Meeting India's future needs of electricity through renewable energy sources

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In this article, an attempt is made to answer the question: Can renewable energy sources eventually supply India's electricity needs in the future? The estimates made here indicate that even with a frugal per capita electricity need of 2000 kWh/annum and a stabilized population of 1700 million by 2070, India would need to generate 3400 TWh/yr. As opposed to this, a systematic analysis of the information available on all the renewable energy sources indicates that the total potential is only around 1229 TWh/yr. It is concluded that in the future as fossil fuels are exhausted, renewable sources alone will not suffice for meeting India's needs.

Keywords: Electricity, future needs, per capita basis, population estimates, renewable energy.

INDIA'S economy is growing at the rate of 8% or 9% every year for the past few years, and a high growth rate is projected for the years ahead. This implies a high growth rate in the consumption of commercial energy, which includes electrical energy. Our focus in this article is on the future needs of electricity in India. In particular, we examine the total potential of renewable energy sources in India and the extent to which they can supply these needs.

The present scenario

We begin by studying the electrical energy scene today. Data on the installed capacity of commercial energy units and the electricity produced are presented in Table 1 (ref. 1). It can be seen from Table 1 that the total installed capacity on 31 December 2010 was 171,644 MW and the total amount of electricity produced in 2009–2010 was 801,828 GWh. Using a population estimate of 1200 million, the amount available on a per capita basis comes to 670 kWh/yr. The contribution of various energy sources is also given in Table 1. It can be seen that fossil fuels – coal, lignite, oil and natural gas – were the principal contributors. Together, they supplied 640,538 GWh (79.9%) of the electricity produced, with coal and natural gas dominating. Renewable sources – large and small hydroelectric power units, wind energy and biomass power – contributed 142,654 GWh (17.8%) to the total. The largest contribution (13.6%) came from large hydroelectric power units. Nuclear energy contributed only 18,636 GWh (2.3%).

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Benchmarking the country's future needs

We will first obtain an estimate of India's needs for electricity in the future. A rational way of planning and projecting the future is to consider the electrical energy required on a per capita basis to satisfy basic human needs and to multiply this number by the population of the country.

Energy planning based on per capita needs

Goldemberg *et al.*[2,3] carried out a seminal study on per capita energy needs. They performed their calculations by considering various activities grouped under the broad headings of residential, commercial, transportation, manufacturing, agriculture, mining and construction, and evaluating the energy inputs under each activity. Adding all these inputs, they arrived at the result that in a country like India, the average requirement of power on a per capita basis would be 210 W of electricity, which corresponds to an annual electricity requirement of 1840 kWh. An essential feature of the calculation done by Goldemberg *et al.*[2,3] was that it was based on the adoption of high-quality energy carriers and energy-efficient technologies in every activity, even if the use required higher initial investments. Since the study was conducted many years ago, it is likely that the energy requirements generated by it would have decreased by 10% or 20% because the efficiencies of most devices and systems have increased over the years.

Before we can make predictions for the future needs for electrical energy, it will be necessary to answer the following question: What is the per capita value for electrical energy which India should aim for in the long run? Should we try to increase the availability from the present

Table 1. Source-wise break-up of installed capacity on 31 December 2010 and electricity produced in 2009–2010 (captive power not included)

Energy source	Installed capacity (as on 31 December 2010) MW	Installed capacity Percentage	Electricity produced in 2009–2010 GWh	Electricity produced Percentage
Coal + lignite	92,378	53.8	539,501	67.9
Oil	1,200	0.7	7,878	1.0
Natural gas	17,456	10.2	93,159	11.6
Hydroelectric (large)	37,367	21.8	109,255[a]	13.6
Nuclear power	4,560	2.7	18,636	2.3
Wind power	13,065	7.6	18,187	2.3
Biomass power	2,664	1.6	7,001[b]	0.9
Hydroelectric (small)	2,953	1.7	8,211[c]	1.0
Total	171,644	100.0	801,828	100.0

[a]Includes an import of 5359 GWh from Bhutan. [b]Assuming annual plant load factor = 0.3. [c]Assuming annual plant load factor to be the same as for large hydroelectric power.

value of about 700 kWh and eventually match the large per capita values (greater than 10,000 kWh) which exist today in most Western countries, or should we be satisfied with values which are not very different from those obtained by Goldemberg *et al.*[2,3]?

Although it would be nice to imagine a future in which the people of India would have at their disposal plentiful supplies of electricity, such is not likely to be the case. Given the size of our population, the limitations of our energy resources and the environmental issues involved, it would be wise for the nation as a whole to plan for a simple lifestyle. Our most viable option would be to provide an annual per capita electricity availability around 2000 kWh and no more. Such frugal use of energy may be the only way to ensure sustainable development in the future. Studies indicate that with the present economic growth rate, a per capita value of 2000 kWh would probably be reached in about 20 years[4,5].

Support for the suggestion that a per capita electricity production around 2000 kWh should be adequate also comes from the notion of the human development index (HDI). HDI is an empirical parameter dependent on the life expectancy, educational level and per capita income in a country. Its value ranges between 0 and 1. When HDI values for various countries are plotted against per capita electricity generation and an average curve is drawn, it is seen that the HDI values increase significantly from about 0.6 to 0.8 as the per capita electricity generation increases from about 600 to 2000 kWh. Thereafter, the value increases slowly from about 0.8 to 0.9, even though the generation increases three times from 2000 to 6000 kWh.

Population estimates

Next, we predict India's future population. Table 2 presents data on the population at 10-year intervals, starting in 1951. The percentage growth over the intervals is also given. Data for 1951–2001 are actual values, while those for 2011 are preliminary values based on the on-going census[6]. It can be seen that the population has grown from 361.1 million in 1951 to 1210 million in 2011. It is also seen that the percentage increase in the six decades from 1951 to 2011 has gone up from 21.6 to 24.8, where it has peaked. Subsequently, the percentage growth has decreased slowly to 24.6 and 23.9 and then more rapidly to 21.4 and 17.8. This is along expected lines. The Population Foundation of India (PFI) has made projections of India's future population[7]. Utilizing the growth values of 14.2% and 9.6% for the next two decades used by PFI, we predict values of 1382 million and 1514 million for 2021 and 2031 respectively. Population figures for the next 50 years from 2031 to 2081 are obtained by making the reasonable assumption that the percentage growth

Table 2. Population of India – past data and future predictions

Year	Population (million)	Percentage change in 10 years
1951	361.1	–
1961	439.2	21.6
1971	548.2	24.8
1981	683.3	24.6
1991	846.6	23.9
2001	1027.0	21.4
2011	1210.0	17.8
2021	1381.7	14.2
2031	1514.3	9.6
2041	1605.2	6.0
2051	1659.7	3.4
2061	1686.3	1.6
2071	1693.0	0.4
2081	1693.0	0.0

(i) Population for 1951–2001 based on actual data. (ii) Population for 2011 is a provisional number based on on-going census. (iii) Population for 2021 and 2031 predicted on the basis of 10-year growth rates obtained by the Population Foundation of India. (iv) Population for 2041 onwards predicted on the basis of a 10-year growth rate gradually declining to zero.

over successive decades will gradually decrease to 6.0, 3.4, 1.6, 0.4 and 0. Thus one obtains the figure of 1693 million around which the population should stabilize around 2070. We will use a rounded-off value of 1700 million.

Total need for electricity

Multiplying the recommended per capita value of 2000 kWh by the population estimate of 1700 million, we obtain the value of 3400 TWh. This will be the electricity production needed about 60 years from today. As we have used a per capita value of 2000 kWh, a total production of 3400 TWh is to be considered as a minimum requirement for the country.

Renewable sources and their potential for supplying electricity

We now list all the renewable energy sources available, the ones being used at present and those which may supply our needs in future. Today, India is following an active policy for developing the use of renewable energy sources for providing energy in the form of heat and electricity. We will describe the developments that have taken place and those that are planned. We will also estimate the potential of each source to supply electricity. This will be done in the following manner.

Wherever possible, we will use quantitative information available in the literature on the potential of a source. When this information is not available, we will estimate the potential of a source based on information which is qualitative or indirect in nature, or make a judgement based on technological developments which have taken place thus far.

Renewable energy sources are all essentially based on the direct or indirect use of solar energy. The only exception is probably tidal energy, which essentially derives its power from the interaction between the earth and the moon. A complete listing of renewable energy sources for generating electricity is as follows:

(i) Solar energy (direct): Solar thermal power and solar photovoltaic (PV) power. (ii) Solar energy (indirect): Hydroelectric power (large and small units); wind energy (on land and offshore); biomass power; wave energy; marine currents, and ocean thermal energy conversion. (iii) Tidal energy.

Solar thermal power and PV power

Solar energy is utilized directly via the thermal and PV routes. Solar thermal applications include water heating, space heating, drying, cooking, etc. The application which is of interest in this article is the generation of electricity in solar thermal–electric power plants. These plants use concentrating collectors to collect the sun's energy at high temperatures and use this energy to generate high-pressure steam. The steam in turn is used in a conventional Rankine cycle to generate electricity. The first such plants were constructed about 25 years ago and over the years, a few more plants have been built. At present, the total installed capacity in the world is rather small, only around 500 MW. For more details, the reader is referred to Sukhatme and Nayak[8]. In India, there are as yet no plants of this type. However, currently considerable attention is focused on the construction of a number of plants, each with capacities of a few megawatts under the Jawaharlal Nehru National Solar Mission[9]. Experience gained from operating these plants will be useful for scaling up and it is planned to have an installed capacity around 10,000 MW by 2022. At the moment, the major impediment is the initial cost of such plants. Typically, the cost is estimated to be around Rs 15 crores/MW for a plant which operates only for about 8 h a day. In order to offset this disadvantage, the Government is offering attractive feed-in tariffs over a period of many years. Adequate solar radiation is available over many parts of the country for more than 250 days during the year. However, the real issue is the need to acquire large areas of open, non-agricultural land for installing the concentrating collectors and related equipment required for collecting the sun's energy. Typically, at least 3–4 ha would be required per megawatt of installed capacity. Recent experiences in the country suggest that acquiring the land may be a difficult proposition in most states. Because of these issues, the total potential for generating electrical power through solar thermal power plants in India is limited.

Photovoltaic conversion is the other direct method of utilizing solar energy. Current production of PV modules in India is around 100 MW, with a significant amount being exported. The current cost is high and is about US$ 4–5/peak watt. In spite of the high cost, PV systems are being used increasingly to supply electricity for many situations requiring small amounts of power. Their cost-effectiveness increases with the distance of the location from the main power grid lines. Thus in the future, PV systems may become one of the important sources of power for providing small amounts of electrical energy for localized use in thousands of remote locations all over India. It is estimated that about 11,000 MW is needed for this purpose. A substantial part of this requirement could eventually come from PV systems which are not connected to the grid. It is often suggested that these systems be located as far as possible on rooftops, so that no land space is used.

It is also possible that a number of grid-connected PV power systems having capacities of a few megawatts each may be installed. At present, the total installed capacity of such plants in India is only 10 MW. Under the National Solar Mission, it is planned to have a total installed capacity around 10,000 MW by 2022 (ref. 9). These plants would also require about 4 ha/MW.

What is the grid-connected capacity that can be installed in the long run? Proponents of solar thermal power and PV power say that the technology has developed significantly and continues to improve. It is also stated that high initial costs will not be a barrier in the long run and that there is adequate solar radiation available over many parts of the country. However, it is fairly clear that the real issue is not the availability of solar radiation as much as the availability of open land. This is going to be the real constraint limiting the use of these sources. An approximate calculation follows.

In India, there is at most 1,000,000 sq. km of open, non-agricultural land which receives adequate radiation. This land is mostly in Rajasthan, Gujarat, Madhya Pradesh, and parts of the Deccan plateau. We assume that 1% of this land (i.e. 10,000 sq. km) can be acquired for generating solar power. Using the thumb-rule that one needs 4 ha of land per MW, we obtain a total generation capacity of 250,000 MW. We will use this estimate. We will assume further that solar thermal and solar PV will have equal capacities, i.e. 125,000 MW each. As stated earlier, these plants would operate for about 7–8 h a day for about 250 days in the year. Thus the annual plant load factor would be $(7 \times 250/8760) = 0.2$ and the annual electricity production from each source would be $(125,000 \times 0.2 \times 8760)$ = 219 million MWh = 219 TWh.

Hydroelectric power

In 1947, the installed capacity of hydroelectric power in India was only 508 MW. It increased rapidly in the fifties at an average rate of 14%/yr. Thereafter, the growth rate has been slower, but nevertheless impressive. The installed capacity on 31 December 2010 was 37,367 MW. These data are for large units with capacities larger than 25 MW (ref. 1).

Hydroelectric power projects are of great importance to India from the long-term point of view because they are the largest contributors amongst renewable energy sources. Apart from generating electricity, they provide water for irrigation and help in flood control. However, in recent years, almost all large-scale projects have been controversial. Serious concerns have been expressed regarding the displacement of people and the destruction of flora and fauna on account of submergence of land. Such concerns need to be carefully addressed if the expansion of hydroelectric power is to progress at a rapid pace.

Hydroelectric power units with capacities less than 25 MW come under the purview of the Ministry of New and Renewable Energy, and the statistics is reported separately. The installed capacity of small hydroelectric power units has been growing steadily over the years and was 2953 MW on 31 December 2010 (ref. 9).

India's reserves of hydroelectric power are reasonable and have been estimated to be 148,700 MW for large-capacity plants. Thus there is considerable scope for generating more hydroelectric power, particularly in the northern and northeastern regions. For small units, 5718 sites with a total capacity of 15,384 MW have been identified all over the country. Based on actual production data of earlier years, we will use an annual plant load factor of 0.37 for large and small hydroelectric power units. Thus the annual electricity production potential for the two cases comes out to be 482 and 50 TWh respectively.

Wind energy

Wind energy is a new entrant on the electrical energy scene. Starting from scratch in 1992, the growth has been spectacular, the installed capacity on 31 December 2010 being 13,065 MW (ref. 9). However, it has to be noted that wind energy is generally available for only 4–5 h a day. As such, the annual plant load factor is only around 15%. Thus, the electricity produced from wind machines in 2009–2010 was 18,187 GWh, corresponding to an annual plant load factor of 16.2%.

The wind machines installed are all of the propeller-type with capacities usually ranging from 1 to 2 MW, and costing about Rs 50,000/kW. It is important to note, however, that all these developments have taken place on land. The time is now appropriate for India to start harnessing the potential of wind energy offshore. The potential offshore may be more than the estimated potential on land because wind speeds offshore are usually higher and steadier. In this context, it is worth noting that one of the world's largest offshore wind farms having a capacity of 300 MW (100 machines, each with a capacity of 3 MW) has gone into operation off the coast of Kent in England in 2010 (ref. 10).

Surveys conducted a few years ago indicated that there was a potential for installing a total capacity of 45,000 MW of wind energy on land in India. This estimate was based on wind machines with hub heights up to 50 m. Today, wind machines with hub heights up to 80 m are available, and it is estimated that the wind resource on land is probably around 65,000 MW (ref. 9). We will use this higher value. As far as the utilization of offshore wind energy is concerned, no reliable estimate is available because data on wind speeds along the coast are still being collected. However, it is generally accepted that the potential offshore may be as much as that on land. Therefore, we will use the same estimate as on land, viz. 65,000 MW as the potential available for developing wind energy off the coast of India. As far as the annual plant load factors are concerned, we will use the value of 0.16 which is normally obtained in India at land-based installations. We will use this value both on land as well as offshore. Using this value, the annual electricity generation comes out to be 91 TWh in each case.

Biomass power

The term 'biomass' is used in a broad sense when one is thinking of deriving energy from it. It includes all plant life and their residues after processing. Plant life refers to trees, agricultural plants, bushes, grasses and algae, whereas residues include crop residues like straw, stalks, leaves, roots, etc. and agro-processing residues like oilseed, groundnut and coconut shells, husk, bagasse, molasses, saw dust, wood chips, etc. There are many ways of obtaining energy from biomass (see Sukhatme and Nayak[8]).

Traditionally, much of India's non-commercial energy required in the form of heat has been obtained by burning wood, agricultural waste and dung cakes. The use of biomass for generating electrical power which is fed into the grid is more recent and relatively limited. Two routes are being followed. One is the combustion of biomass materials like rice husk, straw, cotton stalk, coconut shells, saw dust, etc. to generate steam. Subsequently, a conventional Rankine cycle produces electricity. It is estimated that about 120–150 Mt/yr is available for this purpose. The other route is called the co-generation route. It entails the efficient use of bagasse as a fuel in a sugar mill so that it can not only produce the steam required in the sugar factory, but also produce some excess high pressure and temperature steam, which can be used for generating electricity. The capacity of biomass power units has been growing steadily, the installed capacity up to the end of 2010 being 2664 MW.

In the case of biomass power units, it has been estimated that India's total potential is about 23,000 MW (ref. 9). Of this, 18,000 MW can be derived from the combustion of biomass and 5000 MW could be generated from bagasse-based co-generation units in sugar mills. This relatively small capacity is partly due to the fact that biomass is needed extensively as a source of heat for non-commercial purposes. It is also due to the fact that biomass products for generating electricity cannot be allowed to displace agricultural products. The availability of biomass is always seasonal. For this reason, one assumes an annual plant load factor of 0.3. Using this value, the annual electricity generated from 23,000 MW comes out to be 60 TWh.

Wave energy

This is the energy available at the ocean surface because of the interaction of the wind with the water surface. It is difficult to collect because of wide fluctuations in amplitude and frequency of the waves at any location. As a result, considerable ingenuity is required in building cost-effective devices. Nevertheless, a number of devices for converting wave energy into electricity have been developed, these being located on the shoreline, near the shoreline or offshore. Two of the devices developed are the oscillating water column (OWC) system and the Pelamis system. The OWC system is setup near the shore in shallow water, 10–25 m deep. In India, an OWC system has been built and operated at Thiruvananthapuram. The system is located at the tip of a breakwater wall at a water depth of 10 m, where the average wave power potential is 13 kW/m. The plant has been generating 18 kW of electrical power[11]. The Pelamis system is a semi-submerged device in which the energy of the waves is transferred through hinged joints to operate hydraulic motors, which in turn drive electrical generators.

A number of pilot systems have been built in many countries. Despite all these efforts, very little commercialization has taken place anywhere in the world. The world's first commercial wave energy plant producing 2.25 MW has been commissioned recently in Portugal[12]. Thus, although one knows that there is a fair amount of energy in the waves[13], the chances that a significant amount will be converted to electricity appear to be poor. This statement is true for India as well. At the moment, we are not in a position to give any estimate of the potential for generating electricity from this source in India.

Energy in marine currents

Like the energy in the winds offshore, there is also considerable kinetic energy available in the marine currents offshore. Attempts have been made to capture this energy by installing submarine-like turbines under water near the coast at suitable depths. These ideas are being tried out on a pilot scale in some locations in the world and need to be experimented within India. No data are available on the capacity which can be installed in India[14], because a database of the marine currents which could be used for this purpose has not been prepared. We are therefore not in a position to suggest any estimate. However, keeping in mind the estimate of 800 TWh for the world as a whole, the length of India's coastline and the overall promise in the concept, it is likely that this source will eventually supply a small amount of electricity in India.

Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) systems utilize the temperature difference between the upper and lower layers of water in the tropical oceans to drive a heat engine and thereby generate electrical power. Typically, a difference of about 20°C is available and the global resource is estimated to be as high as 10,000 TWh/yr (ref. 13).

The concept of an OTEC system was first suggested in 1930 and a few pilot plants have been built in different parts of the world. However, they have been found to be expensive because of the low energy-conversion efficiency and the need for large amounts of parasitic

Table 3. Estimating the total potential of renewable energy sources for generating electric power in India

Source			Total installed capacity (MW)	Plant load factor	Annual electricity production (TWh)
Solar energy	Direct	Thermal	125,000	0.20	219
		Photovoltaic	125,000	0.20	219
	Indirect	Hydroelectric (large)	148,700	0.37	482
		Hydroelectric (small)	15,384	0.37	50
		Wind (on land)	65,000	0.16	91
		Wind (offshore)	65,000	0.16	91
		Biomass	23,000	0.30	60
		Wave energy	?	–	?
		Marine currents	?	–	?
		Ocean thermal energy conversion	?	–	?
Tidal energy			7,900	–	17
		Total	574,984		1229

power. In India, an open-cycle OTEC plant producing 100,000 litres of desalinated water per day has been operating at Kavaratti in Lakshadweep since 2005 (ref. 15).

Remarks similar to those made with respect to 'wave energy' also apply to OTEC systems. Although the global resource is high, conversion of this energy to electricity poses many intractable problems. As a result, no commercialization has taken place in any country and no estimates of the real potential to generate energy from this source are available. With this background, we are not in a position to give any estimate of the potential of this source to generate electricity in India.

Tidal energy

This energy is the energy available in water because of the rise and fall of its level during high and low tides. It can be tapped in some coastal estuaries where the tidal range is high. Basically in a tidal power station, a barrage with sluice gates is built across an estuary. As the water level rises twice a day, it is allowed to flow in through the sluice gates. At high tide, the gates are closed so that the water is impounded in the basin behind the barrage. Then as the tide ebbs, and the water level in the open sea falls; a head of water is created between the water in the basin and that outside. This head is utilized to obtain electricity by making the water flow through turbines connected to electrical generators.

The first commercial tidal power station in the world was constructed in France in 1965, across the mouth of the La Rance estuary. It has a capacity of 240 MW and an average tidal range of 8.4 m. Tidal power has not been exploited in India so far. However, two potential regions have been identified. These are the Gulf of Khambhat and the Gulf of Kutch in Gujarat[16]. Calculations show that it should be possible to have an installed capacity of 7000 MW generating 15 TWh/yr in the Gulf of Khambhat, where the average tidal range is around 7 m. In the Gulf of Kutch, it is estimated that a capacity of 900 MW yielding about 2 TWh/year could be installed.

Total potential of renewable sources

We will now compile the above data on installed capacity and annual electricity production from individual renewable sources. This is done in Table 3. Adding the contribution from each source, we obtain a total installed capacity of 574,984 MW. The total amount of electricity which can be produced annually comes to 1229 TWh. As stated earlier, no estimates are given for the three ocean-based sources, viz. wave energy, OTEC and marine currents. Indications are that wave energy and OTEC systems may not make significant contributions. Only marine currents may provide some energy. Thus, 1229 TWh is probably a good estimate of the electrical energy which can eventually be obtained from renewable energy sources, if their full potential is exploited. In view of the active support of the Government, this value may be realized about 50–60 years from today. As noted earlier, renewable energy sources supplied 142.7 TWh in 2009–2010. Thus, there is a balance potential of (1229–142.7) = 1086.3 TWh, which can be exploited in the future.

Discussion and conclusion

The two major findings emerging from the present study are as follows: (i) India will need to produce 3400 TWh of electricity annually by 2070. This is more than four times the present generation of 801.8 TWh in 2009–2010. This amount will be needed despite setting a low benchmark of 2000 kWh per capita per annum for the future. (ii) The total potential of all renewable energy sources in India is 1229 TWh. This may also be realized around the same time, i.e. 2070. Also, 1229 TWh amounts to 36.1% of 3400 TWh.

Thus, our study has shown that although India has reasonable resources of renewable energy, it is not so well endowed that its future electricity requirements can be fully met by renewable sources. This view is contrary to the popular perception that solar energy in its direct and indirect forms can supply all of India's future needs of electricity. The inevitable conclusion emerging from the data presented shows that renewable energy sources stretched to their full potential can at best contribute 36.1% of the total need.

The implications of this conclusion are that around the year 2070, the balance requirement of 2171 TWh would have to come from fossil fuels and nuclear energy. Eventually, about a 100 years later, the contribution from fossil fuels may be negligible and the balance would have to come from nuclear energy alone.

These statements may get modified if, in the future, the full potential of renewable sources is found to be more than the current estimate of 1229 TWh. This may happen if new sources are discovered, or if additional information results in an increase in the estimates of the potential of currently known sources.

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