Can India's future needs of electricity be met by renewable energy sources? A revised assessment

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In earlier papers, an attempt was made to assess if renewable energy sources alone could meet India's future needs of electricity. With the information available then, it was concluded that this was not possible. However, over the last year, many papers/comments have been published on the subject matter and new research findings have also become available regarding the high potential of wind energy. It has therefore become necessary to make a revised assessment. India will need 3,128 TWh/yr of electrical energy in the future if it adopts a frugal policy for energy use. The present study shows that this annual need may be met through renewable energy sources alone in the form of solar power (photovoltaic and thermal), wind power and hydroelectric power. The study also points out that because of the intermittent nature of solar and wind power, there is a serious mismatch between the diurnal variation of the electricity generated by renewable sources and the diurnal variation of the demand for electricity. Many difficult technical challenges concerning transmission, distribution, control and storage of energy will have to be overcome in order to remove the mismatch. Only then will it be possible to supply power generated by renewable energy sources to match the electricity demand on a round-the-clock basis.

Keywords: Diurnal variation, future electricity needs, renewable energy sources.

THE question posed in the title of this article is an important one from the point of view of the energy policy. Today, 80% of India's needs of electricity are met by fossil fuels – essentially coal and natural gas. Fossil fuels are non-renewable and may at best supply our needs of electricity for another 100–150 years. In addition, they contribute substantially to the increase in greenhouse gases. It is therefore important to ask if eventually in the future, renewable energy sources can take over the role of supplying our needs for electricity. In an earlier article[1], an attempt was made to answer this question. The estimates made then indicated that with a frugal per capita electricity need of 2,000 kWh/yr and a stabilized population of 1,700 million by 2070, India would need to generate a minimum of 3,400 TWh/yr thereafter. As opposed to this requirement, a systematic analysis of the information available on all renewable energy sources indicated that the total potential was around 1,229 TWh/yr, with 438 TWh/yr being supplied by direct solar energy and the balance of 791 TWh/yr coming from all other renewable sources (indirect solar energy and tidal energy). The analysis also revealed that availability of open land would be an important constraint limiting the growth of solar thermal and solar photovoltaic (PV) power.

Subsequently, comments were received that in ref. 1, the land considered for exploitation by direct solar energy was open, non-agricultural land (1 million sq. km) and that it had been assumed that only 1% of this land would be available for direct solar energy exploitation. It was suggested that the land considered for solar power should be barren, uncultivated land (200,000 sq. km) and that it may be possible to acquire up to 20% of this land. Accordingly, it was calculated[2] that the energy available from solar thermal and PV could be 438, 876 or 1,752 TWh/yr depending upon whether 5%, 10% or 20% of the land was acquired. Adding the energy of 791 TWh/yr available from other renewable energy sources, it was concluded that the electrical energy from renewable energy sources could be as much as 2,543 TWh/yr if 20% land was acquired. This value was still less than but closer to the need of 3,400 TWh/yr.

In the last year, a number of notes and papers[3–6] have been published. These have offered comments on the original paper[1], questioned some of the assumptions made and suggested corrections. Sharma[3] feels that the per capita electricity need of 2,000 kWh/yr used for benchmarking the country's future needs is excessive and

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suggests that a value of 1,000 kWh/yr should be adequate. Narayanan[4] suggests that the 'thumb-rule' value of 4 ha of land per MW used in ref. 1 for calculating the energy from solar thermal or PV power plants is high. He has presented some data on plants built elsewhere showing less land is required. Consequently, he feels that it should be possible to generate more megawatts output by the solar power route on a given area of land. Chokshi[5] has stated that distributed rooftop solar PV systems do not suffer from the disadvantage of needing land. He suggests that by 2070, if all 425 million households in India are provided with a 3 kWp solar panel, it should be possible to generate 1,900 TWh/yr from such distributed systems alone. This large input needs to be factored in. Mitavachan and Srinivasan[6] introduce the terms 'land transformation' and 'land occupation' to correctly point out that when it comes to calculating the land requirements for generating electricity from any energy source, it is not enough to consider only the land area (in ha/MW) required for setting up a typical power plant. It is necessary to also include the area needed for fuel mining, transportation of fuel, waste disposal, etc. across the lifetime of the power plant. Amongst renewable energy sources, Mitavachan and Srinivasan[6] present data to show that while solar power plants require around 2 ha/MW, hydroelectric power plants typically require around 22 ha/MW. The purpose of the present article is to consider the comments made in refs 3–6 and take account of them by suitably modifying the estimates made earlier[1,2].

In addition, some promising developments have taken place recently in the field of wind energy. Recent findings[7,8] indicate that the wind potential on land in India is much more than had hitherto been stated[9]. The purpose of this article is to take account of these developments as well.

In the sections that follow, we will follow the same order as in ref. 1. We will first re-visit the issue of 'benchmarking India's future needs of electricity' by considering the comments received[3] on the annual per capita needs of electricity. We will then proceed to consider renewable energy sources one by one and their potential for supplying electricity. Adding up the individual contributions gives the total potential of renewable energy sources.

Benchmarking India's future needs for electricity

Annual per capita needs of electricity

In ref. 1, the annual per capita needs of electricity were fixed based on the systematic studies of Goldemberg *et al.*[10,11]. They arrived at a value of 1,840 kWh/yr by considering various activities under broad headings. These activities with the electricity need of each activity are listed in Table 1.

Table 1. Annual per capita need for electricity for various activities[10]

Activity	Annual per capita need (kWh/yr)
Residential	447
Commercial	193
Transportation	105
Manufacturing	1,060
Agriculture, mining and construction	35
Total	1,840

Using available data and taking an average of electricity needs for residential use in urban and rural areas in India, Sharma[3] has suggested a value of 420 kWh/yr. This value is almost the same as the value of 447 kWh/yr given in Table 1. For all other activities (commercial, transportation, etc.), Sharma suggests that a value of 380 kWh/yr should be adequate. No justification or logic is given for assuming that this amount of electrical energy would be adequate. In contrast, Goldemberg *et al.*[10,11] have obtained a value of 1,393 kWh/yr for these activities. It is to be noted that their value is based on a systematic analysis of data collected for each activity in four countries. Thus it is difficult to accept Sharma's suggestion. It appears best to stay with the value of 1,393 kWh/yr for all activities (other than residential) given by Goldemberg *et al.*[10,11] and a total of 1,840 kWh/yr for all activities.

An alternative approach for determining the annual per capita needs of electricity is to consider its empirical relationship with the Human Development Index (HDI), which is a measure of human well-being. This relationship was first pointed out by Pasternak[12], who plotted values of HDI for many countries against the annual per capita needs of electricity and showed that a fairly good correlation could be obtained. Initially, the value of HDI increases quite rapidly from 0.3 to 0.6 as the electricity use increases from almost zero to 800 kWh/yr. Thereafter, HDI continues to increase (but at a slower rate) to 0.8 and 0.9 as the electricity use increases to 2,000 and 4,000 kWh/yr. With further increase in electricity use (greater than 4,000 kWh/yr), the value of HDI increases very little and appears to level off at about 0.92. At present, India has a per capita electricity use of about 800 kWh/yr corresponding to a HDI value of about 0.6. From the above considerations, it appears desirable to provide an annual per capita electricity use of 4,000 kWh/yr so that an HDI value of 0.9 would be attained.

Thus, we have two values for electricity use. The first value based on the activity-wise studies of Goldemberg *et al.*[10,11] has a magnitude of 1,840 kWh/yr, while the second based on considerations of HDI has a magnitude of 4,000 kWh/yr. Which value should one select? Keeping in mind the need for frugality in energy usage, we will select the lower value of 1,840 kWh/yr. This should be adequate for providing a good standard of living if energy conservation measures are adopted, energy-efficient devices are used and simple lifestyles which discourage wasteful consumption are encouraged. It should be reiterated that the projected per capita value of 1,840 kWh/yr needs to be distributed more equitably amongst all sections of society. As pointed out by Sharma[3], this is not the case in India today.

Total need for electricity

We will stay with the stabilized population estimate of 1,700 million for 2070 obtained in ref. 1. Multiplying the estimated population by the per capita value of 1,840 kWh/yr, we obtain a total need of 3,128 TWh/yr. This annual stabilized need for electrical energy would be required about 60 years from today and onwards. In contrast, we would need 6,800 TWh/yr if we project a per capita need of 4,000 kWh/yr.

Renewable sources and their potential

The following is a complete list of renewable energy sources available for generating electricity.

Solar power (thermal and PV), hydroelectric power (large and small), wind energy (on-land and offshore), biomass power, wave energy, marine currents, ocean thermal energy conversion and tidal energy.

We consider them in order one by one.

Solar power (thermal and PV)

The main issue that has arisen with regard to the use of solar energy directly for generating electricity is the land needed for installation. It should be pointed out that most of the megawatt-based solar plants being installed currently in India and abroad are PV plants. Relatively few solar thermal power plants are being erected. We will therefore focus our attention on the land required for solar PV plants and use that value for all solar power plants.

In the earlier article[1], it had been assumed that 4 ha of land would be needed per megawatt. Some of the earlier plants did need 4 ha/MW. For example, the 30 MW solar PV plant at Gunthawada, district Banaskantha, Gujarat used 4.12 ha/MW. However, it is possible to set up complete PV plants with about 2 ha/MW. Examples of such plants are the 3 MW plant at Yalesandra, Kolar, Karnataka using 2.02 ha/MW; the 2 MW plant at Awan, Punjab using 2.63 ha/MW and the 10 MW plant at Pereruela, Spain using 2.78 ha/MW. Narayanan[4] has provided data about some plants abroad using only about 1 ha/MW. Accordingly, he has suggested a value of 1.25 ha/MW. It is likely that the area referred to in these cases is only that of the PV modules. The space left between the modules and the area occupied by the balance of systems has not been included. On the other hand, Mitavachan and Srinivasan[6] have suggested a value of 2 ha/MW based on their first-hand experience with the Yalesandra plant. Keeping all the above considerations in mind, we will assume a value of 2 ha/MW.

The second issue to be re-considered is the value of the annual plant load factor (APLF) [The term ‘annual plant load factor’ used here is also referred to as the ‘annual capacity factor’.]. In refs 1 and 2, it was assumed to be 0.2. Data available on a number of PV plants indicate that this may be a little high[13]. Typical values lie in the range 0.17–0.19 for plants performing well. We will therefore assume a value of 0.18 for APLF for solar PV plants. We will use this value for solar thermal plants as well because the value is not likely to be very different.

As in ref. 2, we now proceed to calculate the annual production of electricity via the solar (thermal and PV) route assuming that 5%, 10% and 20% of the barren, uncultivated land in India can be acquired for this purpose. As stated earlier, this type of land has an area of about 200,000 sq. km. We obtain the values given in Table 2. It is seen that the electricity produced would be 788.4, 1,576.8 and 3,153.6 TWh depending on the percentage of land used.

Decentralized solar PV systems

In ref. 1, mention was made of decentralized, small-capacity solar PV systems. It was stated that such systems are useful for localized use, particularly in remote locations. Further, such systems are usually located on rooftops and do not use up any land. However, the amount of electrical energy which could be tapped from such systems was not estimated and added onto the total available from renewable sources. Some researchers[3–5] feel that this is a serious lacuna and that this contribution needs to be included.

We will examine the issue by asking two questions. Is it reasonable to expect that rooftop systems having a capacity of 3 kWp or so are installed in large numbers in India? If so, how many millions of such systems can we reasonably expect to see installed? The answer to the first question is that such systems can and will probably be installed in large numbers in the future. The answer to the

Table 2. Electricity produced by the solar thermal and photovoltaic (PV) routes as a function of the percentage of barren, uncultivated land acquired

Percentage of land acquired	5	10	20
Area of land (sq. km)	10,000	20,000	40,000
Generation capacity (GW)	500	1,000	2,000
Annual production of electricity (TWh)	788.4	1,576.8	3,153.6

Note: Land area used per MW = 2 ha; Annual plant load factor (APLF) = 0.18.

second question cannot be given precisely and can only be estimated over a range. As stated by Chokshi[5], 3 kWp systems are often used. Typically, they generate about 4.5 MWh/yr and occupy about 30 sq. m of area. In 2070, India will have about 425 million households. Chokshi feels that if each household could have a PV system, an enormous amount of energy, say around 1,900 TWh/yr, could be generated. However, this is clearly impossible and fanciful. About half the households would be in urban areas and it would be difficult, if not impossible, to install such systems in most of these houses. Even in the other half in rural areas, only those who are economically well-off would be interested in installing such systems. It is also important to understand that a 100% subsidy for putting up such systems is counter-productive. There is no incentive for an individual to maintain such a system and experience shows that it soon falls into disrepair. An additional factor which is worth noting is that all households would not have suitable roofs to install PV systems and that sometimes, surrounding trees can prevent sunlight from falling on PV panels. Keeping all these factors in mind, an optimistic estimate is that with some incentives, it may be possible to induce at most about 10% of the rural households, i.e. 20 million households, to have solar rooftop PV systems. This is still a very large number.

Table 3 shows that the amount of electricity which would be produced if 5, 10 and 20 million households install 3 kWp PV systems is 22.5, 45 and 90 TWh respectively. An inspection of these values shows that rooftop solar PV systems will have an important role to play in the future in a local context. However, their overall contribution to the national output is not likely to be very significant.

Hydroelectric power

In ref. 1, it was indicated that the reserves of hydroelectric power for large-capacity plants have been estimated to be 148,700 MW. For small plants, a total capacity of 15,384 MW has been identified. It was assumed that all the reserves would eventually be tapped and could supply up to 482 and 50 TWh respectively. However, increasingly it has become clear that exploitation of all the potential is improbable because of the large amount of land submerged when most dams are built, the consequent displacement of people as well as the destruction of flora and fauna.

Table 3. Electricity produced by decentralized solar rooftop PV panels

Number of households (millions)	5	10	20
Annual production of electricity (TWh)	22.5	45	90

Note: The rooftop systems are assumed to have a capacity of 3 kWp each and to produce 4.5 MWh per year.

At present, for large plants, the installed capacity is only about 25% of the reserves. We will assume that at least 40% and at best 80% of the reserves will eventually be used. This is a reasonable assumption. Using these lower and upper limits, we will calculate the amount of electricity produced annually with values corresponding to 40%, 60% and 80% exploitation. An APLF of 0.37, which corresponds to the average value at present, will be used. The same calculations will be repeated for small units. Table 4 gives details of the electricity produced annually. It is seen that for large units, 193, 289 and 386 TWh of electricity could be produced, while for small units, 20, 30 and 40 TWh could be produced.

Wind energy

One of the most promising developments in the area of renewable energy over the last year is the finding[7,8] that the wind potential on land in India is much more than the value of 65 GW or thereabouts, which had been accepted earlier[9].

Hossain *et al.*[7] have used a GIS-based approach to obtain an estimate for the wind potential of the whole country. They have excluded areas unsuitable for installation of wind machines like the Himalayan region and urban areas. The procedure followed is to use values of wind speeds from the NCEP/NCAR Reanalysis Project as well as measurements made by the Centre for Wind Energy Technologies (CWET), Chennai. These data were extrapolated using a suitable power law and values of wind speeds obtained at a height of 80 m on a 1 sq. km grid over the whole region under consideration. Grid elements having wind power densities and values of APLF above a certain minimum value were then identified and the wind energy potential for the country obtained by summing up the output of each such grid element. The overall result obtained by Hossain *et al.*[7] was that a generation capacity of 2,075 GW with an APLF greater than 0.2 could be installed at a hub height of 80 m. This generation capacity is many times larger than the earlier estimate given by the Ministry of New and Renewable Energy (MNRE), Government of India[9].

Phadke *et al.*[8] have used a different model called 3Tier for obtaining values of wind speed and average wind power density at heights of 80, 100 and 120 m. This has been done for each 5 by 5 km cell of land in India.

Table 4. Electricity produced by hydroelectric power – large and small units

Percentage of reserves exploited	40	60	80
Annual production of electricity (TWh)			
Large units	193	289	386
Small units	20	30	40

Note: APLF = 0.37.

A minimum threshold value of 200 W/sq. m for wind power density was used for identifying the land cells suitable for wind-energy exploitation. For such cells, an annual plant load factor of 0.2 or more was assigned. Next GIS data on topography, land use and land cover were used to include only those cells where it would be feasible to set up wind facilities. The overall conclusion reached was that the total wind potential was 2,006 GW at a hub height of 80 m and 3,121 GW at a hub height of 120 m. More than 95% of the potential is in five states – Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra and Gujarat. It may be noted that the estimate of 2,006 GW is not very different from the value of 2,075 GW given by Hossain *et al.*[7].

We will assume a conservative value of 0.20 for APLF for all wind power densities and use the wind potential estimate of 2,006 GW given by Phadke *et al.*[8] to calculate the annual production of electricity. It is unlikely that all the potential will be developed. However, it would be reasonable to assume that at least 20% will be exploited. Similarly, it would be reasonable to expect that up to 60% of the reserves could be eventually exploited. Table 5 gives details of the electricity which would be produced if 20%, 40% and 60% of the wind potential at 80 m is harnessed. It is seen that corresponding to 20%, 40% and 60%, the electricity produced could be 703, 1,406 and 2,108 TWh respectively. These are large amounts compared to the value of 91 TWh obtained in ref. 1.

As with other energy sources, the issue of land required for setting up wind farms needs to be addressed. It is necessary to recognize at the outset that only a small amount of land area within the overall designated area of the wind farm is permanently used. Thus, unlike solar PV/thermal plants, wind farms do not need to be restricted to barren uncultivated land. They could be located on agricultural land, cattle grazing land, etc. Phadke *et al.*[8] estimate that the land disturbed permanently by installing wind farms may vary from a negligible value to at most 0.6 ha/MW. Thus, the availability of land needs not be considered as a constraint.

Finally, we turn our attention to the wind potential offshore. In ref. 1, it was noted that there is not enough data on wind speeds to estimate the potential offshore. However, as it was known that wind speeds offshore are usually higher and steadier, it was assumed that the electricity production offshore could at least be equal to that on land. It will be difficult to make such an assumption now because the amounts involved are much larger. We would have to accept that the magnitude of the wind potential offshore is not known, but is probably significant.

Table 5. Electricity produced by wind energy on land

Percentage of potential	20	40	60
Annual production of electricity (TWh)	703	1406	2108

Note: (i) Total potential taken to be 2006 GW at a hub height of 80 m. (ii) APLF = 0.20.

Biomass power

In ref. 1, it was stated that India's total potential for generating power from biomass is about 23,000 MW. It is limited by the fact that biomass is needed extensively as a source of heat for non-commercial purposes in rural areas. As the availability of biomass is seasonal, an APLF of 0.3 is assumed and this yields an annual production of 60 TWh. We will stay with this number in this revised estimate.

Wave energy and ocean thermal energy conversion

The development of systems for extracting electricity from wave energy and ocean thermal energy were described in ref. 1. As far as wave energy is concerned, although there is a fair amount of energy in the waves and although some commercial activity has taken place, the chances that a significant amount of wave energy will be converted to electricity are poor. In the case of ocean thermal energy conversion systems, although the global resource is high, the energy conversion efficiency is very low and a large amount of parasitic power is required. Because of these factors, no commercialization has taken place and the real potential to generate electricity is negligible. In the earlier article[1], a question mark was put against the annual electricity which could be produced from these two sources. It appears more correct to state that the output from these sources is likely to be negligible in the national context.

Marine currents

As stated earlier[1], the kinetic energy available in marine currents offshore is significant. However, in India we do not have data available on suitable sites where water turbines (to trap the energy in these currents) can be installed. Even pilot-scale experiments have not as yet been performed along the Indian coast. Given the length of our coastline, it is likely that a small amount of electrical energy may be produced by this source.

Tidal energy

In so far as the exploitation of tidal energy in India is concerned, it was stated[1] that two sites on the Gujarat coast have been identified. There are unlikely to be more. It is estimated from the tidal flows and tidal ranges that if these two sites in the Gulf of Khambhat and the Gulf of Kutch are harnessed, an annual production of 17 TWh could be obtained. We will retain this estimate.

Table 6. Total potential of all renewable sources for generating electrical energy in India

Source	Annual electricity production (TWh/yr)					
	Earlier estimate[1,2]			Revised estimate		
Solar power (PV + thermal)	5%	10%	20%	5%	10%	20%
	438	876	1,752	788.4	1,576.8	3,153.6
Decentralized solar PV systems	Not taken into account			5 million	10 million	20 million
				22.5	45	90
Hydroelectric power				40%	60%	80%
Large units	482	482	482	193	289	386
Small units	50	50	50	20	30	40
				20%	40%	60%
Wind power (on land)	91	91	91	703	1,406	2,108
Wind power (offshore)	91	91	91	?	?	?
Biomass	60	60	60	60	60	60
Wave energy	?	?	?		Negligible	
Marine currents	?	?	?	?	?	?
Ocean thermal energy conversion	?	?	?		Negligible	
Tidal energy	17	17	17	17	17	17
Total	1,229	1,667	2,543	1,803.9	3,423.8	5,854.6

Note: Solar power (PV + thermal): 5, 10, 20 refer to percentage of land acquired. Decentralized solar PV systems: 5 million, 10 million, 20 million refer to households with rooftop systems. Hydroelectric power: 40, 60, 80 refer to percentage of reserves harnessed. Wind power (on land): 20, 40, 60 refer to percentage of wind potential at 80 m height harnessed.

Total potential of all renewable sources

Putting together the above data for each renewable source, we obtain the compilation given in Table 6. For comparison, the values obtained earlier[1,2] are also given in Table 6. For some sources (solar thermal/PV, hydroelectric – large and small, wind – on land), three estimates are given depending upon the degree to which the potential of the source is exploited. It will be noted that the output of decentralized solar PV systems is now included. Much of this output is not likely to be grid-connected. It will also be noted that the outputs from wind energy (offshore) and from marine currents are indicated with question marks. It is possible that out of these two sources, the energy available from wind (offshore) may be significant. As is to be expected, three totals are obtained. The revised estimates of this article show that the total amount produced could range from 1,803.9 to 5,854.6 TWh. The lower value of 1,803.9 TWh is obtained if it is assumed that the exploitation of the resources is at the lowest levels expected, while the higher value of 5,854.6 TWh corresponds to the highest level of exploitation. In all probability, a value between the two extremes will probably be attained.

Discussion

Annual supply and demand of electrical energy

Comparing the results of the present analysis with the results obtained earlier[1,2], we see that there is a significant increase in the total amount produced annually because of the large increase in the output from solar energy (PV and thermal) and wind energy (on land). There is a small increase also because of the inclusion of the output from decentralized solar PV systems. This is offset to some extent by small decreases in the outputs of hydroelectric power from both large and small units.

Based on the present analysis, the overall view that emerges is that in 'future', with a median level of exploitation, it may be possible to generate an 'adequate' amount of electrical energy every year from renewable sources alone. The word 'future' implies a year well beyond 2070 when fossil fuels will cease to be significant suppliers of electricity. The use of the adjective 'adequate' implies that there is acceptance of the suggestion that a per capita need of 1,840 kWh/yr corresponding to an overall need of 3,128 TWh/yr is sufficient for providing a good standard of living. The above viewpoint is a significant one with important policy implications. It is in contrast to the view expressed earlier[1,2] where it was stated that 'the future needs of electricity in India cannot be met from renewable energy sources alone, even if the electricity needs are kept to a minimum and the potential of renewable energy sources is fully exploited'. However, it is worth repeating that this change in viewpoint is because of two main reasons: (i) Recent studies have shown that the potential of wind energy on land is probably much more than that had been indicated earlier. (ii) The land needed per megawatt of capacity in solar power plants is less than that had been estimated earlier.

Table 7. Percentage-wise break-up of energy which would be supplied by different renewable sources in the future if all the energy needs are supplied by renewables

Source	Production (TWh/yr)	Percentage of contribution
Solar power (grid connected and decentralized; PV and thermal)	1,621.8	47.4
Hydroelectric power	319.0	9.3
Wind power	1,406.0	41.1
All other renewables	77.0	2.2
Total	3,423.8	100.0

The supply–demand problem on a 24 × 7 basis

The fact that in principle, renewable energy sources may be able to supply the future annual demand of electrical energy in India is clearly not enough. The demand has to be met not just on an annual basis, but continuously round-the-clock on a daily basis, an hourly basis and even a minute-to-minute basis. We will now examine this exacting requirement. In order to do so, we will first present the percentage-wise break-up of the energy which would be supplied by different renewable energy sources in the future if all the energy needs are supplied by renewables. This is done in Table 7 for the median case when the total annual supply is 3,423.8 TWh. It is seen that if renewable sources are to meet the whole demand in future, solar and wind power would be the major suppliers. Solar power would provide 47.4%, wind power would provide 41.1% and hydroelectric power would provide 9.3%. All the other renewable sources are likely to provide just 2.2%. Both solar power and wind power are intermittent suppliers. On a sunny, cloudless day, solar energy is available for only about 7–8 h with a peak around noon. Consequently, electricity is generated only during those hours unless the sun's energy is stored. Similarly, at any one location, wind energy is generally available for only about 4–5 h during a 24 h cycle and electricity is produced by a wind machine only during that period. This production is generally not at a steady rate. However, when one considers a large group of wind machines located over a region like a state, wind energy is usually available at all times at some location or the other. Thus, the average diurnal variation of the electrical output of all these machines considered together tends to have two components – a reasonably constant component for all 24 h (like the output of a base load station) and a component which increases, goes through a maximum and then decreases.

We will plot the diurnal variation of the solar, wind and hydroelectric power production on a typical sunny day over a region. Let us assume that the percentage break-up given in Table 7 is valid on this day and that the production for the day corresponds to the median case. Thus the production is (3,423.8/365) = 9.380 TWh. We will also make the following idealizations: (i) The solar power is produced for 8 h from 0800 to 1600 h and the production can be approximated by a half-sine wave symmetrical about 1200 noon. (ii) The wind power profile is made up of two components – the first is produced uniformly at a constant rate for all 24 h, whereas the second increases linearly and then decreases linearly from 1000 to 2200 h with a peak at 1600 h. The peak value of the second component is assumed to be 0.4 times the first component. [The value of 0.4 is based on data from one state. The discussion on mismatch is not sensitive to this value. It is also not affected much by the nature of variation assumed for the wind power generated.] (iii) The hydroelectric power is produced uniformly at a constant rate for all 24 h of the day. (iv) The small contribution from other miscellaneous sources is also produced uniformly at a constant rate for all 24 h of the day.

Figure 1 shows the variation in power produced over the day by each of the renewable sources; curve 1 is for solar power, curve 2 for wind power and curve 3 for hydroelectric power and other miscellaneous sources. In Figure 2, the contributions of all sources are added to yield the variation of production over a day. It is seen that with the idealizations made, the production is constant from midnight to 0800 h. It peaks from 0800 h to noon and falls rapidly thereafter till 1600 h. After that it decreases slowly till 2200 h and then is constant up to midnight.

We will now compare the production with the diurnal variation of the demand. Typical data for Maharashtra for 31 March 2011 given by Kale and Pohekar[14] are also plotted in Figure 2. We will assume that the same variation is valid for a typical day over the country and proportionately adjust the power output so that the total area under the demand curve over 24 h is the same as the production, i.e. 9.380 TWh. The demand curve thus obtained is also plotted in Figure 2. It is seen to have two shallow peaks, one around noon and the other in the late evening around 8 p.m., and passes through a minimum value in the early hours of the morning around 3 a.m.

Figure 2 shows that there is a wide mismatch between the supply and demand curves. The supply is more than the demand for about 7 h from 9 a.m. to 4 p.m. when the sun is shining. For the remaining period of about 17 h, it is less than the demand. Thus, many technical challenges will have to be overcome if renewable sources alone have to meet our energy needs fully. A major challenge will be to coordinate the supply of thousands of relatively small, distributed solar and wind power sources using appropriate computers and software and to take that supply with the help of an extensive and robust transmission grid from where it is produced to where it is consumed. A similar challenge on the demand side will be to develop computer-controlled load-controlling capabilities. These are currently not available. A further challenge will be to develop large-scale storage systems not only to even out the mismatch in diurnal variation on a sunny day (shown in Figure 2), but also to provide power to match demand during days when there are lulls in wind speeds or periods of cloudy weather which block sunshine. The most likely energy storage option is to build a vast network of pumped water storage systems which pump water into reservoirs at a higher level during periods of excess generation of electricity and release the water through turbines to generate electricity during periods of deficit. At the moment, systems with very limited energy storage capacity are available. There are no clear-cut economic solutions to the above-mentioned problems. Although researchers in many countries are working on a wide variety of issues, it is not clear if the challenges posed can be satisfactorily solved. In India, the problems have not even been articulated.

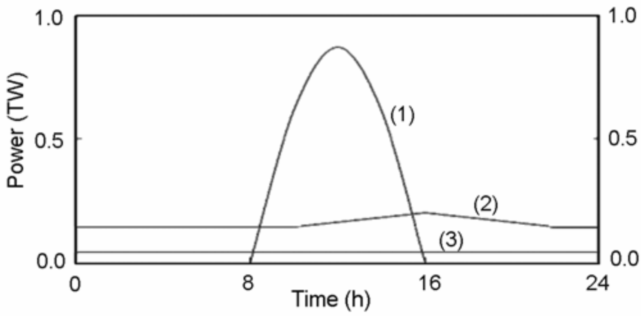

Figure 1. Diurnal variation of power produced by renewable sources over a typical sunny day. Curve 1 – Solar energy (4.446 TWh). Curve 2 – Wind energy (3.855 TWh). Curve 3 – Energy from hydroelectric power and other miscellaneous sources (1.079 TWh). Total production = 9.380 TWh.

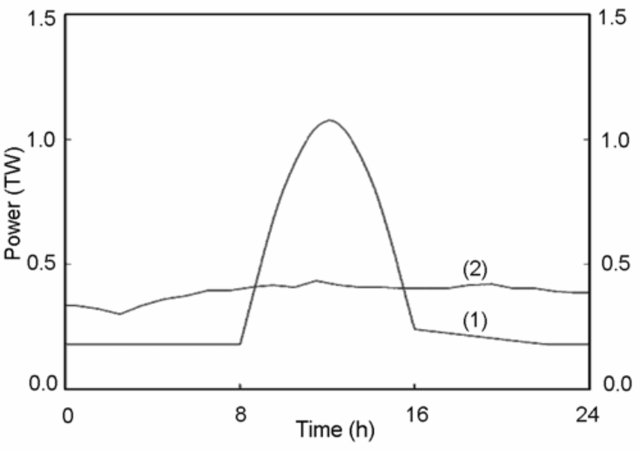

Figure 2. Comparison of diurnal variation of production (curve 1) and demand (curve 2) over a typical sunny day.

In this regard, it is particularly important to note the efforts being made in Germany[15]. In 2010, the government there decided to switch from fossil fuels to renewable energy sources in order to reduce greenhouse gas emissions. The targets set were to cut emissions existing in 1990 by 40% by 2020 and by 80% by 2050. These goals were very challenging and have become even more so because of the recent decision of the German Government to phase out nuclear power by 2022. Apart from the techniques described in the preceding paragraph for meeting the challenges posed by the introduction of renewable energy sources on a large scale, new strategies are also being tried in Germany. For example, it is known that wind speeds offshore are generally steadier than those on land and that the steadiness increases with the distance from the shore. The German industry is therefore planning to install very large wind farms with a combined capacity exceeding 10,000 MW in the North Sea, more than 100 km from the shore. This will entail locating structures in water depths exceeding 50 m. In addition, there is the additional complexity of bringing the power generated on land through longer transmission lines. In order to reduce the transmission losses, it is planned to convert the AC output of the wind machines to DC in sub-stations located offshore. At the moment, Germany is the only country putting in exceptional efforts to enable a transition to the use of renewable energy sources alone for generating electricity.

Conclusions

(1) Keeping in mind the need to be frugal in our use of energy, it appears desirable for India to plan for a per capita electricity use of 1,840 kWh/yr in the future. This will correspond to a stabilized need of 3,128 TWh/yr when the country's population is expected to level off around 1,700 million by 2070. A per capita use of 1,840 kWh/yr should result in a good standard of living if energy conservation measures are adopted, energy efficient devices are used and wasteful consumption of electricity is discouraged.

(2) The revised estimate presented in this article indicates that the total amount of electrical energy produced by renewable sources per year could range from 1,803.9 to 5,854.6 TWh, the major contributors being solar energy (PV and thermal), wind energy and hydroelectric power. The lower value of 1,803.9 TWh is obtained if it is assumed that the exploitation of the resources is at the lowest levels expected, while the higher value of

5,854.6 TWh corresponds to the highest level of exploitation. In all probability, a value somewhere between these two extremes will be attained. Thus, in the future, it is possible that on an annual basis, the overall need of 3,128 TWh of electricity may be met by renewable sources alone.

(3) Meeting an annual requirement of electrical energy is necessary, but is not enough. It is also necessary to meet the daily need for electricity on a continuous round-the-clock basis all over the country. Because of the intermittent nature of both solar and wind energy, there is a serious mismatch between the diurnal variation of the supply and the diurnal variation of the demand. Thus, many technical challenges exist and these problems will have to be successfully resolved if matching is to be achieved and renewable energy sources alone are to meet our electricity needs in the future.

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