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# Introduction of an environmentally optimized energy scenario for the future of Indian power industry

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**Abstract.** Coal has made a wonderful contribution to the production of cheap electricity. Coal based power plants have been the backbone of world's electricity for a long time now. Coal while being cheap and easily available is also a source of various solid, liquid and gaseous effluents which are responsible for the environmental degradation. Environmental issues caused by coal need to be studied and analyzed, then a common global consensus must be formed. Efficient action must be taken against each and every type of pollutant that is produced by this particular industry. The research aims to provide a brief overlook of the environmental impact of India's coal-based power plants. The aim of this study is to introduce a novel environmentally feasible energy scenario for the future of Indian power sector which has been named as "OPES". OPES is mathematically simulated using the combination of GAMS and LEAP. OPES is simple to comprehend and can be reproduced easily for other case studies as well. Results show that OPES can help the Indian power sector to minimize its environmental impact without causing any problems in the energy supply.

**Keywords:** coal-based power production; environmental pollution; LEAP; GAMS; renewable energy

## 1. Introduction

Coal is a revolutionary substance which laid the foundations of the industrial revolution. Coal has made a significant and impressive contribution to industrial development but coal is also the source of various kinds of pollutants which tend to contaminate air, water, and land. Coal based power industry utilizes huge volumes of water and occupies a vast amount of land for its operation and maintenance.

Shahzad Baig and Yousaf (2017) states that coal will continue to remain the major energy source in various countries for the coming two decades as coal reserves are high in these nations, moreover it has been stated that coal is the most abundant energy source in our world. Jeon (2010) claims, that 50% of the global GHG emissions come from the combustion in power plants. Pokale (2012) states that thermal power plants damage the environment, human health and deteriorate the flora and the fauna with the exceedingly large amount of $SO_x$, $NO_x$ and SPM production. The energy sector has a severe impact on the environment due to the air emissions and waste

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generation, development of management based services is paramount (Mesjasz-Lech 2015). Guttikunda and Jawahar (2014), estimated the total annual emissions for the year 2010-2011 to be the following; 580 Kilotonnes for $PM_{2.5}$, 1200 Kilotonnes for PM10, 2100 Kilotonnes of $SO_2$, 2000 Kilotonnes of $NO_x$, 1100 Kilotonnes of CO, 100 Kilotonnes of VOCs and 665 million tonnes of carbon dioxide. According to Li *et al.* (2017), the power generation sector contributes 59.1% and 25.0% to $SO_2$and $NO_x$ emissions in India. Lu *et al.* (2011) states, that significant use of coal in India is responsible for the generation of large amounts of $SO_2$ and $NO_x$ and power sector is the largest consumer of coal in India.

Oskarsson and Bedi (2018), states that despite recent policy developments and environmental science expertise, air pollution in India have continued to worsen to the level that nearly all the citizens are under its effect. Mishra (2004), rates coal power plants to have a higher health risk than nuclear power plants of the same capacity. Gao *et al.* (2018), claims that a large portion of human population both in China and India are exposed to air pollution caused by anthropogenic activities mostly power generation. It has been estimated that power generation emissions contribute to 0.5 million death in China and 0.3 million in India. Gupta and Spears (2017) asserts the fact that Indian districts which have gained coal plants from 2005 to 2012 experienced an increase in reported cough.

Sen and Ganguly (2016) suggests the future of world energy to be based on renewable energy, energy efficiency, broader policies and also an appropriate mix of energy instruments is suggested as well. Hairat and Ghosh (2017) reviews the 100 GW solar power in India by 2022 and states that, considerably high amount of attention is being given to SPV technologies with CSP technologies being ignored moreover, in addition to this it has been stated that India's solar program is extensively import dependent which might compromise energy security. Dawn *et al.* (2019) states that India has taken strong steps in the promotion of wind energy moreover India has been included in the top 5 countries in the world for capacity additions, installations, creation of job opportunities in the renewable energy field. Mishra (2015) asserts that $CO_2$ emissions from India's coal power plants will be directly proportional with the growth of coal-fired power plants and the choice of future power plants technologies, moreover, factors such as future energy demand, renewable energy growth, cost of coal and environmental regulation would be paramount. Phasing out of coal power plants is quite a challenge for nations all over the world. Coal is becoming less popular as countries prefer using renewable energy for power production. According to theworldcoal.com, multiple countries have set coal phase out deadlines and the most prominent amongst them are the UK, Denmark, Canada and Germany. UK has approved October 2024 to be the starting date for limiting the amount of emissions from coal power plants. They also intend to close down the plants which do not have carbon capture technology. UK was the first country to officially commit to phasing out its coal operations in 2015. There has been a sharp decline in the usage of fossil fuels in power generation in UK since 2012 as well. Denmark has successfully reduced its overall emissions by reducing the usage of coal by 25% and simultaneously increasing the amount of renewable energy by 11.4%. In 2016 Canada announced that it would phase out all its coal power plants by 2030. Canada's energy policy also includes plans to ensure that 90% of its electricity demands are met by sustainable energy. On the other hand Germany plans to phase out its coal power plants by 2038. The phase out process is very significant as Germany has the largest fleet of coal power plants in Europe, with an installed capacity of 50 GW (Cassey 2020).

The purpose and aim of this research is to add on to the knowledge already provided by the esteemed researchers of this field. Early researchers have studied and analyzed various aspects of coal based power plants but very few have actually formulated a mathematically verified action plan. The authors intend to introduce an environmentally optimized energy scenario also known as "OPES". OPES uses linear optimization to optimize the emissions related to coal power production. It a novel policy based model which is completely based on environmental optimization of the power industry. A future energy based analysis has been provided by the authors, which includes a hypothesis regarding the growth and future of the Indian power sector. A solution has also been provided which has been simulated using GAMS and LEAP.

LEAP is a software used for analysis related to energy policy and climate change. This software has been developed by Stockholm Environment Institute. LEAP provides a long term emission graph of the scenarios using input data such as installed capacity and percentage share of generation. GAMS, is a high level modeling system for mathematical optimization. Authors used GAMS for the development of a novel environmentally feasible energy scenario namely OPES.

The data that GAMS provided was again simulated in LEAP. The results proved that OPES helped in reducing the power based emissions in India. The results provided by OPES were compared with a few other energy scenarios which have been formulated by certain research organizations. Emission results of all the scenarios were simulated in LEAP and were compared with OPES. OPES displays better results than all but one of the energy scenarios and provides a very realistic approach towards the solution of the problem.

When compared to earlier work done by the esteemed researchers, this paper provides a theoretical future policy of the coal power industry of India. This approach has been verified by development of a novel environmentally optimized energy scenario. The method used by the authors is conceptually easy to comprehend. It can easily be reproduced for other case studies. The method is mathematically optimized using linear optimization and provides a long term evaluation. The approach taken by the authors is realistic as it does not ask for complete phasing out of coal power plants at once. It proposes to restrict any further growth of the coal power industry and encourages extensive development of renewable energy. A sudden and immediate phasing out of the coal power plants would be difficult for a country like India, as India is heavily dependent of coal for its energy needs. It generates a huge amount of revenue and millions of lives are dependent on it directly or indirectly. Stopping the growth of this sector followed by gradual phasing out of power plants would dampen the shock. Extensive development of renewable energy would help in balancing the energy demand and would also help in providing jobs. Other benefits related to this approach are domestic infrastructure development and investment attraction.

OPES illustrates that emissions can be reduced if renewable energy is promoted while the growth of coal power industry is kept in check. The current policies of Indian power industry which have been represented by BERK-Baseline are shown to be environmentally inefficient. OPES betters the current policies of India power industry and illustrates a tremendous decrease in the overall emissions.

## 2. Indian electricity scenario

Provision of electricity is mandatory for the growth of Indian energy and economy; in 2013 the national demand was 897 TW/hr, this number was 376 TW/hr in 2000, these 13 years have seen an average annual growth rate of 6.9%. Electrical energy is 15% of total energy consumption in India and India with 1/6th of the global population consumes about 1/12th of the global power output (IEA, India Energy Outlook - World Energy Outlook Special Report 2015). As per CEA, India has a power generation capacity of about 344 GW with coal contributing as the main power

| Fuel | MW | % of Total |
|---|---|---|
| **Total Thermal** | 2,21,803 | 64.3% |
| Coal | 1,96,098 | 56.9% |
| Gas | 24,867 | 7.2% |
| Oil | 838 | 0.2% |
| **Hydro** (Renewable) | 45,457 | 13.2% |
| **Nuclear** | 6,780 | 2.0% |
| **RES*** (MNRE) | 70,649 | 20.5% |
| **Total** | **344,689** | |

* Installed capacity in respect of RES (MNRE) as on 30.06.2018.

Fig. 1 Installed capacity – India (Power 2018)

production source with an installed capacity percentage share of about 57%. (Power 2018). Fig. 1 illustrates the fuel based generation capacity of the Indian power industry.

India despite having an increase in capacity and generation, faces some serious issues as far as the structural shortage is concerned, both residential and industrial consumers have faced issues during peak demand time, around ½ of the industrial firms in India have faced cuts of 5 hrs/week. Currently, about 240 million people in India lack access to electricity which is about 20% of the population (Chandra Bhushan 2015), although this figure can be around 25% (IEA, India Energy Outlook - World Energy Outlook Special Report 2015).

### *2.1 Environmental analysis*

#### *2.1.1.1 Resources utilized*

India's coal power industry is a resource-intensive industry. Some of the resources which are extensively used in the coal power sector have been mentioned as followed:

#### *2.1.1.2 Land*

Land is a critically important resource which is utilized by coal power plants. Land usage in a coal power plant is governed by the following factors; unit size, generation capacity, type of coal (indigenous or imported), coal storage, location, water storage capacity and type of condenser cooling system. Coal power plants also utilize a large amount of land for ash disposal and water sourcing. India is increasing its fleet of coal power plants. This would mean more direct and indirect utilization of land. This is a serious issue as India is home to 17.5 percent of world's population but covers only 2 percent of world's total land. Not to forget that almost no statistics have been provided by the Indian Government as far as land utilization of this sector is concerned. CEA's 2010 guidelines recommend about 1.09 acre/MW as maximum land use intensity per MW for new coal plants, according to (Chandra Bhushan 2015); the average land use intensity was above 1.8 acre/MW, in its study GRP even found a few plants using as much 8-10 acre/MW. (Chandra Bhushan 2015).

Estimated annual health impacts and health costs due to PM pollution from coal-fired power plants in India, 2011-12

| Effect | Health impacts | Health costs (crores of Rupees) [a] | Health costs (million USD) [b] |
|---|---|---|---|
| Total premature mortality | 80,000 to 115,000 | 16,000-23,000 | 3300-4600 |
| Child mortality (under 5) | 10,000 | 2100 | 420 |
| Respiratory symptoms | 625 million | 6200 | 1200 |
| Chronic bronchitis | 170,000 | 900 | 170 |
| Chest discomforts | 8.4 million | 170 | 35 |
| Asthma attacks | 20.9 million | 2100 | 420 |
| Emergency room visits | 900,000 | 320 | 60 |
| Restricted activity days | 160 million | 8000 | 1600 |

a – one crore = 10 million
b – using conversion rate of 1 USD = 50 Rupees

Fig. 2 Estimated annual health impacts and costs due to PM from coal power plants in India, 2011-12 (Greenpeace)

#### *2.1.1.3 Water*

Water is inextricably connected to the energy sector. Nearly 90 percent of the water withdrawal by the energy sector is for power generation. Given the coal's dominance in the Indian power sector, coal power plants account for the maximum amount of water withdrawal. Water is used by the coal power plants for the following purposes; boiler water, cooling water, cycles of concentration, ash handling and other uses such as service water and dust suppression at the coal yard. Indian coal power plants are among the worst when it comes to water consumption, the reason behind it is that India still uses old and outdated coal power plants which use OTC or once through cooling systems. These power plants do not have a cooling tower and thus they withdraw a huge amount of water directly from the source. It has been estimated that the water withdrawal of power plants can be 70-200 $m^3$/MWh. In India these OTC systems are barely 17 percent of the installed capacity but they are responsible for 90 percent of the water withdrawal. According to the GRP study, the average specific water consumption of the analyzed plants was 4 $m^3$/MWh (Chandra Bhushan 2015). The International Renewable Energy Agency (IRENA) has estimated that 85 percent of the country's power generation relies on freshwater. Such an enormous usage of freshwater creates a huge amount of pressure directly on the ecology (Earth 2018, IRENA 2018).

#### *2.1.1.4 Greenhouse gases*

According to IRENA, in the year 2016, coal combustion was responsible for an average emission of 990 $gCO_2$/kWh (IRENA 2018). India's $CO_2$ emissions have been on a rise as the year 2017 witnessed a 4.6% increase in the average GHG emissions, India is ranked 4th in the list of the world's largest $CO_2$ emitters with an average annual emission of 2.4 billion tonnes (Brief 2018).

### *2.1.2 Air, Water pollution and effluents*

#### *2.1.2.1 Wastewater generation*

Wastewater discharge and water pollution from a coal power plant is directly related to the amount of water consumed by the plant. Cooling tower blow-down and ash handling wastewater from the ash ponds are the main wastewater streams of a coal power plant. As already discussed, Indian coal power plants utilize huge volumes of water thus it is evident that these power plants waste and contaminate a lot of water as well. An ideal power plant is a zero liquid discharge entity. Coal power plants are the main source of water pollution in India due to improper handling of ash, faulty storage and disposal systems. GRP estimates that Indian coal power plants generate about 1-2 $m^3$/MWh of wastewater on an average. GRP states that plants with a consumption of 2$m^3$/MWh have almost zero or low discharge but as the consumption increases almost half of the water is spilled out as waste discharge, plants consuming 4 $m^3$/MWh have an SWD of 1.5 and this figure reaches 3.5 for the plants consuming 7 $m^3$/MWh (Chandra Bhushan 2015).

#### 2.1.2.2 Ash slurry

According to SPCBs, approximately 31 power plants are noncompliant as far as ash related issues are concerned, 20 power plants have been recorded to cause ash slurry pollution and 10 power plants are directly disposing of ash and waste into water bodies. (Mishra 2018).

#### 2.1.2.3 Fly ash

According to MOP, GOI, fly ash quantities might reach 600 million tonnes in 2031-32 (Wealthy Waste). Ash utilization in India in the year 2014-15 was about 55.69% which is equal to 102.54 million tonnes (CEA, National Electricity Plan 2016).

#### 2.1.2.4 Air pollution

According to the Performance Review of Thermal Power Plants, 2014-15, out of the 406 units (88 coal power plants), 317 units complied with SPM norms, while 67 units were rated as having high SPM stack emissions and 22 as extremely high (more than 350 μg/$m^3$). Despite this report and this mentioned figure, GRP study stated that SPM stack data is not reliable as it found that the SPM emission could range from 24 – 6290 μg/$m^3$ (Authority 2014).

According to GRP, the average PM emissions in India in the year 2011-12 were about 1 kg/MWh which could be integrated on a national level to be round about 0.7 million tonnes, if the trends continued this figure would reach 1.54 MTPA in 2021-22 which would be far higher than the global average. Coal power industry generated 5.5 Million tonnes of $SO_2$ in 2011-12 (8.5 kg of $SO_2$ per MWh) which may reach up to 13 Million Tonnes by 2021. India produced 3.3 Million tonnes of $NO_x$ in the year 2011-12 (7 kg/MWh) and this figure was predicted to reach 7.8 million tonnes by the end of 2022 (Chandra Bhushan 2015).

According to Arctic Monitoring and Assessment Program (2008), India was the world's 2nd largest emitter of mercury with a total emission reaching 172 tonnes/year, coal power plants were responsible for 87% of these 172 tonnes. A separate study by Mukherjee (2010) puts total emissions from India for 2004 at 222–310 tonnes/year; GRP predicted this figure to reach 686 tonnes by 2021-2022 (Pirrone *et al.* 2010, Sloss 2012).

### 2.1.3 Health effects

As can be observed in the figure below, coal power plants were responsible for 80,000 – 115,000 deaths in the year 2011-12 and also resulted in 3.3-4.6 billion dollars of health costs. Million were affected by asthma and other health ailments (Greenpeace, Geonka and Guttikunda 2013). It has been estimated that this figure would rise to 186500 – 229500 with about 42.7 million asthma cases in 2020 (Conversation Trust 2014).

Table 1 Air Based Emissions (CPCB 2015)

| | Installed before 31 December 2003 | | Installed 1 January 2004 – 31 December 2016 | | Installed from 1 January 2017 |
|---|---|---|---|---|---|
| Capacity | Smaller than 500 MW | 500 MW and above | Smaller than 500 MW | 500 MW and above | Any size |
| PM, mg/Nm$^3$ | 100 | 100 | 50 | 50 | 30 |
| $SO_2$, mg/Nm$^3$ | 600 | 200 | 600 | 200 | 100 |
| $NO_x$, mg/Nm$^3$ | 600 | 600 | 300 | 300 | 100 |
| Mercury, mg/Nm$^3$ | - | 0.03 | 0.03 | 0.03 | 0.03 |

Table 2 Emission limits for existing and new power plants in a few selected countries/regions (Centre 2016)

| Country | $SO_x$, μg/m$^3$ | | $NO_x$, μg/m$^3$ | | Pm $_{2.5}$, μg/m$^3$ | |
|---|---|---|---|---|---|---|
| | Existing | New | Existing | New | Existing | New |
| China | 200 - 400 | 100 | 200 | 100 | 30 | 30 |
| EU | 200 - 400 | 150 - 400 | 200 – 450 | 150 - 400 | 20 - 30 | 10 - 20 |
| USA | 160- 640 | 160 | 117 - 640 | 117 | 23 | 23 |
| Indonesia | 750 | 750 | 850 | 750 | 150 | 100 |
| South Africa | 3500 | 500 | 1100 | 750 | 100 | 50 |
| Japan | - | - | 123 - 513 | 123 - 513 | 30 - 100 | 30 – 100 |
| Korea | 286 | 229 | 308 | 164 | 40 | 20 – 30 |
| Thailand | 700 - 1300 | 180 - 360 | 400 | 200 | 80 - 320 | 80 |
| Vietnam | 1500 | 500 | 1000 | 650 - 1000 | 400 | 200 |

### *2.1.4 Indian emission standards*

The latest emission limits for coal-fired power plants set by the Ministry of Environment, Forest and Climate Change and dated 7 December 2015, (CPCB 2015), but prior to that India had tremendously loose emission limits in fact no proper standards were available for $NO_x$, $SO_2$ and Mercury prior 2003.

#### *2.1.4.1 Air-based emissions*

Tables 1 and 2 illustrate the current air based emissions standards of India and a few selected countries. Fig. 3 displays the water consumption limits as issued by Central Pollution Control Board and Table 3 illustrates the liquid effluent limits.

#### *2.1.4.2 Water consumption*

Water consumption limits for thermal power plants

| | Existing plants | | New plants installed after 1 January 2017 |
|---|---|---|---|
| | With once-through cooling shall install cooling tower | With cooling towers | |
| Limit, m$^3$/MWh | 3.5 (within 2 years from date of publication of this notification) | 3.5 (within 2 years from date of publication of this notification) | 2.5 (and achieve zero waste water discharge) |

Fig. 3 Water consumption limits (CPCB 2015)

#### *2.1.4.3 Liquid effluents*

Table 3 Liquid Effluents Limits (Tonnesgia 2017, Authority 2014)

| Source | Parameter | Concentration mg/l |
|---|---|---|
| Condenser Cooling System | pH | 6.5 – 8.5 |
| Boiler Blow Down | Chlorine | 0.5 |
| | Suspended Solids | 100 |
| | Oil & Grease | 20 |
| | Copper | 1 |
| | Iron | 1 |
| Cooling Tower | Chlorine | 0.5 |
| | Zinc<br>Chromium | 0.2 |
| | Phosphate | 5 |
| Ash Pond | pH | 6.5 – 8.5 |
| | Suspended solids | 100 |
| | Oil & Grease | 20 |

## 3. Future policy analysis

India with a population of 1339 million people is currently the world's second most populated country. In the year 2010, 21% of India's population lived below the poverty line. India also ranks low on the HDI list and India's GDP per capita is also quite low for a country with such a vast and fast-growing economy (UNDP 2017).

India has witnessed an immense growth in the production of electricity. In 2007, India produced about 800 TWh of electrical energy. The next ten years saw a steep growth in the generation capacity as the figure reached 1497 TWh in 2017. India generated 1141 TWh using coal in the year 2017. Table 4 shows the energy production comparison by fuel for India and the world. India's share in the global coal-based electrical energy production is about 11.7% (BP 2018). The global average of access of electricity is 87.37%, but India lags behind in this section with about 84% of its population having access to electricity (Bank 2016).

It can concluded with the above mentioned facts that a percentage of the Indian population lives below the poverty line and a significant population of the Indian population does not have access to proper electricity. This could mean that there is a section of people who are economically very weak and have no access to electricity as well. India has a growing economy; in order to support and sustain the economic growth more electrical energy is needed.

Considering the facts we have discussed, we could reach the following conclusions:

1. There is section of the Indian population which is economically backward and does not have proper access to electricity.

2. India's growing economy needs electrical energy to sustain its growth.

3. India's growing population also requires electrical energy to achieve a proper socio-economic condition.

It is evident that provision of electricity to people who live in absolute poverty is a one-sided

Table 4 Electrical energy production comparison by fuel; World and India (2017) (BP 2018)

| S.no | Region | Oil | Gas | Coal | Nuclear | Hydropower | Renewable | Total |
|---|---|---|---|---|---|---|---|---|
| 1 | World | 883 | 5915 | 9723 | 2635 | 4059 | 2151 | 25551.3 |
| 2 | India | 10.3 | 75.5 | 1141.4 | 37.4 | 135.6 | 96.4 | 1497 |

investment for the government. People who barely manage to survive might not have the money to pay electricity bills. This means that the government must subsidize the power for this particular section of the population. It is quite possible that the government could use a fuel which would require minimum capital investment, low operation, and fuel costs. Therefore it is most likely that the Indian government would add more coal power plants. The provision of subsidized electricity using renewable energy to a section of the population which would not be able to pay for the electricity is not economically feasible. This would result in more pollution as the installed capacity of the coal fired power plants would keep on increasing.

As far as the pollution statistics are concerned, the global average of PM was 43.38 mg/Nm$^3$ in 2015. On the other hand, India's PM emissions have been on a rise for the last 15 years and in 2015 average PM emissions of India reached 74.37 mg/Nm$^3$. India's PM emissions are expected to reach 1.5 million tonnes by the end of 2021-22. A similar trend can be observed among other pollutants as well. India was emitting 2.2 Gigatonnes of $CO_2$ in 2015. Even after signing The Paris Agreement, India's $CO_2$ emissions didn't drop. India witnessed a 4.6% increase in GHG emissions in 2017. India is the world's leading emitter of $SO_2$ because of its enormous and ever-increasing coal power plants. Total global $SO_2$ emissions in the year 2010 were about 97 million tonnes out of which India contributed 5.5 million tonnes and this number is expected to reach 13 million tonnes by the end of the current decade. NOx emissions on the global level were reported to be 47.5 million tonnes in 2014. India emitted nearly 3.3 million tonnes in 2012 and this number was predicted to reach 7.8 by the end of 2022. India was responsible for 144 metric tonnes out of the global total of 700 metric tonnes of mercury emitted by the power sector. India's mercury emissions are expected to reach 686 metric tonnes by the end of 2022 (UNEP 2013, Fioletov *et al.* 2016, Hannach Ritchie 2019, NASA, Worldbank 2016, Brauer 2017).

India updated its national emission standards in 2015. Till 2015 India had no proper emission standards for $SO_2$ and $NO_x$. Emission limits had been prescribed for $CO_2$ and PM but these standards were not up to the mark. India has improved its emission standards for power plants which are to be installed after January 2017. These newly prescribed standards are even better than ones used in USA, Europe and far better than other Asian coal-using countries like Vietnam, Indonesia, Japan, and Korea. Despite this improvement, emission standards in India still face some severely problems. An overwhelming number of power plants in India have either been commissioned before 2003 or in between 2003 and 2015. It is surprising that the power plants commissioned before 2003 had no restrictive emission limits. Various countries have resorted to immediate phasing out of coal power plants. India cannot take such robust actions. India needs to phase out the coal power plants at a slow pace. This way India would buy itself enough time to replace the coal power plants with renewable energy options. Slow paced action would protect India from a sudden energy shock or an installed capacity crisis. Taking the mentioned discussion into consideration, authors suggest that stopping the coal power plant growth along with extensive development of renewable energy can be an optimal long term solution for India's energy and environmental needs. This way India would not have to worry about any energy-related issues since the current installed capacity would be feeding the demand. In the meantime India can increase its renewable energy capacity rigorously. This process would eventually lead to much lower energy-related emissions. The next section would support the analysis of the authors using simulation and optimization tools for the formation of an optimized energy scenario, OPES.

## 4. OPES simulation

Simulation section supports the analysis of the authors by introducing "OPES", "Optimized Energy Scenario", an environmentally feasible and optimal energy scenario for India. A series of simulations were performed in order to support the future policy analysis section, this simulation comprises of three parts, a concise description regarding these three parts has been provided as follows:

1. 6 different long term energy scenarios related to India were simulated in the LEAP software. The provided details were used and the scenarios were modelled and simulated in the LEAP environment and the emission trends related to these particular scenarios were plotted.
2. For the second section of the simulation process, GAMS was used, an emission-based objective function "OPES" was defined with certain constraints, this model was optimized using GAMS and certain results were obtained.
3. For the final stage of simulation, the results obtained from GAMS were modelled and simulated in LEAP as the seventh scenario; this optimized scenario was simulated and plotted alongside the earlier plotted scenarios. The comparison of these scenarios was then used to strengthen the theoretical analysis which the authors have provided in the future policy analysis section of the paper.

### *4.1 LEAP scenarios*

LEAP was initially used to simulate a number of different scenarios; these scenarios were taken from different researches that have been conducted by a number of organizations. The data related to these scenarios has been provided in Table 5. Table 6 illustrates the cumulative combined emissions of the mentioned energy scenarios, these emissions have been obtained by simulated the data in LEAP. The names of the scenarios and the respective organizations have been given below:

1. Current Scenario: This scenario provides the current installed capacity and the share of power generation in India; this scenario was formulated using the data provided by the Central Electricity Authority, India (CEA 2018).
2. TERI: TERI University predicts two scenarios in its report namely "Transitions in Indian Electricity Sector, 2017-2030"; these two scenarios are named as TERI-HRES or High renewable energy scenario and TERI-LRES or Low renewable energy scenario (Chauhan 2018).
3. EOL Berkley: E.O.L Berkley National Laboratory formulates three scenarios for the Indian power sector, namely, Baseline, Modestly Secure and Aggressively Secure. Baseline scenario simulates the capacity addition as has been reported in the 12$^{th}$ plan up to 2022 and same policies are continued till 2030, Modestly Secure scenario assumes 40 % share of renewable energy and finally Aggressively Secure assumes this percentage to reach 60% (Abhyankar 2013).
4. IEA-WEO: IEA defines a scenario named as New Policy Scenario (IEA, India Energy Outlook - World Energy Outlook Special Report 2015).

Table 5 Pre-defined energy scenarios details

| S.no | Scenario | Installed Capacity as per the fuel (MW) | | | | | | Power Generation Share as per the fuel (TWh) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Coal | Hydro | Gas | Nuclear | RES | Total | Coal | Hydro | Gas | Nuclear | RES | Total |
| 1. | Current Scenario (2017-18) | 197172 | 45923 | 24897 | 6780 | 69020 | 344,002 | 986,591 | 126 | 50 | 38 | 101 | 1,303 |
| | | | | | | | | 75% | 9.6% | 3.8% | 2.9% | 7.8% | |
| 2. | TERI HRES | 218207 | 70,131 | 29969 | 14380 | 853661 | 1,186,348 | 1815 | 324 | | | 1,102 | 3241 |
| | | | | | | | | 56% | 10 % combined | | | 34% | |
| 3. | TERI LRES | 474855 | 70,131 | 29969 | 14380 | 284147 | 873,482 | 2,354 | 214 | | | 460 | 3057 |
| | | | | | | | | 77% average | 4-10 % (7% average) | | | 16% | |
| 4. | BERK BASE | 410000 | 79000 | 56000 | 54000 | 138000 | 738,000 | 2270 | 226 | 185 | 206 | 358 | 3245 |
| | | | | | | | | 69.9% | 6.9% | 5.7% | 6.3% | 11% | |
| 5. | BERK MODEST | 250,000 | 79,000 | 56,000 | 54,000 | 431,000 | 809,000 | 1322 | 226 | 185 | 206 | 1307 | 3245 |
| | | | | | | | | 40.7% | 6.9% | 5.7% | 6.3% | 40.2% | |
| 6. | BERK AGG | 197,000 | 79,000 | 56,000 | 54,000 | 666,000 | 960,000 | 760 | 226 | 93 | 206 | 1960 | 3245 |
| | | | | | | | | 23.4% | 6.9% | 2.8% | 6.3% | 60.4% | |
| 7. | IEA NPS | 329,000 | 83,000 | 76,000 | 24,000 | 221,000 | 746,000 | 1698 | 253 | 262 | 165 | 439 | 2848 |
| | | | | | | | | 59.6% | 8.8% | 9.1% | 5.7% | 15.4% | |

Table 6 Cumulative Combined Emissions of the mentioned energy scenarios

| | **Scenarios** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026** | **2027** | **2028** | **2029** | **2030** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **BERK AGGRESSIVE** | 327 | 331 | 334 | 337 | 338 | 337 | 335 | 330 | 324 | 315 | 303 | 287 | 269 | 246 |
| 2 | **BERK BASELINE** | 327 | 348 | 370 | 394 | 419 | 446 | 475 | 505 | 538 | 572 | 609 | 648 | 690 | 734 |
| 3 | **BERK MODEST** | 327 | 337 | 348 | 358 | 368 | 378 | 387 | 395 | 403 | 411 | 417 | 422 | 425 | 427 |
| 4 | **HRES TERI** | 327 | 343 | 359 | 377 | 395 | 414 | 433 | 441 | 430 | 418 | 418 | 418 | 418 | 418 |
| 5 | **IEA NEPS** | 327 | 344 | 362 | 381 | 401 | 422 | 444 | 467 | 490 | 515 | 541 | 568 | 596 | 626 |
| 6 | **LRES TERI** | 327 | 350 | 376 | 403 | 432 | 463 | 496 | 530 | 558 | 585 | 612 | 703 | 754 | 808 |
| | **Total** | 1,960 | 2,053 | 2,150 | 2,250 | 2,353 | 2,460 | 2,570 | 2,670 | 2,743 | 2,816 | 2,900 | 3,047 | 3,152 | 3,259 |

### *4.1.1 Leap simulation*

#### *4.1.1.1 Assumptions:*

i) The population of India in the base year of 2017 has been taken to be 1339 million with the growth rate of 1.1% assumed to stay constant till the year 2030 (Power 2018).

ii) According to the National Electricity Plan, the average electricity consumption per capita in India was 1.01 kWh, the Indian Government plans to increase this figure by three folds till 2040.

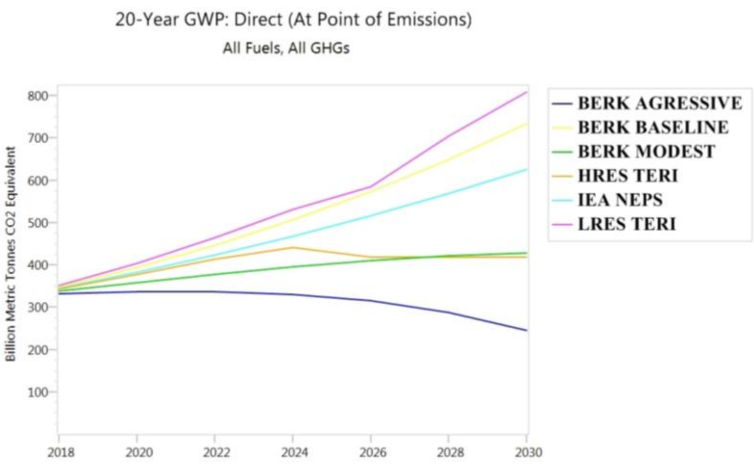


Fig. 4 Cumulative emissions of pre-defined energy scenarios (without OPES)

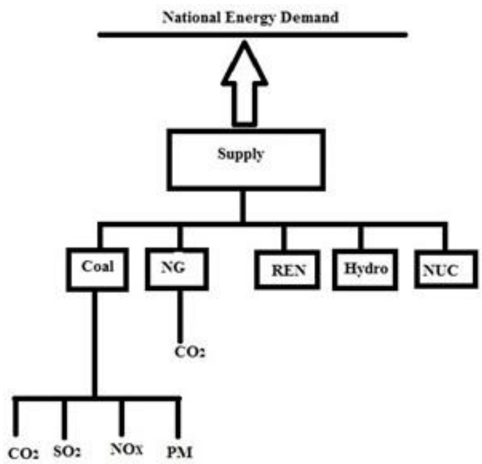


Fig. 5 Basic structure of the Indian power industry

(GlobalTransmission 2017, Indiatimes 2017).

iii) The total energy consumption has been calculated as a product of the above-mentioned variables i.e., population and average energy consumption.

Total Demand = Average per Capita consumption [Thousand kWh]* Population[Million People]

The NEP projects the CAGR for the demand projections to increase at a rate of 7.18% in one scenario and 6.18% in another scenario; we assumed a round figure of 7% for the total energy consumption (CEA 2018).

#### *4.1.2 Optimized energy scenario*

##### *4.1.2.1 System structure*

A structure has been presented which represents the power generation industry of India along with the supply system containing various fossil and non-fossil fuels.

Coal, NG, REN, Hydro, and NUC represent the fuels Coal, Natural Gas, Renewable sources and Hydro-electricity respectively.

#### *4.1.3 Model formation*

##### *4.1.3.1 Parameters*

i) Time Period: the time period has been defined from 2017 -2030

ii) Energy Demand: "Dem(t)", assumed to increase with a percentage of 7% with the base value equal to 1303 TWh i.e., the value for the year 2017 (Power 2018).

iii) Emissions of non-fossil fuel-based power generation: the emission factors related to the non-fossil fuels have been taken equal to zero and thus are constant.

iv) EMISR(t) Emissions of Renewable sources

v) EMISNUC(t) Emissions of Nuclear energy

vi) EMISH(t) Emissions of Hydro electricity

vii) Average Weight factors: The weighted average emission factor describes the average pollutant emitted per unit of electricity generated in the grid. It is calculated by dividing the absolute emissions of all power stations in the region by the region's total net generation. (CEA 2017). The average weight factors have been taken from the reports, (CEA 2017), (Chandra Bhushan 2015) and have been assumed to stay constant and are as follows:

i) Coal – CO2 – 0.99 t/MWh = 0.99 mt/TWh

ii) Coal – SO2 - 8.5 kg/MWh = 0.0085 mt/TWh

iii) Coal – NOx – 5.3 kg/MWh = 0.0053 mt/TWh

iv) Coal – PM – 1 kg/MWh = 0.001 mt/TWh

v) Gas – CO2 – 0.46 t/MWh = 0.46 mt/TWH

vi) ACC(t) Average Weight Factor of Co2 in Coal Power Plants

vii) ACS(t) Average Weight Factor of SO2 in Coal Power Plants

viii) ACN(t) Average Weight Factor of NOx in Coal Power Plants

ix) ACP(t) Average Weight Factor of PM in Coal Power Plants

x) ANC(t) Average Weight Factor of Co2 in Natural Gas Plants;

##### *4.1.3.2 Variables*

i) Supply: Summation of the energy generated by the power industry

ii) Emissions: GAMS was used for the optimization of the emissions that are generated by the fossil fuels in the process of electricity generation, because of the poor availability of the data only major pollutants were taken into consideration. EMISC(t) Emission related to Coal

- EMISNG(t) Emission related to Natural Gas
- CCO2(t) Emissions of CO2 for Coal
- CSO2(t) Emissions of SO2 for Coal
- CNOx(t) Emissions of NOx for Coal
- CPM(t) Emissions of PM for Coal
- NCO2(t) Emissions of CO2 for NG

#### *4.1.4 Objective function and equations*

Hashim *et al.* (2005), defines an environmental mode for an optimization model with the aim of minimizing CO2 emissions, the objective function used is min $Z_2 = \sum CO_{2ij}E_{ij}$. In the model we have defined, the product of total energy generated and the weighted average emission factor has been used for the calculation of the total emissions as defined by (CEA 2017). The equations and the objective function are as follows:

1. Objective Function: Min TotalEmis $=\sum_{2017}^{2030}(EMIS(t))$
2. Emission equation = EMIS(t)=EMISC(t)+EMISR(t)+EMISNUC(t)+EMISNG(t)+EMISH(t)
3. Fuel emissions

i.) Coal emissions= EMISC(t)=CCO2(t)+CNOx(t)+CSO2(t)+CPM(t)

ii.) Gas emissions =EMISNG(t)=NCO2(t)

4. Individual Fuel based emissions[†]:

i) Coal $CO_2$ = (*Average Weight Factor for Coal for CO2* × *Total Coal based generation*)

ii) Coal $SO_2$ = (*Average Weight Factor for Coal for SO2* × *Total Coal based generation*)

iii) Coal-$NO_x$= (*Average Weight Factor for Coal for NOx* × *Total Coal based generation*)

iv) Coal-PM= (*Average Weight Factor for Coal for PM* × *Total Coal based generation*)

v) Gas-$CO_2$= (*Average Weight Factor for Coal for CO2* × *Total Coal based generation*)

#### *4.1.4.1 Constraints*

The minimization of the objective function is subjected to the following constraints:

1. Demand and supply

The total demand should be less than or equal to the supply provided by the fuel based power generation.

$$\sum_{2017}^{2030} Demand \leq \sum_{2017}^{2030}\{Coal(t) + HYD(t) + NUC(t) + Gas(t) + REN(T)\}$$

2. Policy and fuel based constraints:

i.) In the year 2017 India generated about 986 TWh of electricity from Coal, according to the NEP, India plans to add another 67,655 MW to the overall Coal installed capacity while removing 22716 MW of older coal plants [NEP CEA]. OPES uses the amount coal-based generation in the year 2017 as a constraint i.e., 986 TWh would be taken as the minimum amount of electricity produced using coal and the power generation using coal would not get decrease than this proposed amount. (Power 2018)

$$\sum Coal(t) \geq 986$$

ii) India vision care proposes the growth of Nuclear and Hydroelectricity reach up to 165 and 254 TWh respectively with a growth rate of 8 and 3% respectively (Power 2018, IEA 2015).

$$\sum NUC(t) \leq 165, \sum HYD(t) \leq 265$$

iii) The amount of power generated using Gas in the year 2017 was about 50 TWh, as was done in the case of coal; this figure would be taken as the minimum amount of power generated using Natural Gas (Power 2018).

$$\sum Gas(t) \geq 50$$

[†] The Unit for Average Weight Factor is million tonnes/Twh and Coal based Generation is Twh

Table 7 GAMS results for OPES

| S.no | Year / Fuel | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Demand | 1394 | 1491 | 1596 | 1707 | 1827 | 1955 | 2092 | 2238 | 2395 | 2563 | 2742 | 2934 | 3140 |
| 2 | Coal | 986 | 986 | 986 | 986 | 986 | 986 | 986 | 986 | 986 | 986 | 986 | 986 | 986 |
| | | 70.7 | 66.1 | 61.7 | 57.7 | 53.9 | 50.4 | 47.1 | 44.7 | 41.1 | 38.4 | 35.9 | 33.6 | 31.4 |
| 3 | Nuclear | 41 | 44 | 47 | 51 | 55 | 60 | 65 | 70 | 75 | 82 | 88 | 95 | 103 |
| | | 2.9 | 2.9 | 2.9 | 2.9 | 3 | 3 | 3.1 | 3.1 | 3.1 | 3.1 | 3.2 | 3.2 | 3.2 |
| 4 | Gas‡ | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | | 3.5 | 3.3 | 3.1 | 2.9 | 2.7 | 2.5 | 2.3 | 2.2 | 2 | 1.9 | 1.8 | 1.7 | 1.5 |
| 5 | Hydro§ | 129 | 133 | 137 | 141 | 146 | 150 | 154 | 159 | 164 | 169 | 174 | 179 | 185 |
| | | 9.2 | 8.9 | 8.5 | 8.2 | 7.9 | 7.6 | 7.3 | 7.1 | 6.8 | 6.5 | 6.3 | 6.1 | 5.8 |
| 6 | REN** | 187 | 277 | 374 | 478 | 589 | 708 | 836 | 972 | 1119 | 1275 | 1443 | 1623 | 1815 |
| | | 13.4 | 18.5 | 23.4 | 28 | 32.2 | 36.2 | 39.9 | 43.4 | 46.7 | 49.7 | 52.6 | 55.3 | 57.8 |

iv) India produced about 100 TWh of electricity using various types of renewable energy resources, this amount has been taken to be the minimum level of electricity produced using renewable energy in the optimization model (Power 2018).

$$\sum REN(t) \geq 100$$

#### *4.1.5 Results*

Results obtained have been shown in Table 7,

Policy based assumptions related to installed capacities for 2030 for LEAP based simulation of OPES;

1. In the year 2017, India's total coal-based installed capacity was 197172 MW, according to the National Electricity Plan, 2017-2022, for a demand rate of 7% and above, about 19700 MW would be added along with 47855 MW of coal capacity, in addition to this about 25572 MW of coal-based capacity would face retirement, CEA also estimates that no further coal capacity would be added till 2027 (CEA 2018).

2. We can vividly come to the conclusion that India's coal-based capacity would be about round about 240,000 MW.

3. According to the IEA website and the NEP, In 2027 India aims to have 275 GW installed capacity of solar and wind, 72 GW of hydro and 15 GW of nuclear (IEA 2018).

4. India plans to add another 406 MW to its Gas based installed capacity which is 2017 was about 25 GW, the change seems to be highly insignificant and no clear policy based efforts are

‡ Natural Gas

§ Hydro – electricity

** Renewable Energy

Table 8 OPES percent share data 2017-2030

| S.No | Branches | 2018 | 2020 | 2022 | 2024 | 2026 | 2028 | 2030 |
|---|---|---|---|---|---|---|---|---|
| 1 | Renewable | 13.4 | 23.4 | 32.2 | 39.2 | 46.7 | 52.6 | 57.8 |
| 2 | Nuclear | 2.9 | 2.9 | 3.0 | 3.1 | 3.1 | 3.2 | 3.2 |
| 3 | Natural Gas | 3.5 | 3.1 | 2.7 | 2.3 | 2.0 | 1.8 | 1.5 |
| 4 | Coal Steam | 70.7 | 61.7 | 53.9 | 47.1 | 41.1 | 35.9 | 31.4 |
| 5 | Hydro | 9.2 | 8.5 | 7.9 | 7.3 | 6.8 | 6.3 | 5.8 |

Table 9 OPES installed capacity 2017-2030

| S.No | Branches | 2018 | 2020 | 2022 | 2024 | 2026 | 2028 | 2030 |
|---|---|---|---|---|---|---|---|---|
| 1 | Renewable | 86.4 | 117.8 | 149.2 | 180.7 | 212.1 | 243.6 | 275.0 |
| 2 | Nuclear | 7.4 | 8.7 | 9.9 | 11.2 | 12.5 | 13.7 | 15.0 |
| 3 | Natural Gas | 25.3 | 26.1 | 26.8 | 27.6 | 28.4 | 29.2 | 30.0 |
| 4 | Coal Steam | 199.5 | 206.2 | 213.0 | 219.7 | 226.5 | 233.2 | 240.0 |
| 5 | Hydro | 47.5 | 51.6 | 55.7 | 59.7 | 63.8 | 67.9 | 72.0 |

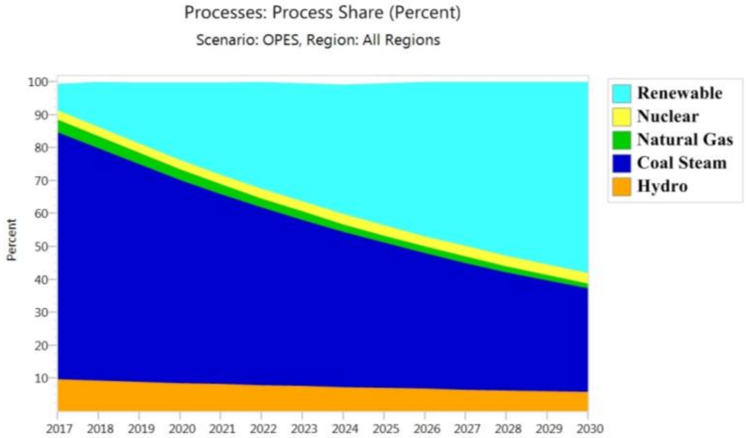


Fig. 6 OPES process share 2017-2030

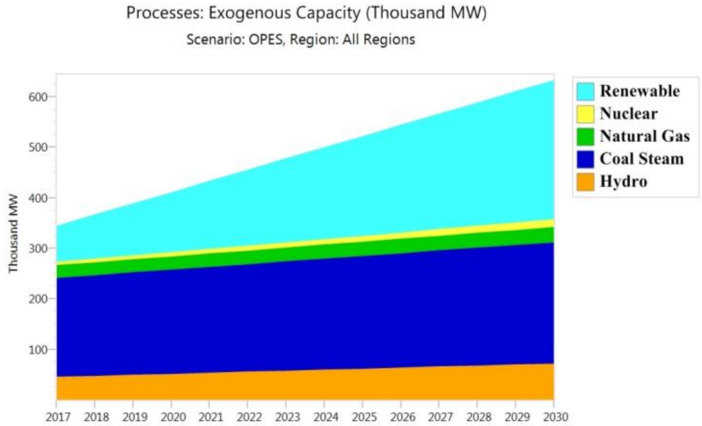


Fig. 7 OPES installed capacity 2017-2030

visible, so we generously assume that this figure might reach 30 GW by the end of 2030.

### *4.2 LEAP based verification of the optimized energy scenario*

The data obtained from GAMS OPES and the policy based installed capacity development was used to develop and simulate the OPES in LEAP software, the data has been shown in Table 8 and Table 9.

### *4.3 Final results*

The results of the simulation of OPES along with the earlier emission results have been provided below in Table 10 and Fig. 8.

Table 10 Emission Comparison of all energy scenarios including OPES

| S.No | Scenarios | 2018 | 2020 | 2022 | 2024 | 2026 | 2028 | 2030 |
|---|---|---|---|---|---|---|---|---|
| 1 | BERK AGGRESSIVE | 331.10 | 336.72 | 337.00 | 330.30 | 314.58 | 287.37 | 245.67 |
| 2 | BERK BASELINE | 347.78 | 393.98 | 446.28 | 505.46 | 572.42 | 648.17 | 733.85 |
| 3 | BERK MODEST | 337.31 | 358.02 | 377.66 | 395.47 | 410.52 | 421.62 | 427.31 |
| 4 | HRES TERI | 342.79 | 376.86 | 413.61 | 441.34 | 418.32 | 418.32 | 418.32 |
| 5 | IEA NEPS | 344.09 | 381.30 | 422.08 | 466.67 | 515.32 | 568.27 | 625.75 |
| 6 | LRES TERI | 350.32 | 402.73 | 462.96 | 530.37 | 584.87 | 703.24 | 808.37 |
| 7 | OPES | 334.78 | 338.91 | 336.91 | 330.09 | 319.18 | 305.99 | 291.43 |
| | Total | 2,388.17 | 2,588.53 | 2,796.50 | 2,999.70 | 3,135.20 | 3,352.98 | 3,550.71 |

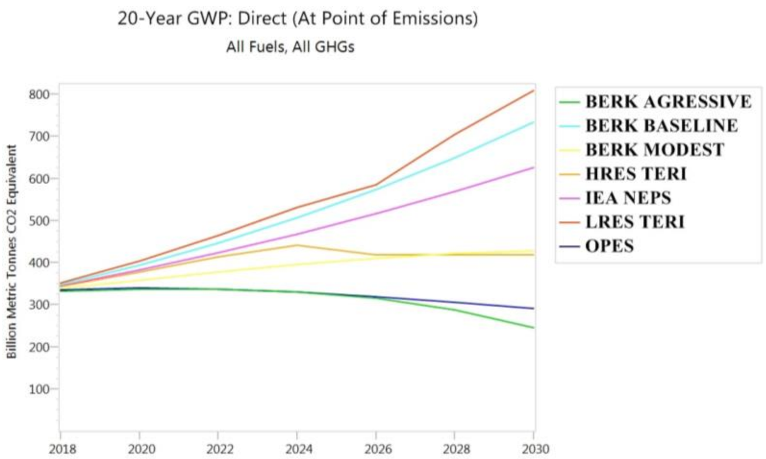


Fig. 8 All energy scenarios emission trends including ORES

### *4.4 Highlights of OPES*

OPES, optimized energy scenario, is a novel energy projection scenario developed for the fuel based emissions of the Indian power sector. The scenario is optimized using GAMS and linear optimization. Tables 8 and 9 illustrate the data that was used as the input data for OPES in LEAP, figure 5 illustrates the LEAP emission simulation of the pre defined energy scenarios, Figures 6 - 7 simulate the changes in the respective fields of installed capacity and process share from 2017-2030 for OPES. Table 10 and Fig. 8 display the final comparative results that were obtained from the LEAP based emission projection of OPES.

The main results related to OPES and its emission trends have been mentioned as follows:

1. OPES projects Coal and Natural Gas based power generation to stay constant over the analyzed time period.
2. Nuclear and Hydro based power generation has been projected to increase linearly at rates of 8 and 3 percent respectively.
3. Renewable energy based power generation experiences a tremendous change; increasing from 13.4% in 2017 to 57.8% in 2030.
4. LEAP validates the emission based accuracy of OPES as can be clearly observed in Fig. 8.
5. Emissions related to OPES observe a constant downward trend.
6. Emission values for OPES in 2018 are 334 billion metric tonnes of $CO_2$, this figure reduces to 291 billion metric tonnes in 2030.
7. The only energy scenario which has better results than OPES is the BERK AGG scenario, although BERK AGG witnesses a slight increase in emission between years 2018-2022 OPES reduces emissions without having any increase during the complete time period.

#### *4.4.1 OPES novelty*

1. Mathematically optimized using linear optimization in GAMS optimization software.
2. Takes into account all emissions i.e., GHG emissions along with $SO_2$, $NO_{x,}$ and PM.
3. Provides the fuel based power generation results for each year starting from the base year.
4. Uses average weight factor methodology for calculation of the approximate amount of emissions for the net electricity generation of the country/region.
5. Simple and easy to use and comprehend
6. Policy-based assumptions can be easily taken into account e.g., demand rates, fuel-based generation constraints, etc.
7. Accurate emission and generation data is a pre-requisite for solving optimization issues using ORES
8. OPES is a purely emission based energy model and cost-benefit analysis has not been added since the dissertation did not include financial issues or constraints.
9. The most significant quality of OPES is that it betters the BERK BASELINE scenario considering that fact that both these scenarios are based on the same base of current Indian power sector policies.

OPES proves mathematically that the current Indian power sector based policies are environmentally infeasible as was seen by its comparison with BERK BASELINE, but also confirms that these policies can be managed to produce results that would satisfy the current and future power needs while having a minimal detrimental effect on the environment.OPES is an overall moderate energy scenario as it does not fully exclude coal and natural gas from the energy politics but regulates them so that the overall growth is maintained and promotes renewable energy based power generation. Using the policy as simulated by OPES, Indian power sector can reduce the emissions effectively in the next decade by increasing renewable energy and stopping the growth of coal power industry.

## 5. Conclusions

The main conclusion of this research is the development of LEAP and GAMS based energy scenario, OPES. OPES quite clearly illustrates that emissions can be reduced if renewable energy is promoted while the growth of coal power industry is kept in check. The current policies of Indian power industry which have been represented by BERK-Baseline are shown to be extremely inefficient environmentally. OPES betters the current policies of India power industry and illustrates a tremendous decrease in the overall emissions while maintaining a certain amount of fossil fuel based industry by checking its growth. In addition to the mentioned facts, India has not provided any standards for land use, water withdrawal water pollution, and thermal pollution. India lacks proper laws for making the emission standards obligatory, no legal or financial action has been mentioned against the non-complying parties, and moreover reporting of pollution emissions is weak, improper and haphazard.

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