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Authors' addresses:

Subhash Kumar, Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-mail: SKumar@eonerc.rwth-aachen.de, RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de

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Subhash Kumar*, Reinhard Madlener

Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany

* Corresponding author. Tel.: +49 241 80 49 840, fax: +49 241 80 49 829, E-mail addresses: skumar@eonerc.rwth-aachen.de (S. Kumar), RMadlener@eonerc.rwth-aachen.de (R. Madlener).

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Abstract

The Indian power sector is experiencing a lot of pressure to supply sustainable electricity at affordable cost due to heavy demand especially in the summer peak season. Most of India's electricity is produced by fossil fueled power plants, which are the source of CO_2 emissions. In this case, renewable energy sources play a vital role in securing sustainable energy without environmental emissions. This paper examines the effects of renewable energy use in electricity supply systems and estimates the CO_2 emissions by developing various scenarios under the least cost approach. The LEAP energy model is used to develop these scenarios. The results show that in an accelerated renewable energy technology (ARET) scenario, 23% of electricity is generated by renewables only, and 74% of CO_2 reduction is possible by 2050. If the maximum energy savings potential is combined with the ARET scenario, the renewables share in electricity supply rises to 36% as compared to the reference scenario, while the CO_2 emission reduction in this case remains at 74%.

Keywords: CO_2 mitigation, Electricity generation, LEAP, Least cost method, Renewables, India

JEL classification: C70, P48, Q41, Q42

1. Introduction

India's substantial and sustained economic growth is putting enormous pressure on the country's energy resources. The threat of severe energy demand and supply imbalances is pervasive, requiring serious efforts by the Government of India to augment energy supplies. India imports about 80% of its oil (Ministry of New and Renewable Energy (MNRE), 2011). There is a risk that this capacity cannot be increased much further, which will create serious problems for India's future energy supply security. There is also a significant risk of lesser thermal capacity being installed on account of a lack of indigenous coal in the coming years because of both production and logistic constraints, and an increased dependence on imported coal. Significant accretion of gas reserves and production in recent years is likely to mitigate power needs only to a limited extent. The difficulties of large hydro are increasing because of the displacement of people living in reservoir areas, and nuclear power is also beset with problems due to international agreements for nuclear fuel. The country thus faces potentially severe energy supply constraints. Economic growth, increasing prosperity and urbanization, the rise in per capita consumption, and the spread of energy access are the factors most likely to substantially increase the total demand for electricity, threatening the security of energy supply. Already today, official peak deficits in the electricity sector are in the order of 12.7%, a value which could increase even more over the long term.

Renewable energy can make a substantial contribution in each of the above mentioned areas. It is in this context that the role of renewable energy needs to be seen. It is no longer "alternate energy", but is increasingly becoming a key part of the solution to the nation's energy needs.

In 2002, the installed capacity for renewable energy-based power generation was 3475 MW, which amounted to 2% of the total installed power generation capacity in India (MoP, 2013). By the end of 2010, it had reached 18,655 MW, which is about 11% of the total installed capacity of

168,945 MW, and which corresponds to a percentage contribution of about 4.13% to the electricity mix (MNRE, 2011). Figure 1 provides the fuel-wise break-up of the installed power capacity in the country.

During the first three years of the 11th plan period and the current (base) year up to 2010, renewable power capacity addition was 8395 MW, while the conventional power capacity addition amounted to 25,598 MW, which corresponds to over 24% of the total capacity addition (MNRE, 2011). It should also be noted that 23% of the total capacity installed today is large hydro, which is renewable but not counted as such. The major contribution to the existing capacity has come from wind power, which amounts to about 70% of the total renewable capacity.

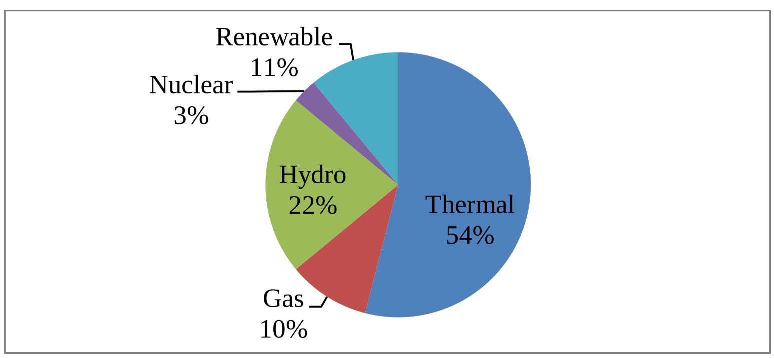

Fig. 1. Installed capacity, by fuel type

This paper investigates the future sustainable electricity supply by using the renewable energy resources in India. Various scenarios have been developed to estimate the most favorable energy future for the Indian economy by considering the demand of these sectors. The economic demands are projected using the LEAP inbuilt methods up to the year 2050, and some of the projection are adopted from reports made available by the Ministries. The LEAP optimization feature has been used to find the least-cost solution of the energy mix and the corresponding CO_2 emissions. Mainly renewable energy and energy-saving potentials in various sectors of the economy have been considered in order to access the requirement of new power plants to be built and the potential of carbon emission abatement.

2. Renewable energy overview

India is endowed with an enormous potential of renewable energy resources to meet its energy needs. However, in spite of this large potential, the high cost and the need for storage are some of the major barriers for the large-scale diffusion of renewable energy technologies (PC, 2006). It is recognized that there is a downward trend in the cost of renewables, and that the reliability of renewable energy technologies is gradually improving. In the Indian context, power generation from wind and solar have become commercial both in the large-scale (grid-connected) applications and small-scale (decentralized) applications, respectively. However, decentralized energy applications require significant further cost reductions in order to be adopted on a large scale, or alternatively, will require subsidies from the Government. The long-term benefit of renewable energy technologies and the associated social and environmental gains in many cases justify the granting of subsidies for renewables. In this context, the potential of different renewable energy technologies that can be effectively harnessed would largely depend on future technological developments and breakthroughs, leading to further cost reduction. Table 1 shows the total installed capacity vs. renewable installed capacity in India. The trend shows an increasing percentage of renewables over the years.

Table 1. Growth of installed capacity and percentage shares of renewables in the total installed generating capacity (CEA, 2011).

Year	Total installed capacity (GW)	Total installed renewables (GW)	% of total capacity
1990	63.6	0.02	0.03
1992	69.0	0.03	0.05
1997	85.7	0.90	1.05
2002	105.0	1.65	1.58
2007	132.3	7.76	5.86
2008	143.0	11.13	7.78
2009	147.9	13.24	8.95
2010	159.4	15.52	9.74
2011	173.6	18.46	10.63
2012	199.9	24.50	12.26

Figure 2 shows that the major contribution of the renewables comes from wind power, while small hydro only accounts for 12 % of the total installed capacity from renewables. This is because the estimated small-scale hydro potential in India is only 15 GW. Solar and biomass have an enormous potential that still needs to be harnessed.

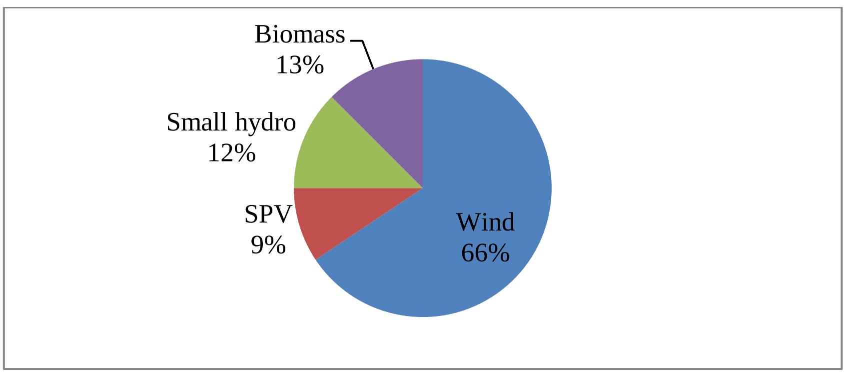

Fig. 2. Percentage shares of individual renewables with regard to the total installed capacity from renewables in 2012 (MNRE, 2013).

The different renewable energy resources available to the Indian energy market are explained next.

2.1. Large hydro power plants

Hydro power is the second most widely accepted technology for power generation in India, after coal power plants. The much quoted estimated potential of slightly more than 84 GW in capacity is for sites offering a minimum of 60% plant load factor (PLF) due to the availability of water resources. This potential is considered as the economic potential for hydro power in India. This value increases to 150 GW if some additional sites, offering more than 40% PLF, are also considered (Naidu, 1996). As the reference value, however, the established figure of economic potential (rounded-off to 150 GW) is used in the LEAP analysis only as a lower bound for this technology.

Besides the availability of water, environmental impacts of hydro power plants also need to be examined thoroughly while considering construction of large hydropower plants. Some of these considerations are the mass resettlement of families, the threat of catastrophic structural failure, the loss of tourism and recreational potential, the impact of silt buildup, the loss of agricultural land, the runoff of pollution into the reservoir, the effects on local flora and fauna, and decommissioning of the dams. Other positive benefits related to hydropower plant construction, including flood control and improved navigation, also need to be considered. The construction of hydro power plants is relatively more capital intensive and time consuming. Coverage of rehabilitation and restoration costs (that are very much site specific) further increase the overall project costs. For the basic case of this study, average rehabilitation and restoration (R&R) costs have been considered, made available through the sources of the National Hydro Power Corporation (NHPC, 2010) and the Power Finance Corporation of India (Govil et al, 2000). The installed capacity in 2013 was approximately 39.8 GW, which is equivalent to 17.39% of the total electricity generation in India. India is blessed with an immense amount of hydro-electric potential and ranks 5th in terms of exploitable hydro-potential on a global scale.

2.2. Small hydro power plants

Unlike large hydro, small hydropower plants usually rely on run-of-the-river configuration and do not require large reservoirs. Therefore, while this characteristic eliminates many of the environmental impacts of larger dams, such as deforestation, submergence, and rehabilitation, it also reduces the project gestation period and offers a higher operational flexibility. In India, capital costs per unit capacity for small hydro power plants are higher than the larger units due to economies of scale and also due to a lack of proper thrust to related research. However, the costs are likely to come down in the future (Naidu, 1996). The definition of small hydro power differs in different parts of the world. In India, plants with a declared capacity of less than 15 MW are put in this category. In the UK and Germany, this limit is 5 MW, in Australia 20 MW, in China 25 MW, and in the Philippines and New Zealand 50 MW (Naidu, 1996). The World Bank, on the other hand, accepts the classification based on the financial outlay of the projects. This financial ceiling is subject to revisions due to factors like inflation. A contradiction has been observed between this and previous value of limits. The World Bank limit is corresponding to a maximum capacity of 25 MW (approx.) as per the contemporary costs (Naidu, 1996). With this new limit of 25 MW, the potential of small hydro increases from 10,000 MW to close to 20,000 MW. As the World Bank is one of the major funding agencies in the Indian power sector, the latter value is considered in this study as an upper bound against the much quoted potential of 10,000 MW. The Indian Renewable Energy Development Agency (IREDA) is a national level funding agency and nodal agency for the World Bank as well as for the funding of renewable energy projects in India.

This agency also offers special loans with the limit of 25 MW capacity under the heading "small hydro" (Mathur, 2001). Key parameters that are considered in the base case of this study are given in Table 4.2. Unlike most of the other technologies, there is much variation in parameters related to small hydro power plants. Due to non-availability of reliable information for this break-up, just one category has been created, as is also done by CEA in their analysis (CEA, 2012).

With a capacity of 3395 MW of small hydro power installed in India in 2012, it constitutes nearly 14% of installed renewable energy capacity. Presently the capacity stands at 3686 MW. So far, 898 small hydro power (SHP) projects with an aggregate capacity of 3411 MW have been set up, and 348 projects aggregating to 1309 MW are under implementation (CEA,2012). While SHP is already cost-competitive with conventional power, increased efficiencies and capacity utilization factors would make it even more viable in the future. In order to further enhance the total power generation from SHPs, it is essential to harness all potential sites. According to the MNRE, the focus of the SHP program is to lower the cost of equipment, increase its reliability, and set up projects in areas which give the maximum advantage in terms of capacity utilization.

2.3. Wind power plants

Wind power is the most widely accepted renewable energy technology to date besides hydro power. One of the large barriers to greater use of wind-based power plants is the relatively low and varying capacity utilization of these plants. It is evident from the very fact that sites offering a utilization factor of more than 20% are often considered to be attractive. However, the estimated economic wind energy potential of 48 GW in India is corresponding to a 40% utilization factor, which is considered to be very good in its category. Wind is not a very dependable source of energy, so that uncertainties in wind velocities over a time period are to be covered through Weibull's distribution. One way to overcome these limitations is by using storage devices which can continue producing power for the grid even when the wind is not blowing. In many areas, where world class winds are available, there are water shortages preventing its use as a storage medium. Compressed air energy storage (CAES) or flywheels might help to overcome the poor capacity factors of many wind sites in these water-poor regions. Use of any energy storage technique tends to increase the plant costs; such variations in cost and utilization factors with respect to relatively less economical sites for wind energy systems can be covered through sensitivity analysis. In India, due to its long coastal line, however, many sites are found to offer even higher utilization factors than 50% and relatively stable wind profiles (Mani, 1993). Therefore, many wind energy systems are feeding electricity into the main grid without requiring large energy storage systems. Details have been taken for this study from many working power plants, and the basic parameters given below are from two recently commissioned wind energy power plants at Deogarh and Falaudi in the state of Rajasthan (REDA, 2005).

2.3.1. Onshore wind power plants

With 17,353 MW of wind power installed in the country in 2012, it constituted the mainstay of renewable power in the country, contributing about 70% of the total installed capacity for renewable energy. The capacity was 19,564 MW in 2013, most of which is located in the southern and western high solar resource states of Tamil Nadu, Karnataka, Maharashtra, Gujarat, and Rajasthan (Ramchandran, 2011). The target for grid-connected wind power under the 12th plan is set for an additional 15 GW. With regard to wind power, while the recently revised official figure stands at 102 GW, various studies indicate that the actual potential could be anywhere between 500-1000 GW, which indicates that the wind resource availability is not a constraint for wind power development (IESS2047, 2013). Availability of land, transmission infrastructure, and reliable integration of variable generation would be key factors as well that may limit the uptake of wind power in the future.

2.3.2. Offshore wind power plants

Presently, India does not have any offshore wind power plants in operation. However, the country does have an extensive coastline of 7500 km^2, which is indicative of a large potential offshore resource. Offshore wind is growing at a fast pace especially in Europe, and the EU already has close to 5 GW of installed capacity operational. With next generation turbines having capacities larger than 3 MW, better scheduling and forecasting technology and software for offshore wind could play a large role within the RE sector in India. Offshore wind power is a potential source of electricity generation, primarily due to better quality wind resources along with the absence of land constraints. However, as of today, the costs of installation and operation are almost twice as high as those of onshore wind power. These costs are set to decline with technological improvement, including increased hub heights, turbine capacity, CUFs, and floating turbines (Wüstemeyer et al. 2012). MNRE came out with a draft offshore wind policy in 2013. The policy suggests setting up 2 GW of capacity on the southern coast to begin with. While a detailed assessment of the resource potential for India has yet to be done, some studies suggest that it could be in the range of 350 - 500 GW, which indicates that the resource availability is not a constraint for wind power development (IESS2047, 2013). Higher costs, transmission infrastructure, and reliable integration of variable generation would be key factors that might limit the uptake of offshore wind power in the future.

2.4. Solar power plants

2.4.1. Solar PV

While the solar resource was never a bottleneck for the development of this sector in India, it was the very high price of solar PV power that prohibited this technology from being considered a serious contender in the supply mix in India. However, with the launch of the Jawaharlal Nehru National Solar Mission (JNNSM) under the NAPCC, the solar PV sector got a kick start on a large scale in India. And it was the much lower price of solar power that was discovered through the process of competitive bidding and the prediction of further cost reductions that has allowed solar PV to be considered as one of the mainstay supply options in the coming years. With 941 MW of installed capacity in the country in 2012, solar PV was possibly the smallest in terms of supply from any one resource. The capacity was 1760 MW in 2013, most of which is located in the western high solar resource states of Gujarat and Rajasthan (MNRE, 2011). The target for grid-connected solar power (i.e. PV and concentrating solar power, CSP) under the JNNSM is set at 20 GW by 2022. However, given the present price advantage of PV over CSP it looks likely that a significant share of the 20 GW would be met by PV. Going beyond the JNNSM, the National Tariff Policy was amended in 2011 in order to have a separate solar renewable portfolio obligation (RPO) for all obligated entities in the country. This is expected to begin with 0.25% in 2012 and to increase to 3% by 2022. According to MNRE, this translates to a need of roughly 34 GW by 2022. Most of the solar PV plants are based on either c-Si or thin film technology (MNRE, 2013).

2.4.2. Concentrating solar power

CSP is a source of utility-operated large-scale electricity generation. Unlike PV, CSP only exploits the direct normal radiation fraction of the solar irradiation, and uses solar heat for steam generation and finally electricity production. This technology has been tried and tested in many parts of the world (Madlener and Mathar, 2009) but is relatively new to India. Up to now, it has been most widely used in Spain and the US. The total technical potential of CSP in India (with land use limited to barren areas) according to one study is 2324 TWh/yr. According to another, it is much higher at 10,928 TWh/yr (Ramachandran et al, 2011). Similarly to PV, the resource potential is unlikely to be the limiting factor for CSP; rather, it will more likely be due to technology availability constraints, price barriers, or the need of water for cooling. It was the JNNSM that kick-started the CSP program in India. Under phase 1 (2010-13) of the Mission, 50% of the allotted capacity was earmarked for CSP. A total of 470 MW was bid out. The first large-scale plant of 50 MW was commissioned very recently in the country (CEA, 2012). Phase 2 of the Mission (2013-17) has earmarked roughly 30% of the capacity for CSP. Going beyond the JNNSM, the National Tariff Policy was amended in 2011 to have a separate solar RPO (PV+CSP) for all obligated entities in the country. This is expected to begin with 0.25% in 2012 and to increase to 3% by 2022. According to MNRE, this translates to a need of roughly 34,000 MW in 2022 (MNRE, 2011). Additionally, the Solar Energy Corporation of India (SECI) would be setting up pilot CSP plants to test out various possibilities in India, namely hybrid and storage projects. While solar thermal electricity is relatively new in India, given the potential, it is expected to gain pace in deployment. In light of expected reductions in the cost of technology and the benefit of energy storage ability, CSP can contribute a significant portion to the RE share. Since CSP competes with PV for the same high solar irradiation resource sites, however, there could be some trade-offs with regard to technology choice. While CSP is presently costlier than PV, its ability for storage and support of the grid with ancillary services could prove very valuable. Similarly, CSP also allows the possibility of hybrid plants with natural gas or coal.

3. Methodology

The model LEAP (Long range Energy Alternatives Planning system) (Wei et al., 2006), is a static energy-economy-environment model developed by the Stockholm Environment Institute since the early 1980s. Treating energy demand, consumption, and environmental impact as objects, this model forecasts the energy demand, consumption, and environmental impact of each sector and analyzes the economic benefits of each energy scenario in detail. The model is the simulation of the energy system and is called an end-use energy consumption model (Siteur, 2004). Various studies have been conducted using the LEAP model so far in different countries in the world. Guo et al. (2003) studied the development scenarios and future energy demand in China, using the LEAP model. Kumar et al. (2003) assessed the GHG abatement effects and potential of biomass energy technologies in Vietnam's energy system under alternative scenarios. Shin et al. (2005) analyzed the impacts of the expansion of landfill gas electricity generation capacity on the energy market, the cost of generating electricity, and greenhouse gas emissions in Korea. Bose and Srinivasachary (1997) analyzed factors influencing energy consumption patterns and emission levels in the transport sector of Delhi; and extrapolated total energy demand and the vehicular emissions using both LEAP and the associated environmental database (EDB). Bala (1997) studied rural energy supply and demand with LEAP, and assessed the contributions to global warming for Bangladesh caused by the shortcomings of the traditional uses of biomass fuels in rural areas.

Typically, the new capability of the LEAP software tool will be used to calculate the optimal expansion and dispatch of power plants for the German electricity system, where "optimal" is defined as the energy system with the lowest total net present value (NPV) of the social costs of the system over the entire period of calculation (from the base year through to the end year). A least cost system can optionally be calculated subject to a number of user-specified constraints including maximum annual levels of emissions for any given pollutant (CO_2, SO_x, NO_x, PM_{10}, etc.) and minimum or maximum capacities for certain plant types. For example, an expansion pathway for an energy system could be calculated that met a minimum renewable portfolio standard whilst also staying within a target for reducing greenhouse gas emissions (Heaps, 2012).

The optimality of a given pathway may be very sensitive to input assumptions, such as future capital costs, future efficiency, future fuel costs, or future GHG mitigation targets. A system that is optimal for a country under one set of assumptions may be far from optimal under another set. Generally, the goal in energy planning is not to identify a single optimal solution, but rather to identify robust energy policies that work well under a range of plausible input assumptions. Moreover, we use the LEAP model's scenario capabilities to calculate and to explore different optimal solutions under different sets of input assumptions. LEAP includes the capability to automatically calculate least cost capacity expansion and dispatch of supply-side transformation modules. The key characteristics in terms of parameterization required for the LEAP estimation are shown in Table 2.

Table 2. Overview of key characteristics of candidate generation technologies used in the LEAP model (Johnson et al., 2006; TERI, 2006).

Technology	Start year	Lifetime (years)	Efficiency (%)	Availability fraction	Investment cost (US$/kW)	Fixed O&M cost (US$/kW)	Variable O&M cost (US$/kWh)
Coal thermal	2010	40	32	0.80	890	10.7	0.014
Gas thermal	2010	40	35	0.80	667	23.5	0.029
Large hydro	2010	50	80	0.70	1334	12.9	0.9
Nuclear	2010	40	35	0.75	1446	42	0.002
Solar	2010	25	15	0.30	3500	10	-
Wind power	2010	30	35	0.35	889	10	-
Small hydro	2010	35	80	0.64	1557	15.18	-
Other renewables	2010	30	54	0.65	885	41.5	0.48

In an integrated energy policy report by the Planning Commission (PC, 2006) only new fossil fuel and renewable energy technologies have been considered for future supply options. In another report, the National Energy Map for India Technology Vision 2030, prepared by TERI (2006), supply scenarios have been developed for new and renewable energy sources. These two reports have not taken into account the energy-saving potential in various sectors of the economy. We feel that it is also necessary to take a holistic approach to introducing energy-saving potentials in various sectors of the economy. Considering the vast potential of energy savings and expected benefits of energy efficiency, the Government of India enacted the Energy Conservation Act, 2001 (BEE, 2005). The Act provides for a legal framework, institutional arrangement, and a regulatory mechanism at the central and state levels to embark upon an energy efficiency drive i.e. for accelerated action towards energy efficiency in the country (BEE, 2005). Energy efficiency improvements not only reduce the energy consumed per unit of products and services made available, but also improve energy security of the country to ensure sustained availability of energy resources at an affordable price. The estimated energy-saving potential in various sectors is given in Table 3.

Table 3. Maximum electricity saving potential in different sectors of the Indian economy (BEE, 2005).

Sector	Electricity Saving Potential (%)
Industrial	25
Agricultural	30
Domestic	20
Commercial	20
Transport	20
Other	23

For the LEAP model, first of all a reference scenario, which assumes that the present situation will continue until the end of the modeling horizon, has been developed to compare the alternative scenarios with. Considering the discussion about renewable and energy savings potential (ESP) in the previous sections, we have developed two renewable energy scenarios called renewable energy technology (RET) and accelerated renewable energy technology (ARET), respectively. Other scenarios have also been developed by considering the energy savings potentials together with renewable energy technologies in this work. In the ARET scenario, it is considered that the total available technical potential of various renewables (cf. Table 4) are exploited completely up to 2050.

Table 4. Potentials of renewable energy sources (MNRE, 2011).

Renewable Technology	Installed capacity (GW)	Potential (GW)
Large hydro	39	150
Wind	17.30	48.5
Small hydro	3.40	15
Solar	1	20-30 MW/km^2
Others (biomass etc.)	3	69

4. Results and discussion

4.1. Base Case (BAU)

The base case results presented in this section are LEAP results generated by running the reference scenario from 2010 to 2050. Fig. 3 shows the energy mix of various electricity generation technologies. The total electricity generation increases very quickly from the base year 2010 to 2020, at an annual rate of 10%. From the year 2020 to 2030, the growth rate slows down. The annual increase is only 1.4%. After the year 2030, again the average annual growth rate becomes 6% until 2040, and again rises to a 12% annual growth rate. Coal is the major source of electricity generation technology throughout the modeling period. Large hydro and nuclear present the significant values after 2030 up to the end of the planning horizon. Electric installed capacity of plants using gaseous fuels remains constant during the modeling period. Overall, 720

GW of installed capacity will be required by 2050 if the present situation continues. All renewables, except for large hydro, contribute only 12% of the total installed capacity, which leads to an unsustainable situation in terms of environmental mitigation.

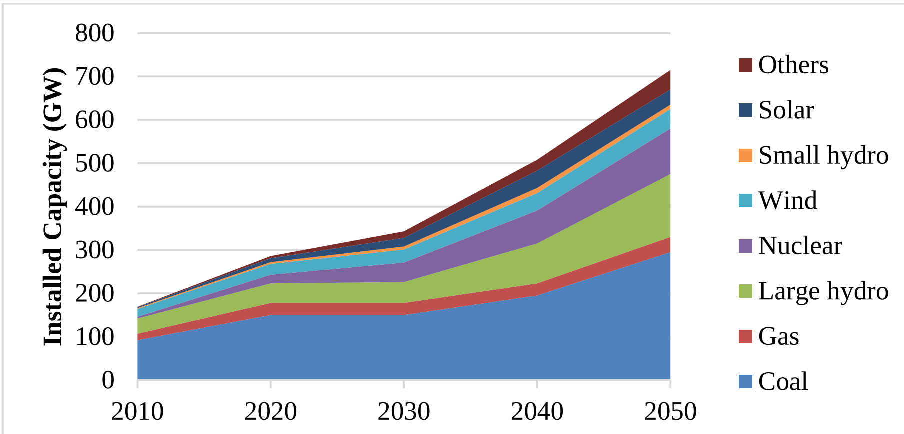

Fig. 3. Installed capacity in the base case (BAU), by resource type.

4.2. RET scenario

Considering the demand in the reference scenario and the technology mix of energy sources, the resource-wise energy mix for the least-cost options are shown in Fig. 4 for the renewable energy technology scenario. It becomes evident from the figure that, similar to the BAU case, coal remains the major source of energy generation. However, it remains constant between the years 2020 and 2030 and then starts rising again, reaching 245 GW by the year 2050 (in the BAU scenario, i.e. without the renewable energy scenario, it was 295 GW).The contribution of large hydro becomes 183 GW, and other renewable energy technologies (except wind and small hydro) do not get allocated in substantial proportions due to their high investment costs. Large hydro is the second-largest installed capacity in 2050 in this scenario. Power generation capacity using gas increased slightly over the years and becomes 45 GW, which is a threefold increase compared to

2010. The renewables together increased to about 18% of total installed capacity in 2050 compared to only 12% in the BAU scenario.

Figure 5 shows the electricity generation by individual technologies from 2010 to 2050 in the RET scenario. Coal-fired power generation is dominant among the energy mix. It increases from 1600 PJ in 2010 to 6100 PJ by 2050, which is roughly a fourfold increase over the modeling period. Large hydro and nuclear power plants together generate some 45% of total electricity generation by 2050. Power generation capacity using gas is negligible compared to other major generation sources. Renewables show a significant increase in 2050 compared to 2040. The share of renewables is 18% of total energy generation by 2050. Total electrical energy generation has jumped to about 17.7 TJ by 2050, in comparison to 2.5 TJ in the base year. The main contribution comes from coal, large hydro, and nuclear.

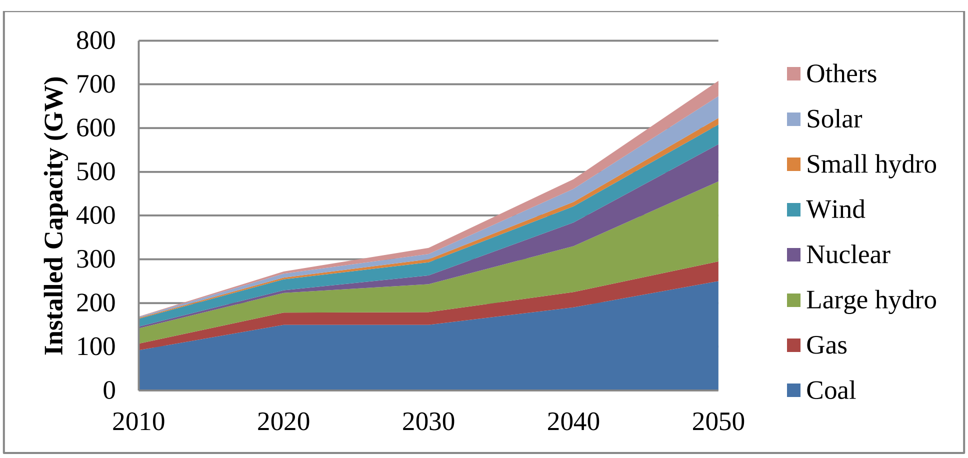

Fig. 4. Installed capacity in RET scenario, by resource type.

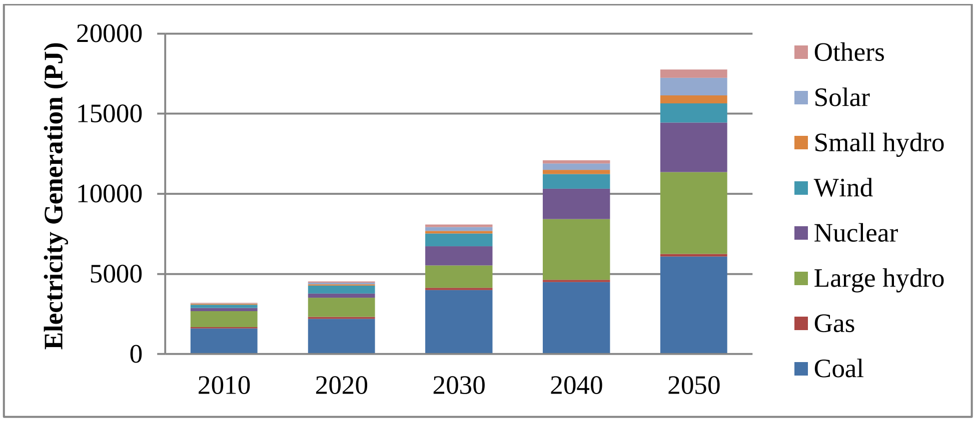

Fig. 5. Electricity generation in RET scenario, by resource type.

4.3. ARET scenario

In this scenario, we made it essential to fully exploit the renewables potential until 2050. The optimized results are reported in Fig. 6. It can be observed that the share of coal remains stagnant between the years 2020 to 2030 and increases only slightly until 2040. After the year 2040, coal capacity decreases sharply up to 2050. Installed generation capacity using coal comes down to 100 GW as compared to 190 GW in 2040. Gas-fired capacity remains almost constant during the modeling period. Large hydro installed capacity has risen drastically to 320 GW by 2050 as compared to only 35 GW in the 2010 reference year, corresponding to a nine fold increase. Nuclear, wind, and other renewables rise steadily. The renewables contribute 23% of total installed capacity. The installed solar energy capacity is significant, because the government of India is accelerating solar power generation under the Jawahar Lal Nehru National Solar Mission launched in 2010. The overall capacity increases from 180 GW in 2010 to 702 GW in 2050, which corresponds to about a fourfold increase.

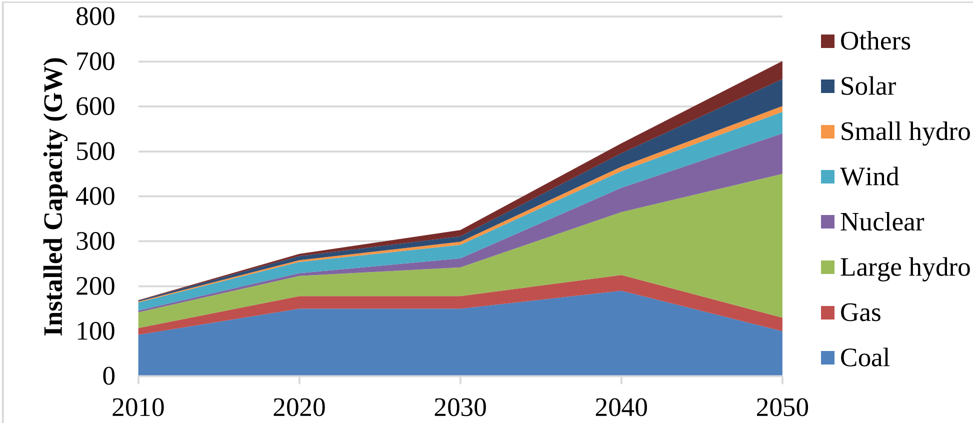

Fig. 6. Installed capacity in ARET scenario, by resource type

Figure 7 shows the electricity generation from different resources from the reference year 2010 until 2050. As can be seen, the coal electricity generation first increases up to 2040 and then has rapidly decreased by 2050 almost to the 2010 level. This shows that if we implement some policy for clean energy generation, it will take some time for its technological development and its adoption by the people of the country. The large hydro remains almost constant from the year 2010 to 2030 and doubles in the year 2040. By the year 2050, almost 50% of electricity production is due to large hydro alone. The renewables contribute significantly by 2050 at about 4200 PJ or 25% of total electricity generation. The total electricity generation has increased about nine fold by 2050, as compared to the base year 2010.

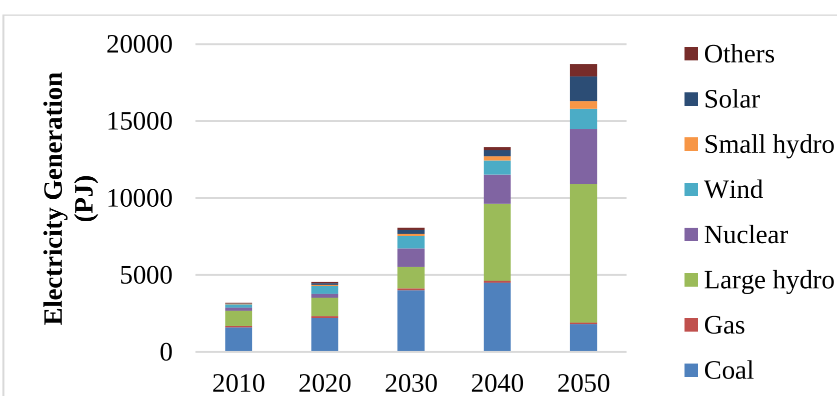

Fig. 7. Electricity generation in ARET scenario, by resource type.

4.4. CO_2 emissions in BAU as well as in RET and ARET scenarios

The CO_2 emissions under the various scenarios discussed above are shown in Fig. 8. The corresponding CO_2 emissions from various fuels are given in Mallah and Bansal (2010).

The CO_2 emissions in the BAU scenario show the rapid increase over the modeling horizon until 2050. The RET scenario remains similar to the BAU until 2030 and after that shows a significant decrease until 2050, as compared to the BAU, but still shows an ascending pattern. The decrease in CO_2 emissions is about 21% compared to the BAU scenario.

In the case of the ARET scenario, the CO_2 emissions have decreased drastically by the year 2050. As can be seen from Fig. 8, the CO_2 emissions are lower compared to other scenarios from the very beginning in year 2010 and until the end of the modeling period. Until 2040, they also show an increasing pattern but after that suddenly decrease and become 100 Mt by 2050. The ARET scenario shows a CO_2 reduction of about 74%, compared to the base case scenario, by the year 2050. This situation will achieve a carbon-free environment and a significant contribution to the slow-down of global warming.

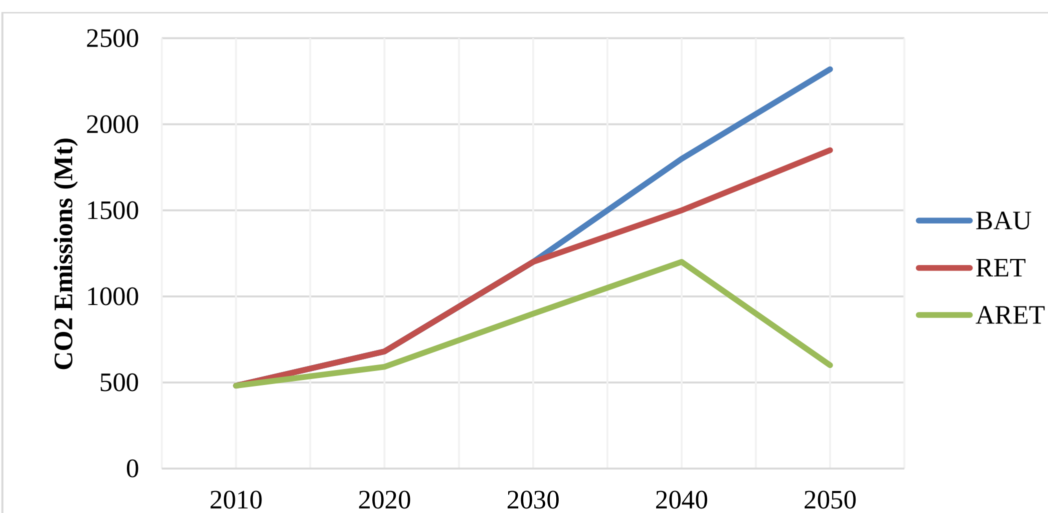

Fig. 8. Carbon dioxide emissions in the various energy scenarios considered.

4.5. RET and ESP scenarios

Next, we use the energy savings potential of Table 3 in various economic sectors of India and combine it with the RET scenario, which yields the results depicted in Fig. 9. In this scenario, installed coal capacity remains constant from 2020 to 2040 and after that only shows a slight increase, which is almost negligible. Installed capacity using gas remains constant from 2020 to 2050. Large hydro shows an increase of about 2.8 times from the base year 2010 until 2050. Nuclear installed capacity also increases steadily. Renewables have gained a significant proportion of 27% by 2050. The overall installed capacity decreases to 500 GW, as compared to 720 GW in the reference scenario in 2050, which is about a 30% decrease in total installed capacity.

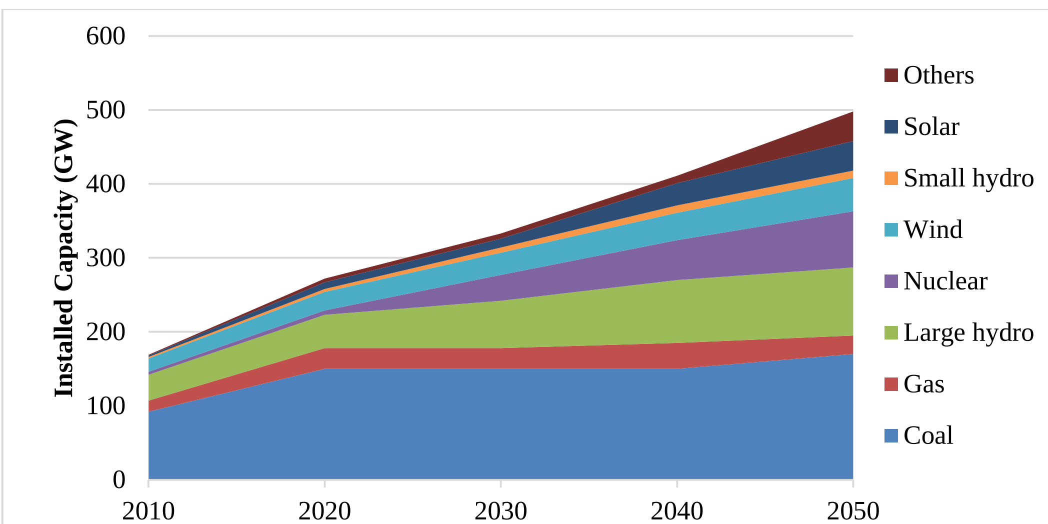

Fig. 9. Installed capacity in renewable energy technology with maximum savings potential scenario, by resource type.

In another scenario, we used the energy savings potential and accelerated renewable scenario together. The results of this scenario are shown in Fig.10. In this scenario, installed capacity using coal increases from 2010 to 2020 and then stagnates from 2020 until 2040. After that, it has decreased rapidly to 2010 levels by 2050. Nuclear and large hydro become significant and exhibit shares of about 40% of total installed capacity by 2050. The contribution of renewables also increases to some 36% of total installed capacity in the energy mix.

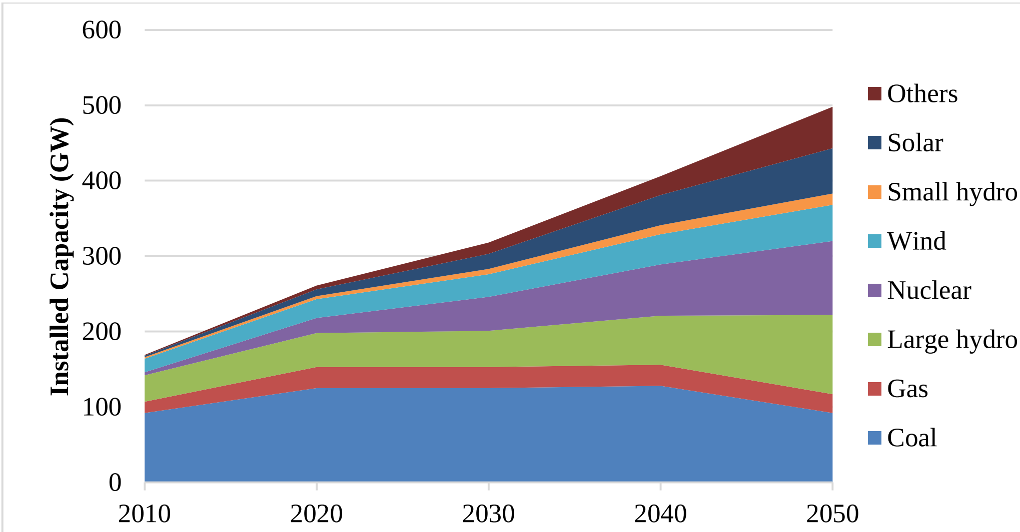

Fig. 10. Installed capacity in accelerated renewable energy technology with maximum savings potential scenario, by resource type.

4.6. CO_2 emissions in RET and ESP scenarios

The greenhouse gas (mainly CO_2) emission reduction from power plants is the ultimate aim for the policy-makers due to international pressure. The renewables have the potential not only to supply energy but to supply without environmental emissions. The above two developed scenarios show the substantial reduction in carbon dioxide from the Indian power sector if properly implied. Figure 11 shows the CO_2 emissions in the RET scenario with and without the energy savings potential, and ARET with and without the energy savings potential scenarios. For the maximum energy conservation potential with RET, about 1000 Mt of carbon dioxide have been reduced by the year 2050 which amounts to a reduction of about 42%. Interestingly, the GHG emission reduction starts from the base year 2010 but still shows an increasing pattern over the modeling period. From 2040 to 2050, it increases very quickly in comparison to previous periods.

The ARET scenario with the energy savings potential emission reduction is very significant and fast. In the base year 2010, the amount of CO_2 emission is 450 Mt, which has risen to 602 Mt by 2050. The reduction in CO_2 emission is 74%, compared to the reference scenario in 2050.

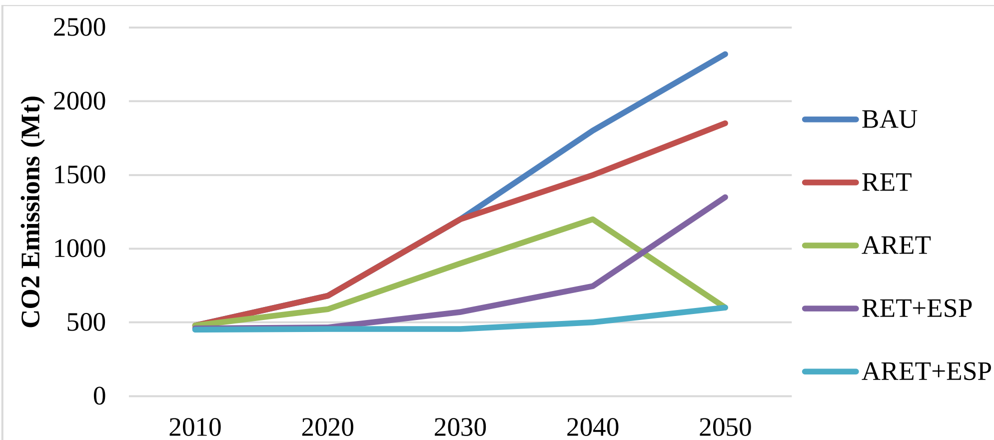

Fig. 11. Carbon dioxide emission in aggressive renewable technology and its various energy savings scenarios, 2010-2050.

5. Conclusions

India's fossil fuels are likely to last about 50 more years if the consumption pattern continues to grow at the existing rate With the uncertain and volatile nature of international crude prices (and possibly supplies), it is important that we look for alternatives to reduce this dependence. Therefore, we must expand and accelerate the RD&D efforts in renewable energy technologies so that we can secure supply of low-cost, clean, and sustainable energy sources. The renewable energy technologies have the potential to meet India's emerging energy needs. However, much action is still required for a rapid large-scale diffusion of renewable energy technologies, mitigating the staggering energy import-dependence of the country. This will require time-bound and planned research and development efforts to reduce their cost and improve their efficiency, and to make them reliable, long lived, and easily accessible.

In this study, the LEAP energy model is used to develop various scenarios and to find useful results. The reference scenario BAU shows that the current trend follows about 700 GW of installed capacity required by 2050. In the two alternative scenarios, namely RET and ARET, significant amounts of electricity are generated by renewables, and 21% and 74% CO_2, respectively, will be reduced by the year 2050. The renewable energy shares are more than 35% in the energy mix in both the alternative scenarios with energy savings potential in 2050. In the case of combining RET and ARET with the energy savings potential scenarios, energy demand has reduced to about 30% by the year 2050. The corresponding CO_2 reductions are 42% and 74%, respectively. This implementation of renewables and energy efficiency in the power sector will give India more energy independence in the future and will reduce the carbon dioxide emissions.

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