes will not be able to satisfy the demands.

The thermal energy stored in the earth is certainly enormous, but it is not extractable with present technology or with technologies being developed. Most technologies being developed seem to be limited to regions where underground superheated water is available or to existing oil extraction wells. Some methods for utilizing the dry hot rocks several kilometres underground are also under consideration. But, these can reach only a small fraction of the heat stored in earth. Also, it may not be prudent to extract without working out the seismic effects.

Figure 3 gives approximate ideas about the length of periods the exhaustible sources may last. One should however note that in case of oil, the rate of discovery of new reserves have kept pace or even outstripped the amount being mined. So at this moment it is not clear how long these can last. For gas also large deposits like hydrates at ocean bottom are known to exist, but have defied commercial exploitation so far.

Both the table and the figure show that solar is the largest source, the only one that is sufficiently large to cover the energy demand. Even then, it should be noted that the stabilized energy demand is nearly 0.5% of the total solar energy received on land. For collection and conversion, this is a very high fraction, considering the restrictions on land availability and conversion efficiencies. This is a tough task, even without considering the other problems mentioned later.

During the discussions so far "pessimistic" estimates of both population and per capita consumption have been used. It is likely that world population will stabilize at levels well below 15 billion may be around 12 billion or less, and also current "first world standard of living" can be maintained with per capita energy consumption well below the current US per capita consumption of 10 kW, may be even with 6 kW. But in computing the total figure for energy consumption rate, energy penalty for "recovery and recycle" has not been taken into account. Hardly, any work has been done on these aspects and no reliable estimate exists. So whether the energy consumption rate used here is really "optimistic" or "pessimistic" cannot be decided at this point of time.

Global warming and carbon dioxide

For gas, oil and coal, currently, the effect on climate is a greater issue than their eventual exhaustion. It has been established beyond any doubt that there is a "global warming". Ice cover in the arctic region has diminished remarkably, glaciers are retreating almost all over the world. Though some initial studies reported ice accumulation, longer period data seems to indicate that total Antarctic ice is also decreasing (IMBIE team 2018; Zwally et al. 2015). Carbon dioxide level in the atmosphere is also increasing, and a large part of it is anthropogenic. A distinct correlation between carbon dioxide content in atmosphere and global temperature has also been observationally verified and accepted.

There have been many models and attempts since Arrhenius to explain various aspects of climate and weather pattern. The overall consensus is that increase in CO_2 in atmosphere aids global warming. But there are many factors involved. Several models also show chaotic behaviour of climate. Despite a few dissenting works, it is apparent that the effect of CO_2 on global and even local climate cannot be ignored (IPCC 2007).

Increased CO_2 in atmosphere also leads to ocean acidification, which affects ocean life strongly, but is still not completely understood. There are indications that this decreases biodiversity.

This has led to vast efforts and actions—R&D, technological and commercial ventures, even economic and business transactions like carbon credit. Many countries have accepted reduction in carbon in atmosphere as a policy and have already started adopting to renewable energy. Coal is being replaced by gas in many cases, carbon capture and sequestration technologies are being developed and implemented.

Nuclear options

Nuclear energy has a very small carbon footprint, and is being promoted by many as a substitute for fossil fuels. World Nuclear Association is such a body formed formally in 2001 to promote the interests of the nuclear industry. From perspective of sustainability steady state, there must be a very large reserve of energy, and it must not leave wastes. Currently, uranium reserves are estimated at about 6 million tons, and thorium reserves are also estimated to be of similar amount (World Nuclear Association 2017, 2018). At current rate of consumption, it will last about 800 years and at "stabilized" rate about 100 years. It does not include the 0.003 ppm uranium in sea water or the

2.8 ppm uranium in earth crust. Science for recovery of uranium from sea water has already been developed (Abate 2017; Nor Azillah Fatimah et al. 2015; Parker et al. 2018), and if this becomes technologically and economically feasible, nearly three GT will be available, sufficient for nearly million years.

Fusion reactors have not been considered. Fusion energy has long been recognized as "the ultimate" energy source, virtually unlimited in extent, considerably more environment friendly than fission energy, coal, oil or gas, without the disadvantage of intermittency suffered by wind or solar. Technicalities have still not been solved, but several progresses made in last several years by different approaches such as ITER tokomak under construction, Wendelstein 7-X stellarator, inertial confinement and reported attainment of temperatures of the order of billion degrees in a Z pinch apparatus give hope that fusion energy may become feasible in 40–50 years. There is of course a common joke in the fusion research community that "fusion energy is perpetually just round the corner and will be reality within perpetually next 40 years". Safety, environmental and other consequences have not really been investigated properly—only its positive sides have been advertised so far and that also generally qualitatively. Sustainability steady state concept will certainly imply some restrictions, which cannot be decided before the technology is developed.

On the fission front also, there have been some developments. Work is in progress on generation IV reactors, which are FNRs (Fast Neutron Reactors). Of these developments, works on molten metal reactor are in most advanced stage, liquid sodium reactors being one of the major choices. Generation IV reactors exhibit more efficient use of uranium—they are able to burn U238-as well as higher actinides—thus increasing the output by a factor of 60 and also eliminating the long-lived components of nuclear wastes. All the FNRs are versatile that can be designed to be a breeder or a burner, burn all the uranium and plutonium and actinides or allow these to be produced. These are also supposed to be safer as it operates at atmospheric pressure, no melt down possibility, and may be designed to produce ashes without long-lived radioactive wastes. Russia is reportedly using FNRs for burning up plutonium from decommissioned nuclear weapons. These types of reactors can be made very compact; Russian BN 600 (560MWe) reactor has a core 0.75 m dia and 0.88 m active height. On the safety side, liquid metals particularly sodium is fairly dangerous substance to handle being extremely reactive, will explode in contact with water or oxygen and are also corrosive.

However, generation IV plants are still under development, and will require quite some time before being fully commercial. The main impediment to nuclear reactors is probably the cost; availability of cheap gas was probably more responsible for stoppage of orders of nuclear reactors during 1980 s than environmental concerns and currently, falling prices of some renewable energy options may make the nuclear option economically less viable.

But nuclear energy has several significant drawbacks.

- It is not considered safe, particularly due to its weapons connection.

Everyone agrees that there must be strong state and even international surveillance on production, processing, reprocessing of fuels—a situation with complex political overtones.

- Waste disposal problem has so far not been satisfactorily resolved. No community or country seems willing to host sites for storage of long-lived radioactive wastes (Feiveson et al. 2011).
- It is becoming increasingly less competitive, due to developments in renewable energy technologies, prices of which have come down drastically.

For sustainability steady state on earth, nuclear energy is thus not a good option. This does not however mean that nuclear energy should be totally abandoned. Compact reactors may be very useful or even unavoidable in many specialized cases like long-life space probes for far away regions though there is always a possibility of misuse, for example, in naval vessels for military purposes.

Renewable sources

Wind, wave and tide

Wind is considered to be one of the most environment friendly renewable energy sources. It is often thought of as a virtually limitless source. In some countries like Denmark or Germany, a considerable fraction of power requirement is met from wind turbines. However backup power plants and inter country energy trading are required to ensure matching of demand with supply. The atmosphere absorbs about 20% of solar power incident on earth that is about 2.6×10^{16} J/s as heat. It acts like a heat engine that converts this heat into other forms of energy, particularly kinetic energy of the wind. So there is a limitation on the rate of production of kinetic energy of wind. However, there are large discrepancies between values reported by different workers.[5] Various aspects of wind energy have

---

[5] De Castro et al. (2011), Huang and McElroy (2015), Marvel et al. (2013), Davidsson et al. (2012), New Scientist (2011), Herbert et al. (2007), Adams and Keith (2013).

Table 4 Estimates of wind energy

	Marvel et al. (2013)	Huang and McElroy (2015)
Atmospheric kinetic energy inventory (EJ)	160	765
Total kinetic energy creation rate (TW)	1800	1254
Kinetic energy creation rate (W/m^2)	3.53	2.46
Average air velocity (m/s)	7.9	17.3
Other	Low altitude turbines capability 400 TW	Heat engine with effective high temp 256 and low temp 252 K

been discussed in the works cited. Table 4 shows a comparison. Marvel et al. (2013) suggests that wind energy will be sufficient to meet all energy needs, all the time in future, without any need for exploitation of other forms of renewable sources. The authors also suggests that extraction of such energies will not reduce the wind velocities significantly or cause any impact on the weather. Huang and McElroy (2015) calculate effective heat source and heat sink temperatures of the atmospheric heat engine and report conversion efficiency of the order of 1%.

The total amount of wind kinetic energy produced by all accounts seems to be large compared to the human consumption, even at steady state. But only a small fraction can actually be extracted as the entire land surface area cannot be used for wind energy farm. Kleijn and van der Voet (2010) gives maximum practical realizable wind power as 5.7 TW and technical potential as 15 TW, an order of magnitude less than the expected demand.

Reported power extraction density actually achieved in Denmark, Germany, Netherlands, places where wind provides a significant fraction of power, is of the order of 0.27–0.44 W/m^2 of farm area, about a magnitude less than 4 W/m^2 indicated in some studies. But this value is for “most suitable” places, that is, places with high wind energy densities. As with other resources, wind energy is not evenly distributed, with very little scope in south and south-east Asia, the largest population zones in the world

In wind turbine energy computations, it is usually assumed that only the kinetic energy is captured, there being no conversion of enthalpy to kinetic energy. This makes some of the models and computations somewhat suspect. Some model predictions and also some observational evidence suggest that large-scale extraction of wind energy can have substantial effects on wind velocities and temperature, affecting local and global weather (New Scientist 2011).

The important features of wind energy may be stated as

- Atmosphere acts as a large heat engine converting solar power to kinetic energy.
- Rate of production of this kinetic energy is orders of magnitude larger than what is likely to be consumed by human society.
- Extraction of this power requires large land areas and since wind energy is spread out unevenly, only a small fraction of it would be harvestable, not sufficient to meet the requirements.
- Wind may still provide a useful fraction of power.
- It is considered most environment friendly, though its effect on avian biosphere is debated and effect of offshore turbines is not yet known.
- It has the lowest carbon foot print.
- It is available during night and is available to some extent almost everywhere.
- Land occupied by wind farms can be used for many other purposes as the actual mechanical foot print of turbine towers is very small compared to the total area of the farm.
- It is fickle and need to be backed up by other power sources.
- It can be produced only in medium to large scale; small single installations are not considered viable in most cases.
- There is some evidence that very large-scale farms may considerably lower the energy extraction density and also significantly change temperature and wind velocities, causing perturbation to local and may be global weather pattern.
- It is highly capital intensive.

Thus, it seems that wind energy may be a significant contributor to renewable energy, but will fall far short of the total requirement and also will have to be planned and installed with careful selection of sites and grid availability.

Tidal and wave energy capture are dependent on the type of coastlines and also require large areas. Potential for these forms are considered inadequate. The same is applicable to hydropower; its availability is dependent on the geography. Potentials for these sources are not sufficient, and these, particularly large hydropower projects, can be damaging to environment and society. These are also capital intensive projects. Potential for micro-hydroprojects, that is hydropower plants with capacities less than 5 MW, has been assessed to be very small. But the micro-hydropower technology may come in handy as an energy storage method for

Table 5 Estimates of total bio-energy potential

1 (calculated)	Total forest + agricultural area (km^2)	9.00E+07
	Approximate rate of solar energy absorption by biomass (PW)	15
	Bio-energy formation rate assuming 1% conversion (TW)	150
2 (Barber 2007)	Production of dry biomass per annum in billion tons	100
	Assume energy content of 4 kcal/g (similar to heat of combustion of cellulose)	
	Total energy produced per annum (EJ)	16,800
	Energy production rate (TW)	53
3 (Kling 2016)	Bio-energy production (million cal/m^2 per year)	5.83
	Total yearly energy production (EJ)	2193
	Energy production rate (TW)	70

other forms of intermittent renewable sources. Large hydropower projects require vast areas of land and are also capital intensive and almost invariably require state involvement. It may however be noted that Costa Rica now runs almost entirely on renewable energy, with hydropower accounting for almost 80 per cent of the requirement.

Summing up the potentials for tidal, wave and hydropower it may be said that.

- potentials for these are inadequate and available only in limited areas
- require land and capital, and may often adversely affect environment and society
- new installations should be planned carefully to avoid environmental effects
- micro-hydropower technology may be helpful in providing means of storage of energy from intermittent renewable sources like wind and solar.

Bio-energy

Bio-energy is considered to be another significant source of renewable energy (Miyamoto 1997; Parlevliet and Moheimani 2014). But this also is limited by the solar energy flux. Conversion of solar energy to plant biomass energy occurs approximately with efficiency of 1% (Kling 2016). Some plants may offer upto 2–3%; some algae may offer even higher values. Several estimates of annual generation of biomass or biomass energy are available. One estimate (Barber 2007) is that formation of dry plant biomass per year is about 100 billion tons. Assuming all these to have an average usable energy content equal to that of cellulose, which is about 4 kcal / g, the total available bio-energy becomes about 50 TW, which is about 1.5–2% of the solar radiation absorbed by the total forest and agricultural area of the entire world. Two other methods of estimation also produce similar rates of bio-energy production. These figures are approximate, but unlikely to be off by an order of magnitude either way. These values are shown in Table 5. A major part of this energy will be consumed as food, or left undisturbed to maintain the ecological balance. The energy harvestable from bio-sources is therefore likely to be small compared to even wind energy. Thus bio-energy is unlikely to become the major contributor to renewable energy.

One important feature of bio-energy however is that it will come in the form of liquid/solid / gaseous fuel, not directly as electricity, and therefore will be directly useable to replace fuel for transport systems of current technology. Also this will be able to provide the reducing agents for recovery of metals, and provide starting materials for needed chemicals. So while this source is not likely to be adequate for providing energy, it will still be essential to provide important chemicals and materials, which cannot be produced from direct solar energy.

Production of chemicals through bio-processes is already under investigation. But mostly the routes are through fermentation, pyrolysis or charring and gasification. Production routes utilizing genetically modified bio-entities should not be avoided. Hydrocarbons are primary fuels for current transport system. Some plants like rubber produces polymeric hydrocarbon chains; some algae are known to produce lower hydrocarbons. Genetic modifications may allow plants or algae to produce such chemicals directly in commercially viable amounts. This is one of the many possible lines of development; some important works in this field have already been reported (Howard et al. 2013).

The bio-energy options can be summarized as follows:

- With current land availability, bio-energy will be quite inadequate to meet the stabilized energy demand.
- Bio-energy for direct production of chemicals will be an attractive proposition, and is likely to become essential.

Direct Solar Energy

It is given in Table 1 that about 165 PW solar energy strikes earth. Of this, land surface receives about 29% that is about 48 PW. About half of this, that is, about 24 PW, reaches the earth and is available, rest being either reflected or absorbed in the atmosphere.

This is indeed way above what human race can use within foreseeable future, the current energy consumption being about 17 TW, less than 0.1% of the solar energy flux. However, harvesting requires covering up land—for direct conversion—either PV (photo voltaic) or CSE (concentrated solar energy—heating or power). So the amount that can be harvested depends on the fraction of land area that can be spared for collection. Total habitable land area is estimated as 71% of the land area, with 10% being covered by ice and 19 per cent is barren, that is, deserts and mountains. Urban areas cover about 1% of habitable land. The long-term power demand has been estimated in Table 2 as 150 TW. If we assume 10% conversion efficiency for photovoltaic cells, then to collect this power, about 6.25% of land area will be required. This is a fairly large area, about 9 million km^2, nearly one-third of the entire barren region, and almost equivalent to Sahara desert. Urban area is supposed to cover about 1 per cent of land area that is about 1.5 million km^2. If we quite arbitrarily consider total area for collection to be about the size or about twice the size of urban area, and also assume that 20–25% conversion efficiency will be achievable, then a total power output of 120 TW can be reached, which is still short of the expected 150 TW. Thus, while solar energy is plentiful, capturing it will require fairly large tracts of land, and also cheap high-efficiency solar cells. This will require materials and technology which are now at research level. There are also several other aspects that need to be taken into account.[6]

We may list the major pros and cons of solar PV generation for a sustainability steady state.

- Solar energy, as PV or CSE, is the only renewable source that can meet the energy needs. But, its harvesting requires large areas of land, comparable to the area of land used for crop production.
- While plenty of solar energy is available, not enough of it can be collected without significant occupation of land, which may not be possible in every region of the world. What fraction of land can be set apart for this is still not decided.
- It is intermittent, requiring storage for night time or cloudy day use.
- Large-scale imports or exports of solar energy may affect the weather pattern.
- Solar energy has considerable carbon foot print on entire life cycle basis. It is smaller than fossil fuels, but larger than wind and possibly even nuclear energy.
- Large installation of solar power plant may in some cases enhance greenhouse effect.
- Solar PV does have an effect on microclimate and micro-bio-habitat.
- Solar cells use up many scarce metals.
- Storage problem has not been satisfactorily solved.
- Solar is the only source capable of meeting sustainability steady state demand with current technology or technology expected to be available in the near future.
- It is a distributed source with advantage that it may be captured and used at almost any scale and at any place and time.
- It does not require any moving part unless tracker cell is used.
- It is “people’s energy”.

When a solar cell is set up, the effective albedo of the land changes. Solar cells in general will absorb a larger portion of sunlight and will radiate more in the GHG absorption region, leading to higher heating of the local atmosphere, effectively equivalent to additional GHG. If the ground albedo prior to solar cell set up was lower, it can have an opposite effect.

There is also a question of local balance of energy.

Large-scale export of solar energy will reduce the energy received at the region of conversion. For example, if a large solar power plant be set up in Sahara, it will capture some of the radiation that heated the desert, thus cooling the region. If this power is exported across the Mediterranean to Europe, this energy will be dissipated as heat in Europe, heating the region receiving the energy. Even small temperature changes over such large patches of land may substantially affect the weather pattern. This may cause local or even global climatic disturbances. Not all the disturbances will be adverse, it may detrimental at one place but be beneficial at some other place (Diffenbaugh and Burke 2019). But one thing is certain; the effects will not be restricted by national boundaries, and may lead to strife between countries. As long as the energy transferred is not a significant portion of the solar energy received by the regions, such effects may not be significant. This aspect should be taken into account while planning any large-scale export or import of solar energy.

One must note that large-scale production of energy, in excess of solar energy, is also not a very desirable option in sustainability steady state. Any substantial addition to the solar energy that the Earth receives will inevitably change its temperature or weather and climate in order to radiate away the additional waste heat generated. A new “equilibrium” will be attained, equilibrium of energy input and output, which may or may not be beneficial to the human society. As long as the energy used is a small fraction of the solar energy received, the effects may not be noticeable. This rules out large-scale use of nuclear energy, fission or fusion, or supply of solar energy from space in large quantities, even if these become technically feasible. Otherwise, global climate

---

[6] Sherwani et al. (2010), Baharwani et al. (2014), IEA (2017), Mulvaney (2014), Meng et al. (2018).

engineering will have to be developed to radiate the extra heat away and keep the environment comfortable.

Solar cell installations are also known to affect microclimate, and micro-bio-habitats.

Of the disadvantages of harvesting and using solar energy, prominence is given to its intermittent nature and lack of proper storage technology. These will not generate power at night nor work well during cloudy days. Energy storage is still an unsolved problem and a field of intense investigation. Major storages are chemical in nature, either as batteries or hydrogen used in fuel cell or in combustion. A breakthrough is necessary in this field for successful implementation of solar energy. The major advantage of solar energy is that it is readily usable by anybody and at almost any scale and almost anywhere. In this sense, it is "energy for the people".

The figures for possible energy demands and limits of practical availability of renewable sources, tells that more efficient utilization of energy is required. It has been assumed that the average power expenditure will be about 10 kW, about same as the consumption by the USA. However equally high standard of living is maintained by many other countries, like Japan, Germany, with much lower power consumption. Thus, it is definitely possible to use lower consumption, by as much 20 to 30 per cent, yet maintain the same quality of life. However, one important item has not been considered—this is the energy requirement for recovery and recycle of materials. There is no estimate available for this. But, this will certainly increase our energy demand considerably.

There is also scope for making industries considerably more energy efficient. In several countries in Europe, and also in Japan, over last couple of decades, output or production has gone up considerably without virtually any increase in consumption of energy. The developing countries now catching up often use energy inefficient manufacturing processes. If energy efficient processes become available at comparable costs, there will be significant decrease in energy demand. If PV conversion efficiencies can be raised to 15–20% and 2–5% of land can be made available for collection, solar energy may just meet the energy requirements. So, while it may give an impression of being unlimited, it will probably be just about sufficient.

Recovery and recycling of scarce metals and other material

Finally one has to realize that the energy system cannot be considered to be renewable if equipment required to harvest and convert are not available in adequate amount. Now, many of the materials needed for construction of solar cells for direct conversion of solar energy belong to the category of scarce resources, which are available only in small quantities and are also not available widely but only at certain regions. This question of resource crunch has been discussed by many authors[7] and many national governments have also conducted studies on "critical metals" and their supply. Unless these are recovered and recycled from the used or expired equipment, it will not be possible to replace the equipment. This will require additional energy. No estimate or method of calculation is available at this time, but needs to be done urgently. Nature has a means of recycling materials using solar and geothermal energy, but in many cases, the cycling period is of geologic scale, or a scale that is too lengthy for our utilization. The scarce resources—some metals in particular—are not known to have quick natural cycles. This will require development of entirely new technologies in many cases, and energy requirement for such processes is not known. But, these will certainly be significant, considering the difficulty of the job.

Kleijn and van der Voet (2010) report a study on the availability of materials for construction of wind turbine and solar cell systems for meeting projected energy needs in 2050, along with materials needed to transport the energy by hydrogen pipeline or electrical network. They conclude that with current technology, availability of a few elements may be problematic or "critical", that is, these elements may be in short supply due to various reasons. These elements include Ni, Nd, Platinum Group Metals (PGM), Rare Earth Elements (REE), Cd, Te, Ga and Ru. There may not be enough reserves of some of these elements to meet the demands for building equipment/ structure of solar/ wind energy. In some cases, these elements are produced only as by-products, and supply may stop if the demand for the primary product drops. In some such cases, known natural concentrations or ores are not plentiful or even known, and new sources have to be found and new technologies may be required. High-efficiency thin-film solar cells require Cd, Te, Se, Ga, In, Ge and Ru. Estimated reserves for all these seem to be much less—even orders of magnitude less than the requirement—if only thin-film cells of the present day technology have to be used for making necessary amount of solar cells. Also presently, very little, except for In, of these materials are recycled. All the materials are discarded after single use. There are of course other types of cells which do not require these materials, but those have lower efficiencies. Bradshaw et al. (2013) analyse the concept of criticality and points out that several elements like Dy may be actually in short supply in nature, and for other elements supply may be limited for commercial reasons or supply chain problems. In fact, several detailed studies have been conducted in the

---

[7] Hancock (1984), Rankin (2012), Jones (2013), Bradshaw et al. (2013), Henckens et al. (2014), Freiman and Madsen (2012), Wouters and Bol (2009), Kleijn and van der Voet (2010).

USA and EU to identify the “critical” elements and means to maintain their steady supply. As explained earlier, even when the total amount occurring in earth’s crust is not negligible, the concentrations in which these occur are often too low for extraction.

It is therefore necessary to recover and recycle as much as possible of these “rare elements” for maintaining sustainability steady state.

It will be wrong to assume that only the “rare” or scarce elements need to be recovered and recycled. Even bulk materials like Al, Cu will need recovery and recycle. It is to be noted that scraps of many metals including iron and aluminium are routinely recycled, but there is little effort to recover these. In fact, notions of recovery of these metals are considered ridiculous. In case of Al, the energy cost of recycling is much less than the energy requirement for winning the metal from its natural ore. It is of course not possible to recover and recycle 100%, without taking help of natural recycling processes which unfortunately take times of geologic scale. Recovery of uranium from sea water is an example of process capable of concentrating extremely dispersed material, but such process may not be feasible for all the elements. But even when recovery/ recycling processes are scientifically feasible, a large amount of energy will be necessary to attain it. Firstly, there will be a second law limitation, and secondly, most scientifically feasible routes will involve many irreversible steps and efficiencies attained will be orders of magnitude below the second law limitation. No estimates for such energy requirements seem to be currently available. Helium for example, is an element with many important uses, is mined primarily from natural gas and sometimes from other geothermal sources and is dispersed after single use and is virtually lost. One may note that this is the second most abundant element in the universe and even within solar system yet almost absent on earth, but its capture/production has hardly attracted the attention it deserves.

From discussions above, we note that for critical components of PV systems as well as large number of electronic gadgets, we use scarce metals and have become dependent on these. These are scarce, as usually these exist in dispersed state, with very few commercial “ores”. Unless these are preserved, recovered and recycled the present day gadgets and any new ones dependent on similar materials will become unavailable. The same applies to materials used for electrical motors, long-distance energy transmission systems that will become essential for supporting the solar energy-based society. Not only these, even bulk materials like Al, Cu need to be recovered and recycled if a sustainability steady state is to be attained. Such a state will allow only small quantities of “make up material” to be extracted from primary sources or ores.

Equally important, many of these metals are toxic and polluting agents and hence cannot be allowed to disperse into the environment. Also process of recovery of one element must not allow or cause other materials to get dispersed.

Thus, we note that

- Availability of some “rare” or “scarce” metals may pose serious problems. Science and technologies to bypass these limitations need to be developed. An example may be organic solar cells.
- Since there is no appreciable material flux through the human habitat, recovery and recycling will become very important if not the most important challenge. Make up streams for necessary ingredients must be kept very small compared to the actual amount in circulation. This will apply to even such bulk materials like silica or sand, lime, iron and steel, aluminium, copper.
- Science and technology need to be developed for recovery and recycle of all types of materials used.
- The energy penalty for such recovery and recycle is unknown but will surely be a major energy consumer.

Societal considerations

Social, political or economic deliberations are not quite appropriate for this publication. Yet sustainable development and renewable energy are so intertwined with society that it becomes imperative to mention these aspects. In fact whether the human society adopts “sustainability” or “market first” approach, will be the primarily decided by societal attitude. This is one of the main reasons for many countries deciding to halt nuclear energy programmes, particularly post Chernobyl and Fukushima.

While there is a general and hazy awareness about the environmental degradation and loss of quality of life, there is also a great reluctance to adapt to less wasteful lifestyle. Societal acceptance of a “steady state” will certainly be a major factor. The society seems to be affected only by dramatic events like Chernobyl, Fukushima, Katrina or the Indonesian tsunami, or path breaking expositions like “Silent Spring” and propaganda in the print and electronic media. Sustainability and survivability will also depend on the political wisdom and international cooperation. Moore’s law unfortunately does not seem to be applicable to growth of political wisdom and international cooperation.

From the discussions, it appears that there is no alternative to renewable energy from the sun for a sustainable human existence.

The question of its being “uneconomic” will become largely irrelevant as it becomes essential for survival.

The figures presented earlier show that for the world as a whole, there is sufficient solar energy. But certain restrictions need to be followed or enforced. A tentative list is presented below:

- Overall per capita consumption should be restricted to a level well below the current value for the US, that is, 10 kW or about 315 GJ per year per capita.
- Strict energy discipline must be maintained to reduce wastage primarily through phasing out of energy inefficient gadgets and better design of energy consumption processes.
- Renewable energy other than direct solar—like wind and bio, particularly bio must also be developed—without causing excessive changes in the environment. Wind energy may supply a substantial fraction. Bio-energy should preferably be directly in form of hydrocarbons, that is, the hydrocarbons should be directly biosynthesized without necessity of extra processing. Many plants and microorganisms do synthesize hydrocarbons
- All commercial and industrial processes should be energy optimized.
- Solar energy should be used close to the harvesting site as much as possible, and not bulk exported or imported.
- All scarce metals used must be recovered and recycled and not discharged into the environment. In fact not just scarce metals, many bulk metals like iron, copper, aluminium may also need to be recovered and recycled.
- Wind energy should not be over harvested.

There is just about the required amount of solar and renewable energy available for sustainability steady state. We still need to develop many new and critical technologies to make the transition to such a steady state. We also need to optimize energy consumption and reduce wastage.

More about sustainability steady state

For a system to be "sustainable", it should not accumulate or lose material or energy, and should get rid of internally generated entropy. There has to be at least a flux of energy through the system, energy flowing in from the surroundings and going back to the surroundings. The surroundings are the "rest of the universe" and should be large—virtually infinite compared to the system. We keep ourselves restricted to situations where this condition of infinite unchanging surroundings is valid. There may be a similar material flux as well. But the system of our primary interest is the earth, and this is virtually a closed system. In such a system, all materials must be recycled, and any stored low entropy energy cannot be "used up". In case these restrictions are not followed, there will be inevitable degradation. This is the consequence of the second law. (Geological or astronomical observations into the past of several billion years have not detected any violation, and it is unlikely to be repealed within next thousand or even million years.)

It may be argued that if the timescale of the range of our interest be small compared to the timescale of the degradation, the system will be effectively "sustainable" even with depletion of internal energy sources and material resources. However, it does become subjective at this point, and depends heavily on what amount of degradation the society would allow. However, the option to take a path back to "sustainability steady state" will remain open, but the extent of degradation will be greater if it is delayed. It is therefore prudent to achieve such a state as early as possible.

It may also be argued that "sustainability steady state" may mean "stagnation" and end of "development". But it is not so. For a closed system with a constant energy flux, there can be virtually infinitely many such states, differing in the amount of "energy utilization" and fraction of material in "use or fixed mode". Development will be transition from one such state to another with greater "energy utilization" and change in the fraction of material in "use or fixed mode". There will of course be a maximum energy utilization limit.

Conclusions

For sustainability steady state, renewable energy will be essential, and major contributor will be direct solar. Wind and bio-energy will also be important contributor. A large fraction of the materials used must be recovered after use and recycled, only a small makeup fraction being extracted from earth. Also this objective is not going to be easy to attain. The earlier we start on transition the better. These and other points have already been presented in the last section.

It is assumed that technological innovations will remain more or less within lines of present day investigations in energy field—for example compact lightweight batteries or fuel cells, high temperature super conductors, carbon-based solar cells and electrodes. Exploitation of geothermal energy in large scale has not been considered nor controlled fusion in compact light weight engines.

Similar assumptions have been made for other fields as well. Thus, almost limitless possibilities of use of genetic engineering have not been considered, import of extra terrestrial raw materials to any substantial extent have not been considered, nor planetary scale climate engineering. The sustainable steady state envisaged here is just one option for long-term survival with current day technologies but hardly any other alternative seems to exist within the limitations mentioned.

No attempt is being made here to predict or intercept future developments. The path to sustainability implied here may not be accepted by the society—there is very little chance of such acceptance. There may also be some dramatic scientific or technological or social discovery or innovation or change that will produce easier passage to such state or expand the boundary of the system and remove the constraints and produce a new system making the observations totally irrelevant.

References

Abate T (2017) How to extract uranium from seawater for nuclear power. Energy Environ. https://engineering.stanford.edu/magazine/article/how-extract-uranium-seawater-nuclear-power

ACS Climate Science Toolkit (2016) It's water vapor, not the CO2. American Chemical Society. https://www.acs.org/content/acs/en/climatescience/climatesciencenarratives/its-water-vapor-not-the-co2.html. Accessed 12 Dec 2017

Adams AS, Keith DW (2013) Are global wind power resource estimates overstated? Environ Res Lett 8:015021. https://doi.org/10.1088/1748-9326/8/1/015021

Anderson TR, Hawkins E, Jones PD (2016) CO2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models. Endeavour 40(3):178–187

Arrhenius S, Holden ES (1897) On the influence of carbonic acid in the air upon the temperature of the earth. Publ Astron Soc Pac 9(54):14–24

Baharwani V, Meena N, Dubey A (2014) Life cycle analysis of solar PV system: a review. Int J Environ Res Dev 4(2):183–190

Barber J (2007) Biological solar energy. Philos Trans R Soc A 365:1007–1023. https://doi.org/10.1098/rsta.2006.1962

Batts V (2017) Solar panel manufacturing devastates the environment with toxic heavy metals, warns report. http://www.naturalnews.com/2017-07-13-solar-panel-manufacturing-devastates-the-environment-with-toxic-heavy-metals-warns-report.html

BP Energy Outlook (2018). https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2018.pdf

BP Energy Outlook (2019). https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-energy-outlook-2019.html

Bradshaw AM, Reuter B, Hamacher T (2013) The potential scarcity of rare elements for the Energiewende. Green. https://doi.org/10.1515/green-2013-0014

Brundtland GH (1987) Our common future. Report of the World Commission on Environment and Development, Commission created by General Assembly resolution 38/161 adopted at the 38th Session of the United Nations. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf. Also as book Oxford University Press, Oxford (1987). ISBN: 9780192820808

Callendar GS (1938) The artificial production of carbon dioxide and its influence on temperature. Q J R Meteorol Soc 64(275):223

Clack CTM, Qvist SA, Apt J, Bazilian M, Randt AR, Caldeira K, Davis S, Diakov V, Handschyb MA, Hines PDH, Jaramillo P, Kammenm DM, Long JCS, Grangerorgan M, Reed A, Sivaram V, Sweeney J, Tynan GR, Victor DG, Weyants JP, Whitacre JF (2017) PNAS 114(26):6722–6727

Davidsson S, Höök M, Wall G (2012) A review of life cycle assessments on wind energy systems. Int J Life Cycle Assess 17(6):729–742. https://doi.org/10.1007/s11367-012-0397-8

De Castro C, Mediavilla M, Miguel LJ, Frechoso F (2011) Global wind power potential: physical and technological limits. Energy Policy 39(2011):6677–6682. https://doi.org/10.1016/j-enpol.2011.06.027

Diffenbaugh NS, Burke M (2019) Global warming has increased global economic inequality. PNAS 116(20):9808–9813. https://doi.org/10.1073/pnas.1816020116

FAO Forestry Paper 154 (2008) Forests and energy: key issues. Food and Agriculture Organization of the United Nations, Rome. ISBN 978-92-5-105985-2. http://www.fao.org/3/i0139e/i0139e00.pdf

Feiveson H, Mian Z, Ramana MV, von Hippel F (ed) (2011) Managing spent fuel from nuclear power reactors experience and lessons from around the world. International Panel on Fissile Material, Princeton. ISBN 978-0-9819275-9-6. http://fissilematerials.org/library/rr10.pdf

Freiman SW, Madsen LD (2012) Issues of scarce materials in the United States. Am Ceram Soc Bull 91(3):42–48

Geiger M, Picel J, Walcher A, Yang J (2008) Evaluation of the T. Boone Pickens plan for United States energy independence energy & energy policy final paper. http://franke.uchicago.edu/bigproblems/team5.pdf. Accessed 10 Dec 2008

Gold T (1999) The deep hot biosphere: the myth of fossil fuels. Springer, New York

Gregory P (2017) 100% renewables by 2050—Germany pays the price for its ambition. https://www.forbes.com/sites/uhenergy/2017/03/31/100-renewables-by-2050-germany-pays-the-price-for-its-ambition/#6c8013911e98

Halkema JA (2006) Wind energy: facts and fiction. Energy Environ 17(4):675–678

Hancock GF (1984) Energy requirements for manufacture of some non-ferrous metals. Met Technol 11:290

Henckens MLCM, Driessen PPJ, Worrell E (2014) Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. Resour Conserv Recycl 93:1–8

Herbert GMJ, Iniyan S, Sreevalsan E, Rajapandian S (2007) A review of wind energy technologies. Renew Sustain Energy Rev 11:1117–1145

Howard TP, Middelhaufe S, Moore K, Edner C, Kolak DM, Taylor GN, Parker DA, Leea R, Smirnoff N, Aves SJ, Love J (2013) Synthesis of customized petroleum-replica fuel molecules by targeted modification of free fatty acid pools in Escherichia col. PNAS 110(19):7636–7641

Huang J, McElroy MB (2015) A 32-year perspective on the origin of wind energy in a warming climate. Renewable Energy 77:482–492

IEA (2017) Report PVPS T1-31: 2017. A Snapshot of Global PV (1992–2016). 2016 Snapshot of Global Photovoltaic Markets. IEA. ISBN 978-3-906042-58-9. http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-_A_Snapshot_of_Global_PV_-_1992-2016__1_.pdf

IMBIE team (2018) Mass balance of the Antarctic ice sheet from 1992 to 2017. Nature 558:219. https://doi.org/10.1038/s41586-018-0179-y

IPCC (2007) Climate change 2007: Impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 976

IRENA (2018) Global energy transformation: a roadmap to 2050 (2018). International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-059-4. www.irena.org/publications

Isenberg G, Edinger R, Francis G (2013) A critique on Germany's renewable energy strategy. Energy Brief 01/2013, Live Energies GmbH, Scharnhauser Strasse 35, 70599 Stuttgart

Jacobson MZ, Delucchi MA, Bazouin G, Bauer ZAF, Heavey CC, Fisher E, Morris SB, Piekutowski DJY, Vencill TA, Yeskoo TW (2015) 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energy Environ Sci 8:2093

Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, Cameron MA, Bozonnat C, Chobadi L, Clonts HA, Enevoldsen

P, Erwin JR, Fobi SN, Goldstrom OK, Hennessy EM, Liu J, Lo J, Meyer CB, Morris SB, Moy KR, O'Neill PL, Petkov I, Redfern S, Schucker R, Sontag MA, Wang J, Weiner E, Yachanin AS (2017) 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule 1:1–14

Johnson K (2013) Six myths about renewable energy. Wall Str J J Rep Energy 5:17

Jones, N (2013) A scarcity of rare metals is hindering green technologies. Yale Sch For Environ Stud. https://e360.yale.edu/features/a_scarcity_of_rare_metals_is_hindering_green_technologies. Accessed 18 Nov 2013

Kleidon A (2012) How does the earth system generate and maintain thermodynamic disequilibrium and what does it imply for the future of the planet? Philos Trans R Soc A 370:1012–1040. https://doi.org/10.1098/rsta.2011.0316

Kleijn R, van der Voet E (2010) Resource constraints in a hydrogen economy based on renewable energy sources: an exploration. Renew Sustain Energy Rev 14:2784–2795

Kling G (2016) The flow of energy: primary production to higher trophic levels. https://globalchange.umich.edu/globalchange1/current/lectures/kling/energyflow/energyflow_F2015.html

Kunzig R (2015) Germany could be a model for how we'll get power in the future. Natl Geogr 228(5):32–63

Marvel K, Kravitz B, Caldeira K (2013) Geophysical limits to global wind power. Nat Clim Change 3:2–118

Meng L, Zhang Y, Wan X, Li C, Zhang X, Wang Y, Ke X, Xiao Z, Ding L, Xia R, Yip H, Cao Y, Chen Y (2018) Organic and solution-processed tandem solar cells with 17.3% efficiency. Science 361(6407):1094–1098. https://doi.org/10.1126/science.aat2612

Miyamoto K (1997) Renewable biological systems for alternative sustainable energy production. FAO Agricultural Services Bulletin 128. FAO. http://www.fao.org/3/w7241e/w7241e05.htm#chapter

Moalem M (2016) We could power the entire world by harnessing solar energy from 1% of the Sahara. https://www.forbes.com/sites/quora/2016/09/22/we-could-power-the-entire-world-by-harnessing-solar-energy-from-1-of-the-sahara/#3d3d8ecdd440. Accessed 22 Sept 2016

Mulvaney D (2014) Solar's green dilemma. IEEE Spectr 51(9):30–33. https://doi.org/10.1109/MSPEC.2014.6882984

New Scientist (2011) Wind and wave farms could affect earth's energy. New Scientist, London

Nor Azillah Fatimah O, Jamaliah S, Siti Fatahiyah M (2015) A review of uranium extraction from seawater: recent international R & D. https://inis.iaea.org/collection/NCLCollectionStore/_Public/44/100/44100529.pdf

OECD (1999) Energy: the next fifty years. OECD Publications Service, Paris

Owusu PA, Asumadu-Sarkodie S (2016) A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Eng 3:1167990. https://doi.org/10.1080/23311916.2016.1167990

Parker BF, Zhang Z, Rao L, Arnold J (2018) An overview and recent progress in the chemistry of uranium extraction from seawater. Dalton Trans 47(3):639–644. https://doi.org/10.1039/c7dt04058j

Parlevliet D, Moheimani NR (2014) Efficient conversion of solar energy to biomass and electricity. Aquat Biosyst 10:4. https://doi.org/10.1186/2046-9063-10-4

Perez R, Perez M (2009) A fundamental look at energy reserves for the planet. Int Energy Agency SHCP Solar Update 50:2–3

Perez M, Perez R (2015) A fundamental look at energy reserves for the planet. Int Energy Agency SHC Programm Solar Update 62:3–6

Rankin J (2012) Energy use in metal production. In: Book of abstracts, 4th annual high temperature processing symposium 2012. Swinburne University of Technology, Melbourne, Australia. https://researchbank.swinburne.edu.au/file/9976c710-7740-4d81-90f4-b787ee381d4a/1/PDF%20%28Published%20version%29.pdf. Accessed 6–7 Feb 2012

Rosenbloom E (2004). A problem with wind power. http://www.aweo.org/problemwithwind.html

Sherwani AF, Usmani JA, Varun (2010) Life cycle assessment of solar PV based electricity generation systems: a review. Renew Sustain Energy Rev 14:540–544

Silverman D (2008) Critique of the pickens plan for U.S. Energy in the next 10 years. https://www.physics.uci.edu/silverma/pickensplan.pdf

UNDESA (2004) World population To 2300. UN 2004 ST/ESA/SER.A/236. United Nations Department of Economic and Social Affairs/Population Division, New York. https://www.un.org/en/development/desa/population/publications/pdf/trends/WorldPop2300final.pdf

UNDESA (2017) World population prospects 2017 vol I revision. United Nations Department of Economic and Social Affairs/Population Division, New York

Woods Hole Oceanographic Institution (2019) Life at vents and seeps. https://www.whoi.edu/know-your-ocean/ocean-topics/ocean-life/life-at-vents-seeps/. Accessed 6 Feb 2019

World Energy Council (2013) World energy resources 2013 survey. ISBN: 978 0 946121 29 8. www.worldenergy.org

World Nuclear Association (2017) Thorium. http://www.world-nuclear.org/information-library/current-and-future-generation/thorium.aspx

World Nuclear Association (2018) Uranium supplies: supply of uranium. http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx

worldometers.info (2019). https://www.worldometers.info/world-population/world-population-by-year/, https://www.worldometers.info/world-population/

Wouters H, Bol D (2009) Project MA.09160, material scarcity. An M2i study November 2009. Stichting Materials innovation institute (M2i), Delft. https://mvonederland.nl/system/files/media/m2i20material_scarcity20report.pdf

Zierenberg RA, Adams MWW, Arp AJ (2000) Life in extreme environments: hydrothermal vents. PNAS 97(24):12961–12962

Zwally HJ, Li J, Robbins JW, Saba JL, Yi D, Brenner AC (2015) Mass gains of the Antarctic ice sheet exceed losses. J Glaciol 61(230):1019. https://doi.org/10.3189/2015JoG15J071