

RESEARCH ARTICLE



OPEN ACCESS

Received: 01.05.2021

Accepted: 25.09.2021

Published: 18.10.2021

Citation: Vaidyanathan G (2021) Electricity Generation Options for India-A Critical Evaluation . Indian Journal of Science and Technology 14(33): 2684-2710. <https://doi.org/10.17485/IJST/v14i33.gv>

* **Corresponding author.**

ganesan.vaidyanathan@gmail.com

Funding: Invited article, article processing charge (APC) is exempted

Competing Interests: None

Copyright: © 2021 Vaidyanathan. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Published By Indian Society for Education and Environment ([iSee](https://www.indjst.org/))

ISSN

Print: 0974-6846

Electronic: 0974-5645

Electricity Generation Options for India-A Critical Evaluation

G Vaidyanathan^{1*}

¹ Outstanding Scientist & Former Group Director, Department of Atomic Energy, Kalpakkam, India

Abstract

Objectives: This review is to study the electricity generating energy sources in the world at large and India in particular, considering the impact on the environment and arrive at the energy sources which India needs to focus in the future. **Methods:** The world data on the various aspects like greenhouse emissions, deaths, health effects, levelized cost of electricity, energy return on investment, water, and land requirements for various energy sources have been studied. **Findings:** The need for reduction of energy from coal is clear as its emissions affect the health and contribute to climate changes. The alternative large source appears to be nuclear. Wind and solar power with low emissions of Greenhouse gases are also favored. However, wind is seasonal and solar power can be generated only during daytime which leads to low-capacity factor (~20%) compared to 32% for nuclear and 42% for Coal plants. This has also impact on the grid management. The environmental impacts of Nuclear, Coal, Solar, Wind and Hydro have been brought out in detail. More weightage is given to sources that have a higher growth rate based on the energy return on investment and environmental impacts rather than capital cost. The accidents of nuclear reactors in USA, Russia and Japan have shaken the public faith in nuclear power. The real fact that the impacts on the health of the people due to release of radiation in these accidents is negligible has been brought out. Comparison between natural and manmade radiation has been brought out. Finally, the applicability of energy sources in the context of India are discussed and a ranking approach arrived at. **Recommendations:** Nuclear has been favored based on the availability of natural uranium and thorium in the country and long-term energy security. Solar and wind need to be deployed, wherever possible, in view of the slow introduction of nuclear reactors due to high capital cost. Import of nuclear designs from abroad is also recommended to meet the electricity demands as a stop gap arrangement. **Novelty :** This study has taken a ranking approach considering most important metrics and has applied to India.

Keywords: Pollution; coal; hydro; biomass; nuclear; risk; benefits

1 Introduction

Environmental impacts are an inherent part of electricity production and energy use. Conventional energy sources based on coal, gas, oil, hydro and nuclear are very much helpful for the improvement in the economy of a country, but on the other hand, have their impacts on the environment. As of 2020 the relative contributions to electricity generation are: coal-33.77%, Natural Gas-22.78%, Hydro-16.84%, Nuclear-10.12%, Wind-6.15%, Solar-3.26% and Oil-4.36%⁽¹⁾. Renewable sources like hydro, solar and wind are more environment friendly, in that they do not emit greenhouse gases like those from fossil fuels during their operation. However, the mining of materials required for construction and manufacture of equipment besides transportation of these to site does involve energy, which is related to lifecycle greenhouse gas emissions and hence have some impacts on the environment.

An understanding of the relative environmental impacts of the various electric power sources is essential to the development of sound energy policy. To make an objective assessment, it is essential to examine the environmental impact of all energy sources right from mining, transport, construction, operation, maintenance, and distribution. There exists a nexus between water and energy. We need water to generate energy and energy is required to pump water. In a similar situation is the nexus between metals and energy. We need energy to mine and produce equipment and metals are required to make these products. If we look at biomass as a source of energy, we see a nexus between agriculture and energy.

Way back in 1991 Haddad and Jones⁽²⁾ made comparative risk assessments of the different energy systems for electricity generation. The results based on this study carefully differentiate between the various dimensions of risk, specifically those associated with normal and accident conditions. They classified the risks as immediate occupational risk, delayed occupational risk, immediate public risk, and delayed public risk. Their studies indicate that, under routine operating conditions, nuclear power and renewable energy systems tend to be in the lower spectrum of health risk, and that energy systems based on coal and oil are in the higher spectrum of health risk.

International Atomic Energy Agency (IAEA) in 1996⁽³⁾, brought out a report dealing with only the greenhouse emissions from different technologies. This report provides the estimated values of different authors from different countries. However, no comparison or ranking was attempted. Rashad in 1998⁽⁴⁾ made a comparative assessment of the environmental and health impacts of nuclear and other electricity generation systems. This paper compares the fuel and land requirements, net energy analysis, waste, deaths, and health effects from different energy sources and highlights the role of nuclear power in protecting the global environment as compared to other energy sources.

Okano in 2001⁽⁵⁾ made a comparative study of solar, wind, nuclear fission, nuclear fusion, and coal plants with CO₂ control. He looked at main issues like resources, environmental issues, cost, stability of power supply and safety. In each category he looked at sub issues. In resource he looked at the sub issues: availability of resources and their distribution, while on environment, he looked at the CO₂ emissions and waste disposal. Their findings: drawback of coal is in resource, for solar it is cost and for wind/solar stability. Nuclear was found to be a long-term reliable source but for security concerns. For each issue ranking was done. For sub issue he gave weightages. However, weightages were subjective. Nevertheless, this sort of a ranking gives the direction for the policy makers.

European union EXTERN-E project, 2003⁽⁶⁾ brought out a methodology to evaluate the costs of health damages due to different energy options in nearly 15 countries in the union. They concluded that Nuclear followed by solar and wind have minimal health or external costs. This was in fact a hallmark study conducted first time to evaluate the costs of treating health impacts, which are not paid by the utility. They are paid in terms of health effects (deaths, serious and minor illnesses, etc.) by those exposed to emissions and may not be even using electricity.

ReCiPe 2008⁽⁷⁾ suggests eighteen impact categories which should be considered for any life cycle study. It includes Climate Change, Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication, Marine Eutrophication, Human Toxicity, Photochemical Oxidant Formation, Particulate Matter Formation, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Ionizing Radiation, Agricultural Land Occupation, Urban Land Occupation, Natural Land Transformation, Water Depletion, Mineral Resource Depletion, and Fossil Fuel Depletion.

Jiang-Jiang Wang 2009⁽⁸⁾ reviewed the corresponding methods in different stages of multi-criteria decision analysis (MCDA) for sustainable energy, i.e., criteria selection, criteria weighting, evaluation, and final aggregation. The criteria of energy supply systems are summarized from technical, economic, environmental, and social aspects. The weighting methods of criteria are classified into three categories: subjective weighting, objective weighting, and combination weighting methods. Several methods based on weighted sum, priority setting, outranking, fuzzy set methodology and their combinations are employed for energy decision-making. It is observed that the investment cost takes the first place in all evaluation criteria and CO₂ emission follows closely because of more focuses on environment protection, equal criteria weights are still the most popular weighting method, analytical hierarchy process is the most popular comprehensive MCDA method, and the aggregation methods are helpful to get the rational result in sustainable energy decision-making. However, application of these to any country specific decision

making is not touched upon.

Manfred Lenzen 2010⁽⁹⁾ has made an in-depth review of the electricity generating technologies viz. hydro, nuclear, wind, photovoltaic, concentrating solar, geothermal and biomass power. He also discusses the technology of carbon capture and storage. The objective was to provide the technical information and environmental impacts of different technologies as at that time. No attempt was made to compare or rank the different energy sources. The review is real compendium worth reading.

A report of National Academic Press, USA⁽¹⁰⁾ has brought out the advantages and disadvantages of renewable energy technologies, but no quantitative approach to rank them.

World Bank in 2016⁽¹¹⁾ instituted a study on the assessment of coal and wind representing the non-renewable and renewable technologies. It contained a dynamic energy analysis to model the growth potential of alternative electricity generating infrastructures. They looked at the Energy return on investment as an index of merit. They also considered the capacity factors for each type of generation. They found that with coal higher rate of growth was possible with low energy back period compared to wind.

Study conducted in France⁽¹²⁾ on the material availability for energy brought out the following points. i) the transition to low-carbon energies implies a substantial increase of raw materials and energy consumption, ii) the shorter lifetime of wind and solar facilities and the loss of recycling implies that the total amount of metal to be produced during the deployment of the infrastructure of energy is significantly higher than their amount stocked in the infrastructure, and iii) the needs in materials and energy will occur in a period of expected increase of primary metal consumption at the world scale and limited potential of recycling. Other aspects were not studied.

Recently Dorning, 2019⁽¹³⁾ has made a review of many indicators for comparing the different energy sources. His review indicated that making comprehensive comparisons of the effects of energy development across sources may require efforts to standardize how effects are measured, synthesize effects literature into an open-source database, expand the range of environmental effects analyzed, and establish consistent frameworks for comparison. Again, no application studies are reported.

In the recent past some studies specific to India have been conducted^(14–16). However, they do not contain life cycle data on emissions, costs, and deaths etc. for the different electricity generating options.

All these studies have focused on different aspects but not given an approach with which policy makers could decide. Some of them are highly detailed and do not give an overview. Formation of public perception is highly influenced by media and politicians with biased information. Scientists and Engineers need to provide the public with complete and balanced information bringing out all the relevant facts. In this paper an attempt has been made to compare all generating technologies from various angles like land use, water use, emissions, health effects, indirect cost due to health effects, generation efficiency, capacity factor etc. Finally, it suggests a ranking framework to choose an option.

2 Energy from Coal

Today coal remains the largest contributor (~38.5%) to the electricity generation in the world⁽¹⁷⁾. In the following we touch upon issues related to coal mining, transportation, power generation and ash handling.

2.1 Issues with Coal Mining

Coal mining is mostly through surface or underground extraction. The empty spaces after extraction lead to sudden rock collapse besides leading to land subsidence. Land subsidence can directly affect the soil water and texture due to surface deformation and cause an extensive decrease in the groundwater level⁽¹⁸⁾. In this sense, land subsidence triggered by underground mining can have an immediate and long-lasting impact on the soil quality, soil erosion and thus on the ecosystem services.

2.1.1 Methane

Methane gas that occurs in coal deposits can explode if it concentrates in underground mines. This coalbed methane must be vented out of mines to make mines safer places to work. In 2018, methane emissions from coal mining and abandoned coal mines accounted for about 11% of total U.S. methane emissions⁽¹⁹⁾.

Methane-rich gases, generally containing 80% to 95% methane at underground mining depths, occur naturally in coal seams and are released as Coal mine methane (CMM) when coal seams are disturbed by mining activities. CMM becomes flammable and creates an explosion hazard when allowed to mix with air. Methane is an explosive gas in the range of 5% to 15% methane in air.

2.1.2 Land Subsidence

Coal mining, particularly surface mining can disturb land that is used for grazing, animal habitats, forests, crops, and more⁽¹⁹⁾. But the coal mining industry makes rehabilitating land once mining is complete a top priority. After mining is complete, companies are expected to reshape the area, replace topsoil, and replant vegetation, making the reclaimed land suitable for wildlife, agriculture, and more. However, this is seldom done in practice.

2.1.3 Air Pollution

Pollution of the environment can occur through windblown dust during transportation, where coal is washed, and at export ports. Adding water to coal can significantly reduce dust entrainment; the critical dusting moisture content varies with the type of coal. The use of covered hopper cars is not considered practical for coal transport because of loading difficulties. Chronic exposure to coal dust can lead to black lung disease, or pneumoconiosis, which took the lives of 10,000 miners worldwide over the last decade⁽²⁰⁾.

2.1.4 Water Pollution

Acid mine drainage, a metal-containing water that is formed by the chemical reaction between water and rocks containing Sulphur bearing minerals, can pollute water around a coal mine with heavy metals like copper, lead, and mercury⁽²¹⁾. Coal companies use specialized water treatment plants and recycling contaminated water, to minimize water pollution.

2.2 Emissions during Power Generation

The combustion of coal releases lot of gases including oxides of carbon, sulphur and nitrogen besides rare metals that do not burn. On an average year, a typical coal plant (500 MWe) generates the air pollutants as given in Table 1. One can see the impact of each pollutant on the health and environment.

Table 1. Pollutants from a typical 500 MWe coal plant and impact⁽²²⁾

Pollutant	Quantity	Impact
Carbon dioxide	~3.7 million tons	Climate change
Sulphur dioxide	~10000 tons	Acid Rain, lung damage
Nitrogen oxides	~10200 tons	Respiratory disorders
Airborne particles	~500 tones	Bronchitis, premature death
Hydrocarbons	~220 tons	Smog Formation
Carbon monoxide	~720 tons	Headache, Stress
Mercury	~17 pounds	Brain Damage, neuro disorders
Arsenic	~225 pounds	Skin Cancer, dermatitis
Lead	~114 pounds	Anemia, mental retardation
Cadmium	~4 pounds	Anemia, hepatic disorder
Nickel	~110 pounds	Respiratory problem, lung cancer
Antimony	~3 pounds	Gastroenteritis

The fine particles of fly ash reach the pulmonary region of the lungs and remain there for long periods of time; they behave like cumulative poisons. The submicron particles enter deeper into the lungs and are deposited on the alveolar walls where the metals could be transferred to the blood plasma across the cell membrane⁽²⁰⁾. Particulate control equipment is designed to remove the particulate from the flue gas stream and discharge the collected material. There are several types of particulate removal equipment including electrostatic precipitators (ESP), fabric filters, mechanical collectors, and venturi scrubbers. Each uses a different collection process with different factors affecting the collection performance. Nevertheless, coal-fired electricity generation accounts for 30% of global CO₂ emissions.

2.3 Coal Ash

Some trace elements in coal are naturally radioactive. These radioactive elements include uranium (U), thorium (Th), and their numerous decay products, including radium (Ra) and radon (Rn). Although these elements are less chemically toxic than other coal constituents such as arsenic, selenium, or mercury, questions have been raised concerning possible risk from

radiation⁽²³⁾. To accurately address these questions and to predict the mobility of radioactive elements during the coal fuel-cycle, it is important to determine the concentration, distribution, and form of radioactive elements in coal and fly ash. Coal ashes are roughly 100 times more radioactive than the level permissible for nuclear power plants. Measurements carried out in the Indian state of Maharashtra at a nuclear power plant and a coal-fired power plant have supported this finding⁽²⁴⁾.

2.4 Indirect Environmental Impacts

This largely results from the release of exhaust gases from the diesel locomotives or trucks used for coal transportation. Transportation of coal through trains can cause pollutant emissions, the potential for fires, leaching of chemicals, etc. Transporting coal can be more expensive than the cost of mining coal. Some coal consumers, such as coal-fired electric power plants, are near coal mines to lower transportation costs. Diesel engines hauling the coal wagons would add to the emissions. After unloading the coal, the train returns empty. This aspect cannot be ignored.

2.5 Deaths and Health Effects

Mining is a dangerous occupation. Coal miners die and suffer most often from fires and structural instability of underground mines. Hazards arise from the collapse of parts of a mine, explosions, and gaseous asphyxiation, as well as machinery malfunction and misuse. The coal mine fatality rate in USA and China are indicated in Table 2⁽²⁵⁾. Recent data from India indicate the death rates in the period 2015-19 to be in the range 0.1 to 0.2 deaths/million ton⁽²⁶⁾. Health effects from coal mining include: the release of methane (CH₄), the release of carbon monoxide (CO) from explosives, coal dust and coal particles stirred up during the mining process, as well as the soot released during coal transport, water pollution from acid mine runoff, and coal sludge. Miners can also suffer other serious, long-term respiratory ailments: industrial bronchitis is very common among coal workers.

Table 2. Comparison of Coal Mine Fatality Rates (Deaths/million ton)⁽²⁵⁾

Year	China	USA
2000	6.096	0.04
2001	5.13	0.04
2002	4.64	0.03
2003	4.17	0.031
2004	3.08	0.027
2005	2.81	0.021
2006	2.041	0.04
2007	1.485	0.029
2008	1.182	

2.6 Thermal Pollution

It is the degradation of water quality by any process that changes ambient water temperature. A common cause of thermal pollution is the use of water as a coolant by power plants and industrial manufacturers. When the water used as a coolant is returned to the natural environment at a higher temperature, the change in temperature impacts organisms by (a) decreasing oxygen supply, and (b) affecting ecosystem composition. Cooling water systems could be once through type or a closed cycle system that has a cooling tower to cool the condensate before sending it back to the system. In India the once through type is allowed only for sea water cooling and the temperature rise needs to be kept below 7 deg. C⁽²⁷⁾.

3 Energy from Water

Hydro power is also one of the large-scale electricity generating systems where water is stored in a dam and made to fall from a height on a turbine generator to produce electricity. By controlling the water flow the generation can be decreased or increased very fast unlike a coal fired plant. Hence such plants are used when peak demands of power come in electricity grids while coal and nuclear plants serve the base load. Due to absence of combustion, there are no pollutants or gases released during the operation of such plants. However, there are many issues involved, and they are discussed below.

3.1 Land use

As wonderful and simple as hydroelectricity may sound, there are problems with this energy source also. One problem is the amount of water, money, and land they require. For the sardar Sarovar Dam in Gujarat, the reservoir size before the dam covers an area of 375 sq.km with a height of 138 m. The dam has the potential to generate 1450 MW⁽²⁸⁾. The powerhouse was commissioned during 2005-06 and the generation of energy depends upon inflow of water from upstream projects and need of water for irrigation in Gujarat. Also dams require a very high volume of material, primarily concrete, to construct them and this is an important large component of the cost of the project. Land required for Hydro plant to generate 1 billion KWh/year is ~75000ha. (1ha=10000 m²)⁽²⁹⁾.

3.2 Upstream flooding

Any dam causes the flooding of a very large area behind it, which becomes the water reservoir. The flooding of the area upstream requires the displacement of communities, the abandonment of whole towns, and the relocation of inhabitants. The construction of the "Three Gorges" dam in China was for a long time a very controversial project because it resulted in the displacement of 1,240,000 persons and the abandonment of several towns⁽³⁰⁾. It also caused the extensive ecological change and when it was built, it caused the flooding of several important cultural and archaeological monuments. The huge lakes that many dams create can also bury useful and important things. For example, valuable mineral resources may be buried, along with farmland that has been productive for many decades.

3.3 Effects on Marine animals

Fish can be killed in the blades of the dam's turbines as they rotate. Fishes utilize the dissolved oxygen in the water for breathing. Bacteria in the water use oxygen to break down the organic material brought into the dam. When there is a lot of organic debris, the dissolved oxygen in the deeper water can be used up. In the absence of improper mixing of surface water with water below, there would be no new dissolved oxygen for the deep water. When this happens, the Deepwater can become unsuitable for marine animals. The amount of dissolved oxygen that the water can hold depends on the temperature and salinity of the water. Cold water can hold more dissolved oxygen than warm water and freshwater can hold more dissolved oxygen than saltwater. So, the warmer and saltier the water, the less dissolved oxygen there can be.

Dams may also interfere with the migration routes of marine animals. Dams on the Columbia River in Washington State have special "fish ladders" to help salmon move up the river as they need to. Bacteria present in decaying vegetation can also change mercury, present in rocks underlying a reservoir, into a form which is soluble in water. The mercury accumulates in the bodies of fish and poses a health hazard to those who depend on these fish for food⁽³¹⁾.

3.4 Release of methane and CO₂

Hydroelectric dams produce significant amounts of carbon dioxide and methane. This is because large amounts of carbon tied up in trees and other plants are brought in by the river water as it flows through different areas. In the dry season, plants grow on the banks of the reservoir only to be engulfed when the water level rises. All the loose organic material sinks down to the bottom of the reservoir where bacteria decompose it. If oxygen (O₂) is available, it is used for decomposition, and CO₂ is produced. Due to stratification, it is not as easy for O₂ to diffuse down into deep water.

Decomposition under Oxidic conditions: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Decomposition under Anoxic conditions: $C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$

Carbon dioxide and methane are released into the atmosphere when water passes through the dam's turbines. In effect man-made reservoirs convert carbon dioxide in the atmosphere into methane. This is significant because methane's effect on global warming is 25 times stronger than carbon dioxide's⁽³²⁾. Current estimates suggest that life cycle emissions from hydroelectric plants can be over 0.04-0.18 Kg of carbon dioxide equivalent per kilowatt-hour.⁽³³⁾

3.5 Silting of dam reservoirs

Water flowing in streams or rivers can scour channel bed, to carry particles and to deposit materials. This phenomenon of sediment transport can affect substantially the design of reservoirs. There is a stagnation region in front of the dam, where water comes to a standstill, turbulence is significantly reduced and the small particles that constitute the silt fall to the bottom. Many cases have been recorded where reservoir siltation rendered water storage structures useless in less than 25 years⁽³⁴⁾.

3.6 Dam failures

One significant safety concern with hydroelectric projects is dam failure, which has resulted in several of the largest man-made disasters. Many old dams pose serious safety threats, especially during summer floods. According to China's Ministry of Water Resource, 3,515 reservoirs burst between 1951 and 2011. They include the infamous Banqiao dam in Henan province which, along with another 61 dams, broke after six hours of torrential rain in August 1975, killing 240,000 people⁽³⁰⁾. The failure of the Vajont Dam in Italy, which was built in a geologically unstable region, caused the deaths of 2,000 people. In this respect, the smaller dams and small hydroelectric power plants, create a lesser risk, because they contain a much smaller volume of water, and consequently affect a smaller population. Good design, construction in the right location and quality control measures and preventive maintenance will, in general, help avoid dam failure and disasters. However, this is not an unfailing guarantee of safety, because large dams are tempting industrial targets for terrorism and wartime sabotage.

4 Natural Gas

Natural gas is found in deep underground rock formations or associated with other hydrocarbon reservoirs in coal beds and as methane clathrates. Petroleum is another fossil fuel found close to and with natural gas. Most natural gas was created over time by two mechanisms: biogenic and thermogenic. Biogenic gas is created by methanogenic organisms in marshes, bogs, landfills, and shallow sediments. Deeper in the earth, at greater temperature and pressure, thermogenic gas is created from buried organic material. Natural gas power plants have life cycle CO₂ emission of ~0.08Kg/KWh⁽³⁵⁾. Natural gas also emits 15 to 20 percent less heat-trapping gases than gasoline when burned in today's typical automobile⁽³⁵⁾.

The drilling and extraction of natural gas from wells and its transportation in pipelines results in the leakage of methane, the primary component of natural gas that is 34 times stronger than CO₂ at trapping heat over a 100-year period⁽³⁵⁾.

4.1 Air Pollution

Cleaner burning than other fossil fuels, the combustion of natural gas produces negligible amounts of sulphur, mercury, and particulate (Table 3). Burning natural gas does produce nitrogen oxides (NO_x), which are precursors to smog, but at lower levels than gasoline and diesel used for motor vehicles. Reductions in these emissions translate into public health benefits, as these pollutants have been linked with problems such as asthma, bronchitis, lung cancer, and heart disease for hundreds of thousands of Americans.

Table 3. Effects of Fossil fuels on the environment⁽³⁶⁾ (Kg produced per KJ of energy)

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	50300	70507	89423
Carbon Monoxide	17.1	14.18	89.42
Nitrogen oxides	39.55	192.6	196.48
Sulphur dioxides	0.26	482.37	1113.9
Particulates	3.0	36.11	1179.7
Formaldehyde	0.322	0.09	0.09
Mercury	0.000	0.003	0.006

Some areas where drilling occurs have experienced increases in concentrations of particulate matter and ozone plus its precursors. Exposure to elevated levels of these air pollutants can lead to adverse health outcomes, including respiratory symptoms, cardiovascular disease, and cancer.

4.2 Water Pollution

Releasing natural gas from subsurface porous rock formations may be accomplished by a process called hydraulic fracturing or "fracking". Hydraulic fracturing is a well stimulation technique used to maximize production of oil and natural gas in unconventional reservoirs, such as shale, coal beds, and tight sands. During hydraulic fracturing, specially engineered fluids containing chemical additives and proppant are pumped under high pressure into the well to create and hold open fractures in the formation. These fractures increase the exposed surface area of the rock in the formation and, in turn, stimulate the flow of natural gas or oil to the wellbore.

The US EPA ⁽³⁷⁾ has acknowledged that toxic, carcinogenic chemicals, i.e., benzene and ethylbenzene, have been used as gelling agents in water and chemical mixtures for fracturing. Following the hydraulic fracture, the water, chemicals, and frack fluid that return to the well's surface, called flowback or produced water, may contain radioactive materials, heavy metals, natural salts, and hydrocarbons which exist naturally in shale rock formations. Fracking chemicals, radioactive materials, heavy metals, and salts are so difficult to remove from the water they're mixed with, and would so heavily pollute the water cycle, that most of the flowback is either recycled into other fracking operations or injected into deep underground wells.

5 Wind Power

Since the time of the ancient sailboats and windmills, the power of the wind has been harnessed for ship propulsion and the performance of mechanical work. In modern times, wind has been increasingly used to produce electric power. Wind is a distributed renewable source of energy. The energy of the wind can be viewed as a product of solar energy. The uneven heating of Earth's atmosphere causes the winds, with consequent differences in the atmospheric pressure at different locations. Table 4 gives the potential capacities in the top 10 countries with wind power use for electricity generation.

Table 4. Top 10 Countries Wind Power Generation 2015 ⁽³⁸⁾

Country	MW	% share	Country	MW	% share
P R China	145,362	33.6	UK	13603	3.1
USA	74471	17.2	Canada	11205	2.6
Germany	44947	10.4	France	10358	2.4
India	25088	5.8	Italy	8958	2.1
Spain	23025	5.3	Brazil	8715	2.0

5.1 Environmental Effects of Wind Power Stations

The environmental problems associated with wind power are much less harmful to the environment and the ecosystems than the effects of most other renewable energy sources. However, they have some issues to be considered.

5.1.1 Wind Turbine Noise

Wind turbine operation generates two types of noise: aerodynamic noise from the rotating blades and mechanical noise from the rotating machinery. The aerodynamic noise consists of the swishing sound of the rotor blades scything through the air. It is like the stirring of tree branches during a brisk wind. This is likely to be detectable only for limited periods during low wind speeds. At higher wind speeds, the ambient wind noise from trees and buildings is likely to mask the wind noise of turbine blades. The number and layout of turbines on a wind farm site may be limited by noise considerations. The response of people to noise from wind turbines is highly subjective. In a country area, for example, the ambient noise is likely to be lower than in an urban area. What is acceptable in an urban area may seem unreasonable intrusive in a more remote location. A typical 600 kW machine produces 55 dBA noises, at a 50-meter distance from the turbine and 40 dBA at a 250-meter distance. ⁽²⁹⁾ Table 5 indicates noise level of other generally known noise sources. The table indicates that the turbine at a 50-meter distance produces noise no higher than the average factory.

Table 5. Noise Levels of Common Sources ⁽³⁶⁾

Source	Decibels	Source	Decibels
Turbo jet plane	150	Residence	40
Truck with muffler	90	Quiet room	20
Noisy class, Gymnasium	80	Lowest audible sound	0.1

5.1.2 Mechanical Noise

In addition to aerodynamic noise from the motion of the blades in the air, a wind turbine creates mechanical noise from the rotation of the gearbox and generator, plus auxiliary equipment. This noise is of comparable order with that due to any rotating machinery equipment but is more noticeable and perceptible because a wind turbine is in the open and often remote from other equipment. The noise created by rotating machines, at constant rotational speed is of narrow waveband and sometimes of

singular frequency but it may have a broadband component. The sound transmission path from a wind turbine may be airborne or structure borne from the tower, hub, or rotor, which can act as loudspeakers.

5.1.3 Electromagnetic Interference from Wind Turbines

Given that many wind turbines are located near the top or the sides of hills and mountains, their operation interferes with the transmission of television and radio signals, especially with television retransmission towers⁽³⁰⁾.

1. The turbine operation can create radio frequency noise (30–200 MHz), especially in the presence of the power electronic switching devices used in variable speed systems.
2. The action of the turbine, especially the blade rotation, can cause the interruption and scattering of electromagnetic signals that strike the structure.

5.1.4 Effect of a Wind Turbine on Animals/Birds

The operation of a wind turbine does not appear to have any effect on ground animals. The land on which a turbine or wind farm stands is still available for agricultural use. Cattle and sheep can graze right up to the tower structure and do not appear to be affected by the sight and sound of the blade rotation.

Mountain passes are frequently windy and provide a good wind channel for turbines but may also be a preferred route for migratory birds. The building and operation of wind farms can affect bird populations. During construction, there may be loss of bird habitat. Operation of a wind farm may cause changes to bird foraging habits, disturbance of breeding and nesting behaviour, and an alteration of migration habits. Locating the wind turbines in or near the flyways of migrating birds and wildlife refuges may result in birds flying into the supporting towers and rotating blades. In the United States, with about 13,000 wind turbines installed, an estimated 2,600 birds per year get killed.⁽³⁹⁾ Bat fatalities are another serious concern. Monitoring for bat and bird fatalities and research for the reduction of these should be included in all wind energy planning.

5.1.5 Renewables in the Grid⁽⁴⁰⁾

Although in most power generating systems, the main source of energy (the fuel) can be manipulated, this is not true for solar and wind energies. The main problems with these energy sources are cost and availability: wind and solar power are not always available where and when needed. Unlike conventional sources of electric power, these renewable sources are not “despatchable”, the power output cannot be controlled. Daily and seasonal effects and limited predictability result in intermittent generation.

The major issues involved in wind power generation are:

5.1.5.1 Variability. This is the biggest and most vexing. Power plants that run on fuel (along with some hydro and geothermal plants) can be ramped up and down on command. They are, in the jargon, “dispatchable.” But wind power plants produce power only when the wind is blowing. Grid operators don’t control wind generation, they accommodate it, which requires some agility.

5.1.5.2 Uncertainty. The output of such plants cannot be predicted with perfect accuracy in day-ahead and day-of forecasts, so grid operators must keep excess reserve running just in case.

5.1.5.3 Location-specificity. Sun and wind are stronger (and thus more economical) in some places than in others — and not always in places that have the necessary transmission infrastructure to get the power to where it’s needed.

5.1.5.4 Nonsynchronous generation. Conventional generators provide voltage support and frequency control to the grid. Renewable energy generators can too, potentially, but it’s an additional capital investment.

5.1.5.5 Low-capacity factor. Renewable energy plants only run when sun or wind cooperates. Capacity factors are around 34% for wind, compared to ~80-90% for coal and nuclear power plants. The presence of wind and solar power on electric grids can cause coal or natural gas—fired plants to turn on and off more often or to modify their output levels more frequently to accommodate changes in variable generation. This type of cycling of fossil-fueled generators can result in an increase in wear-and-tear on the units and a decrease in efficiency, particularly from thermal stresses on equipment because of changes in output.

6 Solar Power

Solar energy is radiant energy that is produced by the sun. Every day the sun radiates an enormous amount of energy that maintains the Earth at an acceptable temperature. The sun’s extremely high pressure and temperature cause nuclear fusion.

Four hydrogen nuclei fuse to become one helium atom, a process that is accompanied by a loss in mass. This loss in mass results in the emission of radiant energy. In effect Sun is a nuclear fusion reactor. Only a small portion—approximately one part in two billion of the energy radiated by the sun into space strikes the Earth. In terms of energy strength, the sun constantly delivers 1.36 kW/m^2 of power to the Earth. However, some of this power is absorbed by the atmosphere so that, even under ideal conditions, a receptor on Earth may receive less than 1 kW/m^2 ⁽⁴¹⁾.

Photovoltaic are solar cells that produce electricity directly from sunlight. The solar cells are made of thin layers of material, usually silicon. The layers, after treatment with special compounds, have either too many or too few electrons ⁽⁴²⁾. When light strikes a sandwich of the different layers, electrons start flowing and an electric current result. Photovoltaics are used to provide power to operate appliances, provide lighting, to power navigation and communication aids and power equipment in spaceships and satellites. Despite the advances in the manufacturing of solar cells, in the beginning of the twenty-first century, electricity from photovoltaic devices is still more expensive to produce than electricity from fossil fuel power plants.

Concentrating solar power (CSP) plants use mirrors to concentrate the sun's energy to drive traditional steam turbines or engines that create electricity ⁽⁴³⁾. The thermal energy concentrated in a CSP plant can be stored and used to produce electricity when it is needed, day or night. Computer-controlled mirrors (called heliostats) track the sun along two axes and focus solar energy on a receiver at the top of a high tower. The focused energy is used to heat a transfer fluid (over $1,000^\circ \text{ F}$) to produce steam and run a central power generator. Located across 3,500 acres of federal land in California's Mojave Desert, the Ivanpah facility is a 392-megawatt solar generation plant consisting of 173,500 heliostats and three power towers with the capacity to provide clean, sustainable power ⁽⁴⁴⁾.

6.1 Issues with Photovoltaic

Crystalline-silicon solar cell processing involves the use or release of chemicals such as phosphine, arsenic, arsine, trichloroethane, phosphorous oxychloride, ethyl vinyl acetate, silicon trioxide, stannic chloride, tantalum pentoxide, lead, hexavalent chromium, and numerous other chemical compounds. Perhaps the most dangerous chemical employed is silane, a highly explosive gas involved in hazardous incidents on a routine basis according to the industry. For example, sawing silicon wafers releases a dangerous dust as well as large amounts of sodium hydroxide and potassium hydroxide. Even newer thin-film technologies employ numerous toxic substances, including cadmium, which is categorized as an extreme toxin ⁽⁴⁵⁾. However, all the pollution associated with the production of solar cells is localized and contained at the production facility and can harm occupational workers.

A more significant concern in the production of the photovoltaic cells is the high amount of energy consumed during their manufacturing process. As indicated earlier, the energy consumed for the manufacturing of a silicon-based solar cell is equivalent to the energy the cell will produce in approximately four years. This and the associated labor costs make photovoltaic energy appreciably more expensive. A major limitation of solar PV is the large space occupied per kW. To generate 1 billion kWh/year land required is 2800 ha ⁽³⁰⁾.

6.2 Issues with Concentrated Solar Thermal Plants

One of the salient characteristics of solar is that it is a diffuse form of energy. Vast Solar's Pilot Plant in Australia was built to confirm the ability to safely and effectively use a liquid sodium as a heat transfer medium to drive full power cycle. It consists of five modular, polar solar arrays with a total of 3,500 heliostats and a nominal thermal capacity of 6MWth ⁽⁴⁶⁾. Heliostats are devices that consist of one or more mirrors, which can be individually controlled and moved to keep reflecting sunlight directed toward the central receiver. Heliostats focus the sunlight to the top of a lattice frame tower on which a receiver is mounted. This implies that a solar thermal power plant would utilize a great deal of land area. Land area required to generate 1 billion KWh/year is half of Photovoltaic i.e., 1100 ha ⁽³⁰⁾.

There is evidence that such large area solar concentrating installations can kill birds that fly over them. Near the center of the array temperatures can reach 550° C which, with the solar flux itself, is enough to incinerate birds while further away feathers are scorched leading to the eventual death of the bird. Workers at the Ivanpah solar power plant USA, call these birds "streamers," as they ignite in mid-air and plummet to the ground trailing smoke ⁽⁴⁷⁾. During testing of the initial standby position for the heliostats, 115 birds were killed as they entered the concentrated solar flux. After adjusting the standby position to not focus all the solar energy into a single point, during the following 6 months of operations, a total of 321 birds were killed.

As in the case of wind power generation (sec 5.5.1), integrating solar power into present grids poses problems due to the uncertainty and variable nature.

7 Nuclear Power

More than any other form of energy, safety, and environmental issues are of paramount importance to the nuclear industry. The public got its first glimpse of the power of nuclear energy in the form of atomic bombs that dropped out of airplanes to devastate the cities of Hiroshima and Nagasaki. The average citizen of the globe still associates nuclear energy with nuclear weapons. From the outset, it must be emphasized that, given the design of all civilian nuclear reactors, a nuclear explosion in a reactor is not possible. The number of neutrons created in the nuclear reactor is simply not sufficient for a critical mass to be created and an explosion to occur. A bomb requires high purity Uranium and Plutonium, which cannot be generated in normal power reactors. The explosion in Fukushima was due to hydrogen generated because of the chemical reaction between zirconium and boiling water. The destruction at Chernobyl was caused by a steam explosion. The Chernobyl type of reactors is not built outside Russia and now, these types are not built even in Russia.

7.1 Impact of Mining

Although uranium itself is barely radioactive, the ore which is mined must be regarded as potentially hazardous, especially if it is high-grade ore. The radiation hazards involved are like those in many mineral sand mining and treatment operations. Kazakhstan produces the largest share of uranium from mines (42% of world supply from mines in 2019), followed by Canada (13%) and Australia (12%)⁽⁴⁸⁾. Many of the world's uranium mines have been open cut and therefore naturally well ventilated. Ore grades at most mines worldwide are less than 0.5% U_3O_8 (the actual chemical form of uranium oxide present in the ore). Regulatory authorities in all countries including India with nuclear programmes implement strict health standards for alpha, beta, and gamma radiation and radon gas exposure as well as for ingestion and inhalation of radioactive materials⁽⁴⁹⁾.

The gamma radiation comes principally from isotopes of bismuth and lead. The radon gas emanates from the rock (or tailings) as radium decays. It then decays itself to (solid) radon daughters, which are energetic alpha-emitters. Radon occurs in most rocks and traces of it are in the air we all breathe. Alpha particles discharged in the lung can later give rise to lung cancer.

Many precautions are taken at any mine to protect the health of workers, and those at a uranium mine are slightly greater⁽⁴⁹⁾:

1. Dust is controlled to minimize inhalation of gamma or alpha-emitting minerals. In practice, dust is the main source of radiation exposure in a uranium mine.
2. Radiation exposure of workers in the mine, plant, and tailings areas are limited. In practice, direct radiation levels from the ore and tailings are usually so low that it would be difficult for a worker to come anywhere near the allowable annual dose.
3. Exposure to Radon and its daughter products are limited in an open-cut mine since there is sufficient natural ventilation and the radon level seldom exceeds 1% of the levels allowable for continuous occupational exposure. In an underground mine a good, forced ventilation system is required to achieve the same. Respiratory protection is used in areas identified as hazardous by air monitoring.

After mining is complete most of the orebody, with virtually all the radioactive radium, thorium, and actinium materials, will end up in the tailings dam. The tailings are to be covered over with enough rock, clay, and soil to reduce both gamma radiation levels and radon emanation rates to levels near those naturally occurring in the region. A vegetation cover is also established. Measurements carried out in Jaduguda the biggest Uranium mine in India, indicate that the uranium and Radon levels in the ground water sources in the vicinity of the tailings pond are very similar to the regional average, indicating that there is no ground water migration of radioactive material from the tailings pond⁽⁵⁰⁾.

Process water, from which tailings solids have settled out, contains radium and other metals that would be undesirable in the outside environment. This water is retained and evaporated so that the contained metals are retained in safe storage, as in an orebody. In fact, process water is never released to natural waterways but is stored in tailings retention area and evaporated from there or treated for reuse.

7.2 Spent Fuel Reprocessing⁽⁵¹⁾

The spent nuclear fuel may be reprocessed, and several radionuclides may be removed, but the non-fissile U_{238} remains and becomes nuclear waste. Prior to reprocessing the spent fuel is stored at the plant site in water pools that remove the heat produced due to radionuclide decay of spent fuel. Because of the potential use of these fissile materials in nuclear weapons, the technology remains closely guarded and only a few countries have the operating plants in civilian regime, such as Russia, UK, France, Japan, and India. Even after reprocessing, the radioactive products must be safely stored for many years. Safe storage includes significant cooling for the removal of any decay heat and continuous monitoring for thousands of years. In India, spent nuclear

fuel is not considered as waste. The spent fuel, from present and future reactors is reprocessed to recover unused U235 and other useful by-products. These after separation are put in operating reactors and the fast breeder reactors, which can burn this waste material and generate power. Thus, the net nuclear waste materials even after a proposed major induction of nuclear power in India is far less and an underground repository will not be needed till the next few decades. However, in countries like USA, the spent fuel is totally treated as waste.

7.3 Waste Management⁽⁵²⁾

Nuclear Waste Materials (NWM) is mainly produced from three sources: the spent fuel, the contaminated internal reactor structure, and the mechanical equipment. A nuclear reactor is refueled every 18–24 month and produces a significant amount of waste materials, which are radioactive and will remain radioactive for many years. For example, the non-fissile isotope U238 has a half-life of 4.5 billion years. Other reactor products have half-lives of thousands and hundreds of thousands of years. Equally important is the disposal of contaminated equipment after the decommissioning of the nuclear reactor. Waste management and disposal throughout the world are carried out based on the guidelines of the International Atomic Energy Agency (IAEA). Nuclear wastes, which are classified into low level (90%), intermediate level (7%), and high level (3%). On average, the waste from a reactor supplying a person's electricity needs for a year would be about the size of a brick. Only 5 grams of this is high-level waste – about the same weight as a sheet of paper⁽⁵³⁾.

In Russia there are several temporary storage facilities. Similarly, in France, there are reprocessing and temporary storage facilities with a permanent deep geological disposal site proposed in Bure, Meuse. In Belgium, NWM are reprocessed in the City of Mol and are stored in a central facility at Dessel. Germany already operates two small underground repositories at the Ahaus and Gorleben salt domes.

7.4 Transportation of Nuclear Fuels

Safe transportation of the NWM materials from the power plants to the reprocessing facilities and, finally, to the permanent repository is another activity. Most of the spent fuel from the Japanese reactors is shipped to be reprocessed in Europe. Waste in the form of glass (vitrified waste) and the recovered uranium and plutonium are returned to Japan to be recycled in the reactors. The fundamental principle is that protection comes from the design of the package, regardless of how the material is transported. More specifically, protection is achieved by containment of radioactive contents, control of external radiation levels through shielding, prevention of criticality, and prevention of damage caused by heat and impact. All regulations are implemented as per the guidelines of the International Atomic Energy Agency⁽⁵⁴⁾.

A transportation accident may have an enormous environmental impact over very large areas. The nuclear waste or spent fuel is generally transported in canisters made of SS 304L. During handling and storage of these canisters, there is a remote possibility of an accidental drop of the canister. To assess the integrity of canisters during and after the drop, impact testing by physical testing was carried out in India for four representative orientations⁽⁵⁵⁾. No significant plastic strains were observed in physical drop tests which do not amount to failure. Visually all drop-tested canisters maintained structural integrity. This fact was also confirmed by the dye penetrant and Helium leak tests.

There are custom-built ships designed and tested as per IAEA regulations, which are used for transportation⁽⁵⁶⁾. The custom-built transport ships are designed to withstand a side-on collision with a large oil tanker. If the ship did sink, the casks would remain sound for many years.

7.5 Reactor Accidents

The main concern on the operation of nuclear reactors is a serious accident that may contaminate a whole region or across continents with radioactive materials, as it happened after the Chernobyl and the Fukushima accidents. Contamination of a whole state and evacuation of large regions are risks that many modern societies are not willing to take. For this reason, there are several groups of citizens that actively oppose the construction of new nuclear power plants throughout the world. However, a study of the literature available after these accidents, shows that radiation per se did not affect the people but it was the psychological fear caused due to evacuations that were carried out after the accidents.

7.5.1 Chernobyl^(57–59)

The accident at Chernobyl was a major disaster due to partly poor design and construction, and mainly due to gross disregard of the operating procedures by the operation team. Such a design and that too without a containment building would never be accepted anywhere. It is often said that the reactor at Chernobyl exploded. This is misleading if it is taken to mean that the

reactor exploded like an atomic bomb. What happened was that when the safety circuits were switched off (contrary to rules) the reactor went prompt critical, and there was a surge of power that produced intense heat that blew off the cover of the reactor and set fire to the graphite moderator. Manual switching or bypassing of safety circuits is not possible in the present designs. This fire burned for several days and sent a large amount of radioactivity into the atmosphere. Some of the workers near the reactor received high doses of radiation, and of these 56 died. The much larger figures of fatalities often quoted have no objective basis. There was no evidence of excess cases of leukemia or other types of cancer among the thousands of workers employed in cleaning-up operations after the accident. The only effect was increased rates of thyroid cancer among children due to drinking water contaminated with Iodine 131; this form of cancer can be treated effectively. The chernobyl type reactors have not been built outside the erstwhile Soviet Union.

7.5.2 Three Mile Island^(60,61)

The accident at Three Mile Island NPP in the USA did not result in any public exposure due to the presence of a containment building around the reactor vessel. It has been estimated that the average risks to the population of the United States from a hundred nuclear power plants due to nuclear reactor accidents and radiation emission is less than four deaths per year. The assumption of a linear dose relation between cancers and dose, based on the Hiroshima-Nagasaki bombings where high levels of radiation were seen, is highly conservative for small doses of radiation. However, this has given enough safety margins in fixing the allowable doses to personnel. This figure may be compared with the 300,000 deaths per year due to cancers from other causes, and 50,000 from automobile accidents.

7.5.3 Fukushima^(62–64)

On March 11, 2011, Fukushima units 1, 2, and 3 were in operation, and units-4, 5 and 6, were shut down for routine refuelling and maintenance activities; the unit-4 reactor fuel was offloaded to the Unit 4 spent fuel pool. As a result of the earthquake, all the operating units appeared to experience a normal reactor trip within the capability of the safety design of the plants. The three operating units at Fukushima Dai-ichi automatically shut down, apparently inserting all control rods into the reactor. As a result of the earthquake, off-site power was lost to the entire facility.

The emergency diesel generators started at all six units providing alternating current (AC) electrical power to critical systems at each unit and the facility response to the seismic event appears to have been normal. Approximately 40 minutes following the earthquake and shutdown of the operating units, the first large tsunami wave inundated the site followed by multiple additional waves. The estimated height of the tsunami of 15 m exceeded the site design protection from tsunamis of 5.7 m. The tsunami resulted in extensive damage to site facilities and a complete loss of AC electrical power at Units 1 through 5, a condition known as Station Blackout (SBO). Unit 6 retained the function of one of the diesel generators.

The operators were faced with a catastrophic, unprecedented emergency. They had to work in nearly total darkness with very limited instrumentation and control systems. Loss of total power from all sources led to the loss of cooling of fuel resulting in damage to the nuclear fuel. Units 1, 2, 3, and 4 experienced explosions caused by the buildup of hydrogen gas within primary containment produced during fuel damage in the reactor and subsequent movement of that hydrogen gas from the drywell into the secondary containment.

7.6 Natural and Manmade Radiation

Natural sources of radiation include cosmic rays from outer space, minerals in the ground, and radon in the air. The earth contains a lot of radioactive substances like uranium, thorium, potassium, etc. These were there since the earth was born. These continue to decay and produce radioactivity and we have no control over the radioactivity that gets into us through food and soil. Granite stones have a good level of radioactivity. Naturally occurring background radiation is the main source of exposure for most people. Levels typically range from about 1.5 to 3.5 millisievert per year but can be more than 50 mSv/yr.⁽⁶⁵⁾ The highest known level of background radiation affecting a substantial population is in Kerala and Madras States in India where some 140,000 people receive doses which average over 15 millisievert per year from gamma radiation in addition to a similar dose from radon⁽⁶⁶⁾. Comparable levels occur in Brazil and Sudan, with average exposures up to about 40 mSv/yr to many people. Several places are known in Iran, India, and Europe where natural background radiation gives an annual dose of more than 50 mSv and up to 260 mSv (at Ramsar in Iran). Lifetime doses from natural radiation range up to several thousand millisievert. However, there is no evidence of increased cancers or other health problems arising from these high natural levels.

The breakup of natural radiation exposure in a year is 0.9 mSv through inhalation, 0.3 mSv through food ingestion, 0.3 mSv through cosmic and 0.2 mSv terrestrial(soil) radiation⁽⁶⁷⁾. As shown in figure natural radiation accounts for ~88% of the radiation received by humans, out of the rest 12% ~11% is from medical diagnostics and treatment and just 0.2% from occupational exposures in nuclear facilities (Figure 1).

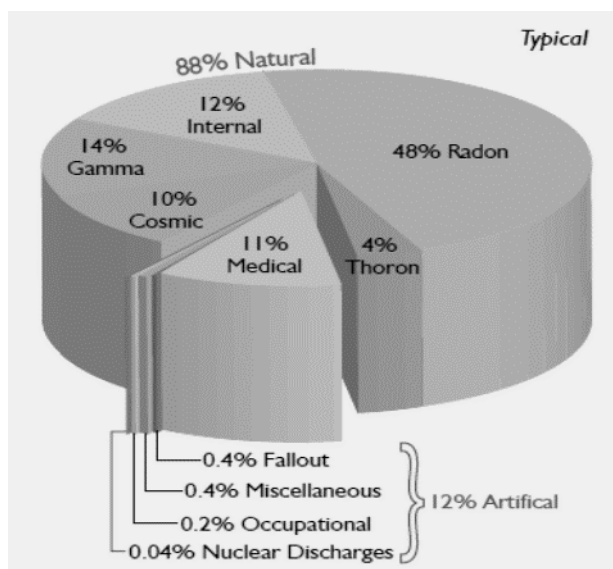


Fig 1. Breakup of natural radiation exposure⁽⁶⁷⁾

Man-made sources of radiation include the X-ray equipment used by doctors, smoke detectors, colour television sets, and luminous dial clocks. Table 6 gives the radiation exposures people get in medical diagnostics⁽⁶⁸⁾.

Table 6. Radiation Exposure in medical diagnostics

Examination	Effective Dose mSv	Examination	Effective Dose mSv
Chest (LAT)	0.04	Mammogram (4 views)	0.7
Chest (PA)	0.02	Dental (LAT)	0.02
Skull (PA)	0.03	Dental (Panoramic)	0.09
Skull (LAT)	0.01	DEXA (Whole body)	0.0004
Pelvics (PA)	0.7	HIP	0.8
Thoraic Spine (PA)	0.4	Hand or Foot	0.005
Lumbar Spine (PA)	0.7	Abdomen	1.2

Table 7 shows the dose a patient could receive if undergoing an entire procedure⁽⁶⁵⁾.

Table 7. Typical Radiation dose -Medical diagnostics (Complete Organ)

Complete Exam	Effective Dose mSv
Intravenous Pyelogram (Kidney,6 films)	2.5
Barium Swallow (24 images,106 sec. fluoroscopy)	1.5
Barium Enema (10 images,137 sec. fluoroscopy)	7.0
Computed Tomography (CT) Head	2.0
CT Chest	8.0
CT Abdomen	10.0
CT Pelvis	10.0
Angioplasty (heart study)	7.5-57.0
Coronary Angiogram	4.6-15.8

7.7 Radiation and cancer

In the public mind there is always the fear of getting cancer due to radiation exposure. There is no single cause for cancer (Table 8). Scientists believe that it is the interaction of many factors together that produces cancer. The factors may be genetic, environmental, or constitutional characteristic of the individual. It is usually not possible to know exactly why one person develops cancer and another doesn't. Any possible adverse health effects resulting from radiation doses below 10,000 mrem (100 mSv) are not detectable. ^(69,70)

Table 8. Causes of Cancer ⁽⁷¹⁾

Causative factor	Cancers	Causative factor	Cancers
Tobacco	33%	alcohol	3%
Obesity & Excess weight	20%	Ionizing and UV Radiation	2%
diet	5%	Drugs	1%
Lack of Exercise	5%	Reproductive factors	3%
Occupation	5%	Pollution	2%
Viruses	5%	Unknown	11%
Family History	5%		

Studies of occupational workers who are chronically exposed to low levels of radiation above normal background have shown no adverse biological effects. Even so, the radiation protection community conservatively assumes that any amount of radiation may pose some risk for causing cancer and hereditary effect, and that the risk is higher for higher radiation exposures. Hence regulations exist universally to limit the radiation exposures. Radiation dose limits are imposed for both occupational workers in nuclear facilities and the public. A limit of 20 mSv per year (averaged over a 5-year period, with no more than 50 mSv in any year) is for occupational workers. For members of the public, it is 1 mSv per year. ⁽⁷²⁾ The dose received from nuclear facilities is just 0.2%. Hence, there should be no concern about getting cancer from nuclear facilities.

8 Comparison of Different Energy Sources

All methods of generating energy have wider effects on the human community. They are all hazardous to some degree in different ways, and these hazards must be considered when choosing which energy source to use. The same applies to their effects on the climate and the pollution of the environment. There is no completely safe way to produce energy. Coal mining is highly dangerous, oil wells catch fire, tankers collide or explode, dams burst, and nuclear reactors accidents can release radioactivity. Renewable energy sources are sometimes described as safe or benign, but if we consider the risks involved in manufacturing the equipment in factories and in constructing and maintaining them, it turns out that they are not so safe after all. To make an objective assessment of safety it is necessary to include all the risks for each energy source. Mining, transport, construction, operation, maintenance, and distribution all involve risks. Some are direct and affect only the workers, while some like pollution affects the whole population. The purpose of this section is to look at the comparison of the different energy sources from different angles.

8.1 Land Use

It is of prime interest to look at the land use by different energy sources as a first step. Land is a scarce commodity with an ever-increasing population. Table 9 gives the comparison of land use for the different sources. Solar-CSP requires the highest area of land followed by hydro, solar, Wind, coal and nuclear.

Table 9. Land Resources (m²/MWh) ^(73,74)

Energy Source	US Data	EU Data	UNEP	Uchiyama
Coal- Underground	0.6	0.2	-	0.2
Hydro	16.9			10
Nuclear	0.1	1.0	-	0.1
Solar Photovoltaic	15.0	8.7	13.0	10
Solar CSP	19.3	7.8	14.0	15
Wind	1.3	0.7	0.3	1.0
Natural Gas	1.0	0.1	0.2	0.2

The variation in values is essentially related to data available on different plants in different countries. Some data may include associated facilities also.

8.2 Energy Return on Energy Investment (EROI)

Energy economists have devised the term EROI to represent the ratio of Energy Returned (ER) over Energy Invested (EI) in output. Net energy gain, or useful energy available to society, is the difference between ER and EI. EROI's value depends on factors like system boundary used for analysis, method of handling heat energy and electricity, and how one addresses the dynamic effect. The issue of dynamic effect arises from the fact that the grid has a certain EROI.

The energy return on (energy) investment (EROI) is defined as:

$$EROI = \frac{\text{Gross quantity of energy delivered over the infrastructure lifetime}}{\text{Energy expended for infrastructure} + \text{Energy expended in O and M over a lifetime}}$$

The first term in the denominator is like a fixed capital cost, while the second term refers to running cost. Since O and M energy is a fraction of the total energy produced, the increase of the lifetime of the plant goes to increase EROI. EROI will be increased by reducing energy to put in place the infrastructure, reducing the Operation and Maintenance energy fraction of production and increasing the plant life.

Lower EROI means that society must divert more of its total economic activity to get the energy to run the rest of the economy. EROI integrates the counteracting effects of depletion and technological improvements. Changes in EROI at relatively high values, above say 10:1, have much less impact than changes at lower values. To understand this, the net energy expressed as a function of EROI is calculated and given in the Table 10. It is the solution of the equations: Energy gain = Eout – Ein, EROI = Eout/Ein.

Table 10. EROI vs Eout

EROI=Eout/Ein	Eout-Ein	% Eout	EROI=Eout/Ein	Eout-Ein	% E out
4	3	3/4=75	20	19	19/20=95
8	7	7/8=87.5	50	49	49/50=98
10	9	9/10=90	70	69	69/70=98.6

With change in EROI from 10 to 20 the Output increases by just 5%, while with EROI changing from 4 to 8 output increases by 12.5%. Hence to have a higher net energy output the system with higher EROI is to be favored. This also shows that the sensitivity of Eout to fluctuations in EROI is very small at EROI above 10.

The total energy delivered over the lifetime is a function of the capacity factor (CF). Since wind and solar are intermittent and seasonal their capacity factors are low. Data available in 2015 for USA shows that nuclear has the maximum capacity factor (90%) followed by coal (65%) and natural gas (50%). Wind, solar and hydro have capacity factors around 40%⁽⁷⁵⁾. An important consequence of these facts is that the substitution of the coal power plants, which are base-load units with CFs higher than 90%, will entail the construction of wind and solar units with significantly higher generating capacity in MW.

The energy output is also influenced by the generation efficiency which is 94% for hydro, 44.5% for coal, 32.5% for nuclear, 30% for wind and 18.5% for solar thermal CSP⁽⁷³⁾. Due to low-capacity factor and low efficiencies, solar and wind power have low EROI. EROI of different energy sources is presented in Table 11.

Table 11. EROI of different energy sources^(74,76,77)

Source	Hodgson 1994	Uchiyama 2007	Forbes 2015
Coal	20	17	30
Hydro	50	50	35
Nuclear	50	26	75
Solar PV	10	7	2
Wind	6-34	22	4
Natural Gas	4-26	6	28

The energy payback period is a measure of the time interval required for the infrastructure—once it is installed—to deliver net energy sufficient to cover the initial energy investment.

$$\text{Energy pay – back time} = \frac{[\text{capital energy for plant} + \text{operational energy} \times 30 \text{ years}]}{[\text{electricity produced} - \text{operational energy}]}$$

This will be small if lifetime of the plant is high, energy needed for infrastructure is low and plant capacity factors are high. Related to the payback period is another metric called doubling time. The doubling time is a measure of the time interval required to accumulate enough excess energy to deploy new infrastructure sufficient to double the power output. The doubling time metric also captures the influence of capacity factor, licensing, and construction time lags. Ioannis N. Kessides and David C. Wade performed a Life Cycle Analysis (LCA) of coal and wind representing the nonrenewable and renewable energies⁽⁷⁸⁾. They developed a dynamic energy analysis framework to model the growth potential of alternative electricity supply infrastructures. For a given EROI and plant life they compared Coal and wind as representatives of non-renewable and renewable energy sources (Table 12).

Table 12. EROI, Payback period and doubling time⁽⁷⁸⁾

	EROI	Plant Life	CF	Energy Pay Back period	CT	EIS	EOM	Doubling time
Coal	6	30	0.75	0.15	4	0.2	0.163	1.3
Wind	6	30	0.20	0.39	1	0.2	0.061	28.5

(Licensing and construction time CT, - Plant life- Capacity factor CF, Energy fraction that is available for new plant infrastructure EIS, Energy fraction utilized for plant O&M, EOM)

The coal-fired generation shows potential to support rapid indigenous growth. Wind, on the other hand, seems quite constrained. The doubling time is 1.3 years for coal and 28.5 years for wind. Thus, the ability of wind to rapidly scale up its production appears to be limited relative to coal. The lower capacity factor and front-loaded capital versus operating energy requirements of wind slow down its achievable growth rate, compared to that of coal. What is true of coal would apply to nuclear and hydro as they have high-capacity factors and what would apply to wind could be taken to be the same for solar as both have low-capacity factors.

Another study was carried out in 2016 by Princeton University⁽⁷⁵⁾. The Princeton study extended the concept of Kessides and Wade to accommodate time-dependent demand scenarios to determine the required expansion of power generation, including the energy plowback needed for new construction and to replace facilities as they are retired in the period 2010-2100. All the net output from each energy source to be used for constructing new infrastructure of the same type. They evaluated a global electricity supply and consumption scenario of the Intergovernmental Panel on Climate Change (IPCC) from the AR5 database called “EMF27-450-Full_Tech” that is associated with one of the more aggressive (and successful) cases that aims to limit greenhouse gases at the end of the century at a 450 ppm CO₂ limit with mitigation using the full set of available technologies. Their study revealed that dynamic EROI was maximum for nuclear-62 followed by hydro-57, wind-39, coal-38, natural gas-8, and solar-6. Dynamic EROI captures the dynamics during rapidly changing energy transition as energy investment is needed to set up a new generator. This then shows that nuclear power is one of the important energy sources to be reckoned with in Energy planning to combat global warming.

8.3 GHG Emissions

It was seen that greenhouse gases including CO₂, SO₂, etc., are produced directly in the case of fossil fuels but other technologies like hydro, solar, etc., do involve indirect emissions at the production, construction, and equipment transportation stages. International Atomic Energy Agency has brought out a nice comparative study on the relative GHG emissions in terms of equivalent CO₂ emissions in the life cycle of different energy generation technologies and the same is given in Table 13⁽³³⁾.

Table 13. Full Energy Chain GHG emissions⁽³³⁾

	Uchiyama	Yasukawa	Friderich	Dones
Lignite	-	-	1175	1340
Hard Coal	990	963	940,1290	973,1020
oil	686	-	-	890
Natural Gas	-	-	-	77
LNG	653	-	-	-
Nuclear power	21	25.7	19	8-24
Hydropower	18	-	-	4
Solar PV	57-123	-	279	141-257
Wind Power	120	-	16	-
Electricity mix	469	-	561	495

8.4 Water Consumption

Water consumption varies between the various energy technologies. Water withdrawn for fossil and nuclear energy is used for cooling in the condensers and is returned to the water source almost immediately after picking up the heat. The water consumed due to evaporation is a much smaller amount of the withdrawal. Table 14 gives the comparison for different types of generation with once through cooling (water taken from river/sea and discharged back) and those using cooling towers.

Table 14. Water Consumption/ Withdrawal⁽⁷⁹⁾

Gen. Technology	Type	Withdrawal Cu.m/MWh	Withdrawal Cu.m/MWh	Consumption Cu.m/MWh	Consumption Cu.m/MWh
		Once Through Cooling	Cooling Tower	Once Through Cooling	Cooling Tower
Nuclear		170	4.16	1.51	2.68
Natural gas	CC	30.28	0.95	0.37	0.74
	Steam	132.5	4.54	1.13	2.68
	CFB	75.7	3.7	0.74	2.08
Coal	PC	132.5	2.65	0.49	1.97
	SC	85.17	2.27	0.37	1.89
	IGCC	-	1.41	1.17	-
Concentrated Solar Power (CSP)	Trough	-	3.4	-	3.33
	Power tower	-	3.02	-	3.02

Legend: CC: Combined cycle, CFB: Circulating Fluid Bed, PC: Pulverized Coal, SC: Supercritical Cycle, IGCC: Integrated Gasification combined cycle, CSP: Concentrating Solar Power

8.5 Levelized cost of electricity (LCOE)⁽⁸⁰⁾

The LCOE can also be regarded as the minimum constant price at which electricity must be sold to break even over the lifetime of the project. This can be roughly calculated as the net present value of all costs over the lifetime of the asset divided by an appropriately discounted total of the energy output from the asset over that lifetime. Typically, the LCOE is calculated over the design lifetime of a plant, which is usually 20 to 40 years. However, care should be taken in comparing different LCOE studies and the sources of the information as the LCOE for a given energy source is highly dependent on the assumptions, financing terms and technological deployment analyzed. Capacity factor has significant impact on the calculation of LCOE. Lazard has conducted this analysis comparing the LCOE for various conventional and Alternative Energy generation technologies to understand which Alternative Energy generation technologies may be cost-competitive with conventional generation technologies.

LCOE was devised before the advent of variable renewable energies (VRE) and therefore, has no parameter to account for intermittency. Hence, it cannot capture additional balancing costs imposed by intermittency. Energy sources used earlier that

is coal, nuclear and large hydro are available round the clock, and lack of a parameter to account for intermittency in the LCOE method was inconsequential for their inter-comparison. When aiming to integrate more intermittent renewable sources (VRE) to the grid, continued use of LCOE as a metric for comparison of technology options is erroneous. In principle, all power generating technologies induce integration costs. However, because VRE interact differently with the power system than non-renewable plants they are much more difficult to integrate especially at high shares.

Cost of integration are often divided into the following three broad categories:⁽⁸¹⁾

- Profile costs are related to the variability of VRE output, and they can demonstrate that in the presence of VRE generation it is generally more expensive to provide the residual load. The overall system thus becomes more expensive even if the plant-level costs of VRE are comparable to those of dispatchable technologies.
- Balancing costs are related to the uncertainty of power production due to unforeseen plant outages or to forecasting errors in relation to production. Unforeseen plant outages or forecasting errors related to electricity generation require that higher amount of spinning reserves be carried out. Uncertainties in VRE power production may also lead to an increase in ramping and cycling of conventional power plants, to inefficiencies in plant scheduling and, overall, to higher costs for the system.
- Grid and connection costs reflect the effects on the transmission and distribution grid infrastructure due to the locational constraint of generation plants. While all generation plants may have some siting restrictions, the impacts are more significant for VRE. Because of their geographic location constraint, it could be necessary to build new transmission lines or to increase the capacity of existing infrastructure (grid reinforcement) to transport the electricity from centers of production to load. Also, high shares of distributed PV resources may require sizeable investment into the distribution network, to allow the inflow of electricity from the producer to the grid when the electricity generated exceeds demand. Connection costs (i.e. the costs of connecting the power plant to the nearest connecting point of the transmission grid) can also be significant, especially if distant resources have to be connected, as is sometimes the case for offshore wind.

In other words, LCOE of wind/solar falling below those of conventional power plants does not imply that wind deployment is economically efficient or competitive. LCOE tends to overestimate the economic efficiency of VRE, and extent of overestimate increases with increase in their penetration.

Levelised cost of electricity is very sensitive to the interest rates prevalent in a country. Nuclear Energy Agency and International Energy Agency jointly studied the economics of electricity generation using a range of technologies⁽⁸²⁾. The report gives cost ratios of electricity generation from nuclear and coal and from nuclear and gas. Experts from 19 countries participated in the study. The results indicate the following.

- At 5% discount rate, nuclear is cheaper as compared to gas in all the 19 countries.
- At 10% discount rate, except Japan and the USA, nuclear is cheaper as compared to gas. USA has offered two gas-based plant designs for this study and gas is cheaper in case of only one.
- At 5% discount rate, except South Korea and the USA, nuclear is cheaper as compared to coal. In South Korea, out of the 4 comparative evaluations given in the study, coal is cheaper for only one case.
- At 10% discount rate, in South Korea, the USA and Germany, nuclear is cheaper as compared to coal. In South Korea, for all the 4 comparative evaluations reported and in the USA for the two cases given, coal is cheaper. For Germany, for 4 cases analyzed, coal is cheaper in case of 2.

Similar studies have been done in India by the Nuclear Power Corporation (NPCIL) as well⁽⁸³⁾. While nuclear power cost is location independent, in case of coal, it is very sensitive to distance of the power plant from coal mine as cost of coal transportation is quite significant. The levelized costs of generation at 2005-06 prices for dominant technologies in India using 5% and 10% discount rates have been evaluated (assuming coal-fired plant is situated at 800 km from coal mine) and the results are given in Table 15. The critical discount rate, below which nuclear power is cheaper as compared to coal thermal, is 7.1%.

Table 15. Levelized Costs (2005-2006 Constant Price)⁽⁸³⁾

Discount Rate	Nuclear	Coal Fired	Gas Fired-LNG
5%	152	164	182
10%	218	200	204

Latest calculations by Lazard as of 2020 indicate that Nuclear has the highest LCOE (in US \$/MWh) – 129 to 198, followed by Solar Concentrated power – 126 to 156, Coal- 65 to 159 and wind 26-54⁽⁸⁰⁾.

There are three significant impediments to the expansion of nuclear power globally: the high capital cost of nuclear reactors; the nuclear waste disposal; and the real or perceived safety risk by the population. On the capital costs Kamerstern and Thompson⁽⁸⁴⁾ provided an econometric analysis for the production technology and generating costs of nuclear power, as well as the efficiency and equity of the nuclear rate structure based on the 112 nuclear plants in USA. They determined that, in the absence (or elimination) of regulatory and politically determined costs – licensing delays, retrofitting, and the handling of plant disallowances and cancellations – nuclear power plants can be very competitive with fossil-fuels plants for the generation of electric power.

8.6 External Costs

One issue regarding energy generation should be highlighted, namely external costs. The term is used to denote the cost that the party responsible for generating emissions does not account for and, consequently, consumers of electricity do not pay for. They are paid in terms of health effects (deaths, serious and minor illnesses, etc.) by those exposed to emissions and may not be even using electricity. The European Union's (EU) Extern E project (Table 16) studied external costs for different sources.⁽⁸⁵⁾ Nuclear has the least external costs (health effects) among the electricity generation technologies studied: lignite, coal, and oil, gas, biomass, wind, solar and nuclear. In case of coal the direct costs and external cost are nearly the same. For nuclear, wind and solar, the external costs are only about 10 to 20 % of the direct costs.

Table 16. External and direct costs of electricity generation in EU (milli Euros/KWh)

External Costs	Coal & Lignite	oil	Gas	Nuclear	Biomass	Solar PV	wind
Austria			11-26		24-25		
Belgium	37-150		11-22	4-4.7			
Germany	30-55	51-78	12-23	4-4.7	28-29	1.4-3.3	0.5-0.6
Denmark	35-65		15-30		12-14		0.9-1.6
Spain	48-77		11-22		29-52		1.-1.9
Finland	20-44				8-11		
France	69-99	84-109	24-35	2.5	6-7		
Greece	46-84	26-48	7-13		1-8		2.4-2.6
Ireland	59-84						
Italy		34-56	15-27				
Netherlands	28-42		5-19	7.4	4-5		
Norway			8-19		2-4		0.5-2.5
Portugal	42-67		8-21		14-18		
Sweden	18-42				2.7-3		
U K	42-67	29-47	11-22	2.4-2.7	5.3-5.7		1.3-1.5
Direct Costs	32-50	49-52	26-35	34-59	34-43	512-853	67-72
Direct cos+ external cost of UK	74-117	78-99	37-57	37-62	40-49	–	69-74

If we add up direct and external costs for UK only, as indicated in the last row of Table 16, the cost/MWh of coal is nearly twice as much as nuclear, wind and solar.

8.7 Radioactivity release during normal operation

The amounts of radioactivity emitted by several types of power stations are given in Table 17⁽⁷⁶⁾. These amounts are all very small compared with the natural background radiation, but it is nevertheless notable that coal power stations emit more radioactivity than nuclear.

Table 17. Collective dose Worldwide (Man Sv/GW yr)

Coal	4.0	Peat	2,0
Nuclear	2.5	Oil	0.5
Geothermal	2.0	Gas	0.03

In India measurements have been made at the Nasik Thermal power plant and the Tarapur Nuclear plant⁽⁸⁶⁾. It is seen from this study that the radiation doses in the vicinity of thermal power plants are comparable to those for nuclear power plants in the vicinity of the power stations. All the doses are in the range of natural background radiation dose. The collective commitments for 80 Km radius area of thermal power plants are an order of magnitude higher than those for nuclear power plant.

9 Ranking of Energy Sources

It is essential to rank the different sources considering the different metrics described so far. In the following discussions reference is to India. Though the data used for ranking is based on international data, nevertheless it will indicate a direction. An attempt has been made to rank the different sources of energy against the following metrics: Fuel Resource, Land required, EROI, LCOE, Greenhouse gases emission (GHG) and external costs. We have not considered Hydro as the potential is very low. Under fuel resource solar and wind take the first two ranks while nuclear comes third and coal is last. Under EROI, as discussed earlier nuclear stand out followed by wind, coal and solar. Rank 1 is given to the best source for a given metric. With addition of individual ranks, the one which has the least value will be considered the best. Here Nuclear and wind appear at the same level. Table 18 shows the ranking for the various metrics, based on the material presented in the previous paragraphs.

Table 18. Comparative indices for Energy sources

Source	Fuel resource	LCOE	Land	EROI (Dynamic)	GHG	External Cost	Total of indices	Ranking
Coal	4	2	2	3	4	4	19	4
Nuclear	3	3	1	1	1	2	11	1
Solar CSP	2	4	3	4	2	3	18	2
Wind	1	1	4	2	2	1	11	1

The above ranking favours Nuclear followed by wind and solar if we give equal weights to all the metrics. From the climate change considerations, we need to give a higher weightage to GHG emissions. Health impacts of energy sources are also of equal importance. However, the ranking does not change with higher weightage.

Nuclear power besides being clean would also bring in energy security. Coming to renewables like wind the potential is a function of the height of the wind turbine. Higher the height higher is the power output. Studies by ministry of nonrenewable energy indicate a potential of 302.25 GWe (100 m height) to 695.50 GWe (150 m Height)⁽⁸⁷⁾. For solar the National Institute of Solar Energy has assessed the Country's solar potential of about 748 GW assuming 3% of the waste land area to be covered by Solar PV modules⁽⁸⁸⁾. In short India should pursue nuclear, Wind and solar power from point of view of clean power and resources.

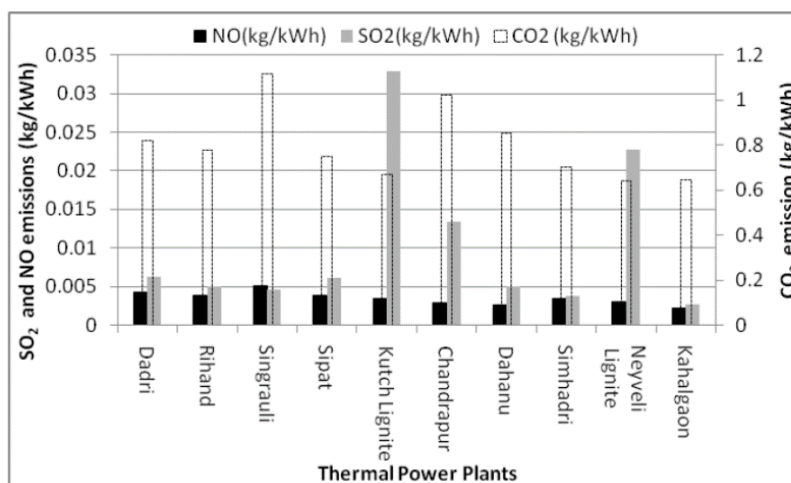
10 Indian Electricity generation Scenario

Potential of different nonrenewable energy sources available indigenously is indicated in Table 19. Despite large deposits in the east and south, the quality of the country's coal is not exceptional, with an ash content of 45% and low calorific values. In contrast, high-quality coal imported from Indonesia, South Africa, Russia, and Australia has only ash content of 10%–15%⁽¹⁵⁾. Based on the CEA data (www.cea.nic.in 2010), specific coal usage at three plants is less than 0.6 kg/kWh, at 19 plants, usage is between 0.6-0.7 kg/kWh, thirty-nine plants use coal between 0.7-0.8 kg/kWh, fifteen plants use between 0.8-0.9 kg/kWh, seven plants use between 0.9-1.0 kg/kWh, and at three plants coal usage exceeds 1.0 kg/kWh. This is due to difference in the coal qualities. Hence the efficiency of the plants and the coal usage per unit of electricity generation also differ at each plant. As of 2018, India consumed 902 million tonnes (MT) of coal, of which 213 MT was imported. Of the imports, 80 MT is thermal coal for power plants⁽⁸⁹⁾.

India's coal-based thermal power sector is one of the country's biggest emitters of carbon dioxide (CO₂). It spews out 1.1 giga tonne of CO₂ every year; this is 2.5 per cent of global GHG emissions, one-third of India's GHG emissions, and around 50 per cent of India's fuel-related CO₂ emissions⁽⁹⁰⁾. The emissions of oxides of carbon, sulphur and nitrogen from typical power plants is presented in Figure 2. Lignite fired plants emit more sulphur oxides. There is a variation of CO₂ emissions between 0.6 to 1 Kg per KWh.⁽¹⁴⁾

Table 19. Generation Potential of Energy Sources India⁽⁹¹⁾

Plant Type	Electricity Potential (GWe.Yr)	Plant Type	Electricity Potential (GWe.Yr)
Coal fired plant	7614	Uranium in Heavy water reactors	328
Oil/Gas fired Plant	5833	Uranium in Breeder Reactors	42231
Hydro	69	Thorium in Breeder Reactors	155,502

**Fig 2.** GHG emissions Indian Coal Fired Plants⁽¹⁴⁾

The main challenge in India with respect to land availability for large power projects is to do with the acquisition of land. There are several legal difficulties with the process for land acquisition for large scale infrastructure projects such as power plants as the current land acquisition laws provide significant privileges and protection to landowners. India continues to have a high degree of conflict over land and over 60% of all conflicts documented are to do with land acquisition by the government⁽⁹²⁾.

The comparative land use life cycle assessment of nuclear power, wind energy, and solar PV in India shows that nuclear energy enjoys significant advantages over both solar PV and wind power with respect to land transformation, as shown in table Table 20. Another study⁽¹⁶⁾ presented the data with respect to land area required to set up a power plant in m²/MW and land area (m²/GWh) that goes into setting up a power plant, fuel mining (coal and nuclear), transportation (coal only) and waste disposal (nuclear only) across the lifetime of the power plant.

Table 20. Comparative land use life cycle requirements

Source	Plant Area m ² /MW ⁽⁹³⁾	Mining to waste m ² /GWh ⁽⁹³⁾	Mining to waste m ² /GWh ⁽⁹²⁾
Coal	10000	600	-
Nuclear	20000	150	30
Hydro	220000	1400	-
Solar	20000	600	450
Wind	-	-	140

The main targets of India's Nationally Determined Contribution (NDC) submitted to Paris Climate Change Agreement consist of (a) reduction of emission intensity of its GDP by 33–35% during 2005–2030, (b) increase in share of non-fossil-based energy resources to 40% of installed electric generation capacity, and (c) creation of an additional cumulative carbon sink of 2.5–3 Gt-CO₂e through additional forest and tree cover by 2030 (INDC 2015). In India, energy sector (which includes electricity generation, transport, building, and agriculture) contributes over 73% of its GHG emissions each year⁽⁹³⁾. As of May 2019, 220 GW of coal-based plants is in operation, 58 GW is in pipeline, and 36 GW is undergoing construction, while 88 GW of plants has been shelved, and about 491 GW of power plants has been cancelled⁽⁹³⁾.

Towards achieving the NDC goals, nuclear, wind and solar have a big role to play. Of the large power generation options nuclear is well suited considering the amount of uranium and thorium available in the country and can replace coal fired plants

in toto. India's non-fossil fuel electricity capacity, which includes renewables, large hydro, and nuclear, was 38% of its total installed electricity mix. Of this, the share of installed renewables alone (grid-connected solar, wind, small hydro, biomass, and waste-to-energy) is 23%. Towards this India has committed to a target of 450 gigawatts (GW) of renewable energy installations, likely by 2030—equivalent to five times more than India's current installed renewable capacity and bigger than the size of India's electricity grid size in 2019 (362 GW)⁽⁹⁴⁾.

With nuclear energy as a clean and long-term option, one must look at the status of the Indian nuclear programme and what needs to be done to hasten the pace of introduction of nuclear plants in the country.

10.1 Nuclear Power Programme-A must for India

The first stage of India's nuclear programme involves using the natural uranium in PHWRs, which produce not only energy but also some fissile plutonium⁽⁹⁵⁾. These reactors use only 0.7% of U235 present in natural uranium. The remaining 99.3% U238 can be converted to fissile Pu239 in fast breeder reactors. Hence the second stage involving fast breeder reactor became essential for India. The second stage will use Pu 239 recovered from the reprocessed PHWR spent fuel along with depleted uranium, mostly containing U238, in sodium cooled fast reactor or SFR. This will convert the fertile U238 to fissile Pu239, thereby effectively utilizing the natural uranium resources. In the latter period of the second stage SFR will use Th 232 as blanket material producing U233 as fissile material. The third stage will then use U233 / Th232 combination in fast and/ or thermal breeders to fully exploit available Thorium to produce power. It must be borne in mind that India can generate up to 300 GWe with depleted uranium itself available from spent fuel of PHWR which may last for about 100 years. The use of burnt fuel after due reprocessing from water reactors in Fast Reactors besides ensuring complete utilization of U238 (which gets converted into Plutonium) helps in minimizing the waste generation. This approach is called closed fuel cycle. USA is one country that does not reprocess and puts the burnt fuel as waste. This is referred as open fuel cycle.

In the 1990s there was a significant mismatch between the demand and domestic supply of uranium and many reactors were operated at lower power. The uranium shortage was due to the poor ore content and due to public opposition to Uranium mining in Andhra Pradesh and Meghalaya, which delayed the mining. In view of this and to add nuclear plants in a faster way through foreign collaborations, India signed a nuclear deal in 2008 for nuclear cooperation. India has also signed nuclear deals with France, Japan, Kazakhstan, Australia, and Canada⁽⁹⁶⁾. The deal has enabled import of natural uranium for our operating reactors. Even before the Indo-US deal, nuclear cooperation existed with Russia and two units of 1000 Mwe built with Russian collaboration are in operation at Koodankulam in Tamilnadu and another four such units are in the pipeline. Fuel for these reactors (enriched uranium) is supplied by Russia. In other words, fuel would not be problem for the nuclear plants. However, all the plants that use imported fuel would be governed by the IAEA safeguards. Safeguards are activities by which the IAEA can verify that a State is living up to its international commitments not to use nuclear programmes for nuclear-weapons purposes. In the light of this India, uses the available natural uranium in the country in about six of the plants while rest use imported uranium. Reprocessed fuel from these six reactors is not subject to IAEA safeguards and the extracted plutonium is used in the fast breeder reactors, which again would not be under safeguards.

The policy makers need to accept that nuclear power is essential to achieve reduction in the GHG gases and to achieve the goal towards cleaner energy. There is a social need to reduce global warming. Climate change is today an important issue consequent to large release of GHG gases through coal plants. China which is the largest contributor to GHG emissions has turned its direction towards nuclear power in a big way based on social need. Countries in Asia have large electricity demands unlike USA or Europe where the demands are low. However, in India, the rate of introduction of nuclear plants is slow due to large capital investment needed, and hence there is urgent need to introduce wind and solar power plants.

11 Discussion

Higher rate of energy growth is possible with nuclear energy only as shown by studies indicated above on EROI. The government must allocate sufficient funds towards development of nuclear energy in the long run, while keeping wind and solar as the near-term options. Lack of funding now will have a negative effect on the indigenous development of all facets of nuclear power programme including thorium technology, which is important to utilize the vast thorium reserves in the country.

11.1 Human Resource

Apart from uranium resource, technology, and economics, one more factor is very important and that is selecting and training human resource for nuclear industry, which is knowledge intensive. Today we have a large skilled manpower in the nuclear field which is one of the best amongst developing countries. With lower funding, the interest of scientists/ engineers would

come down. This could not only lead to exodus of skilled manpower to Middle East (UAE), where nuclear plants are being built and with delays in funding, the skilled manpower would have superannuated from their jobs. Lack of skilled manpower would derail development and progress and finally kill the nuclear programme in toto. Classic example is of United Kingdom, which was a forerunner in developing different types of nuclear reactors and today is dependent on Électricité de France (EDF) for nuclear plant construction as its skilled manpower is getting extinct. Hence it is time, the government decide to go ahead with full funding of nuclear power. It is now or never.

11.2 Industrial Support

All nuclear facilities built in India have taken longer time to build. Initially the vendors needed to set up special shops for nuclear components which demanded a very clean area and involved sufficient investment in setting them up. The problem was not that the industry lacked the technological base and knowledge needed to carry out the fabrication, but that they did not have enough nuclear orders to make such manufacturing economic. Many industries were therefore reluctant, and those that fulfilled the manufacturing orders did so at great expense. This was reflected in much higher costs for such equipment.

In this background, it becomes uneconomic for the industry to set up special facilities for just a few components of a single or two reactors. There is a need for ordering say 6 to 7 reactors at a stretch. Under the present situation, vendors who have quoted for one reactor do not quote for the next one after a few years. A new vendor takes up the order, but he must understand the technology again. Also, with delays in project sanctions and orders for components, the experienced manpower in the department and industries superannuate and then the new set of people must start learning from scratch again. Presently few vendors have been developed, but unless they get substantial orders, the cost of manufacture would be high, which reflects in the capital cost.

12 Concluding remarks

In keeping with the above, the following recommendations are being made. These recommendations are based on the author's personal opinions and do not represent the views of the government. The government must pay additional special attention to the following:

- The exploration and mining of Uranium deposits need to be undertaken urgently after resolving the local issues (Andhra Pradesh & Meghalaya) through a strong public awareness programs involving media and medical professionals.
- While loans from institutions like World Bank are available for constructing coal, solar, wind and Hydro power plants, same is not true for nuclear power. Hence there is the need for governmental support to the Indian nuclear industry. Government must find a strategy to fund the nuclear programme from the profits of public sector units.
- Establishment of spent fuel reprocessing plants in a timely manner is essential to get enough plutonium to fuel the fast reactors.
- A consortium approach is needed to build nuclear reactor plants. There are very few industries with sufficient capability to build components for nuclear reactors and only a consortium approach would bring in these industries which would be assured of orders. Working together with Indian industry, we must look at innovative ways to complete projects on time and within budget.
- Efforts on Thorium utilization must be given an impetus. Use of thorium is of importance to our long-term nuclear power generation. This needs extensive Research and development.
- The introduction of nuclear plants with foreign collaborations must continue, parallelly with our present 3 stage programme.

Future attention needs to be paid to Multi Criteria Decision making Techniques by which different scenarios could be analysed to arrive at the optimum decision for different parts of India. What is fine for coastal power plants may not be true for inland ones. Most important consideration should be technical and social ones. Emphasis needs to be given for database of indian power plants with all relevant life cycle data.

References

- 1) Our World in Data. 2021. Available from: <https://ourworldindata.org/grapher/electricity-prod-source-stacked?stackMode=relative>.
- 2) Haddad S, Dones R. Comparative health, and environmental risks for various energy sources. *IAEA Bulletin*. 1991. Available from: <https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull33-3/33302041419.pdf>.
- 3) van de Vate JF. Comparison of Energy Sources in terms of their full Energy Chain Emissions Factors of Greenhouse Gases. *Energy Policy*. 1997;25(1). Available from: [https://doi.org/10.1016/S0301-4215\(96\)00111-5](https://doi.org/10.1016/S0301-4215(96)00111-5).

- 4) Rashad SM. Comparative Assessment of Environmental and Health Impacts of Electricity Generating Systems. *International Conference on Hazardous Waste Sources*. 1998;p. 12–16.
- 5) Frontiers in Plasma Confinement and Related Engineering/Plasma Science. In: proceedings of joint conference of 12th International Toki Conference on plasma physics and controlled nuclear fusion(ITC-12)and 3rd general scientific assembly of Asia Plasma and Fusion Association(APFA'01). 2001. Available from: [Japanwww.nifs.ac.jp/itc12/Okano.pdf](http://www.nifs.ac.jp/itc12/Okano.pdf).
- 6) Nuclear Electricity Generation: What Are the External Costs? OECD. 2003. Available from: https://www.oecd-neo.org/jcms/pl_13756/nuclear-electricity-generation-what-are-the-external-osts?details=true.
- 7) Goedkoop MJ, Heijungs R, Goedkoop MJ, Schryver AD, Struijs J, Zelm RV. Ruimte en Milieu Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. 2013. Available from: https://www.researchgate.net/publication/302559709_ReCiPE_2008_A_life_cycle_impact_assessment_method_which_comprises_harmonised_category_indicators_at_the_midpoint_and_the_endpoint_level.
- 8) Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*. 2009;13(9):2263–2278. Available from: <https://dx.doi.org/10.1016/j.rser.2009.06.021>. doi:10.1016/j.rser.2009.06.021.
- 9) Lenzen M. Current State of Development of Electricity-Generating Technologies: A Literature Review. *Energies*. 2010;3(3):462–591. Available from: <https://dx.doi.org/10.3390/en3030462>. doi:10.3390/en3030462.
- 10) Electricity from Renewable Resources: Status, Prospects, and Impediments. Washington, DC. The National Academies Press. 2010. Available from: <https://doi.org/10.17226/12619>.
- 11) Ioannis KN, Wade DC. Deriving an Improved Dynamic EROI to Provide Better Information for Energy Planners. *Sustainability*. 2016;3:2339–2357. Available from: <https://ideas.repec.org/a/gam/justa/v3y2011i2p2339-2357d15147.html>.
- 12) Vidal O, Boulzec HL, François C. Modelling the material and energy costs of the transition to low-carbon energy. *EPJ Web of Conferences*. 2018;189:00018–00018. Available from: <https://dx.doi.org/10.1051/epjconf/201818900018>. doi:10.1051/epjconf/201818900018.
- 13) Dorning MA, Diffendorfer JE, Loss SR, Bagstad KJ. Review of indicators for comparing environmental effects across energy sources. *Environmental Research Letters*. 2019;14(10):103002–103002. Available from: <https://dx.doi.org/10.1088/1748-9326/ab402d>. doi:10.1088/1748-9326/ab402d.
- 14) Mittal ML, Sharma C, Singh R. Estimates of Emissions from Coal Fired Thermal Power Plants in India. *2012 International Emission Inventory Conference*. 2012. Available from: https://www.researchgate.net/publication/267687877_Estimates_of_Emissions_from_Coal_Fired_Thermal_Power_Plants_in_India.
- 15) Sahoo B, National bureau of Asian research. India's Energy Mix and the Pathways to Sustainable Development. 2021. Available from: <https://www.nbr.org/publication/indias-energy-mix-and-the-pathways-to-sustainable-development/>.
- 16) Mitavachan H, Srinivasan J. Is land really a constraint for the utilization of solar energy in India. *Current Science*. 2012;103(2):163–168. Available from: <https://www.jstor.org/stable/24084995>.
- 17) IEA. Coal 2018: Analysis and forecasts to 2023. 2018. Available from: <https://www.iea.org/reports/coal-2018>.
- 18) Ma K, Zhang Y, Ruan M, Guo J, Chai T. Land Subsidence in a Coal Mining Area Reduced Soil Fertility and Led to Soil Degradation in Arid and Semi-Arid Regions. *International Journal of Environmental Research and Public Health*. 2019;16(20):3929–3929. Available from: <https://dx.doi.org/10.3390/ijerph16203929>. doi:10.3390/ijerph16203929.
- 19) Economic Commission for Europe Methane To Markets Partnership. Best Practice Guidance for Effective Methane Drainage and Use in Coal Mines. United Nations, New York and Geneva. 2010. Available from: <https://cmmclearinghouse.cmpdi.co.in/contents/BPGuidance.pdf>.
- 20) Senapati, Ranjan MM. Fly ash from thermal power plants, waste management and overview. *Current Science*. 2011;100(12). Available from: https://www.researchgate.net/publication/268334790_Fly_ash_from_thermal_power_plants_-_Waste_management_and_overview.
- 21) Verma C, Madan S, Hussain A. Heavy metal contamination of groundwater due to fly ash disposal of coal-fired thermal power plant, Parichha, Jhansi, India. *Cogent Engineering*. 2016;3(1):1179243–1179243. Available from: <https://dx.doi.org/10.1080/23311916.2016.1179243>. doi:10.1080/23311916.2016.1179243.
- 22) Coal and Air Pollution, Union of Concerned Scientists, 2017. . Available from: <https://www.ucsusa.org/resources/coal-and-air-pollution>.
- 23) Tadmor J. Radioactivity from coal-fired power plants: A review. *Journal of Environmental Radioactivity*. 1986;4(3):177–204. Available from: [https://doi.org/10.1016/0265-931X\(86\)90010-X](https://doi.org/10.1016/0265-931X(86)90010-X).
- 24) Mishra UC. Relative radiation hazards of coal based and nuclear power plants Report. IAEA-R-2717-F, IAEA, Vienna, editors. 1983. Available from: https://inis.iaea.org/collection/NCLCollectionStore/_Public/15/021/15021171.pdf.
- 25) Wei-ci G, Chao W. Comparative Study on Coal Mine Safety between China and the US from a Safety Sociology Perspective. *Procedia Engineering*. 2011;26:2003–2011. Available from: <https://dx.doi.org/10.1016/j.proeng.2011.11.2397>. doi:10.1016/j.proeng.2011.11.2397.
- 26) Ministry. Ministry of Coal, Safety in Coal Mines, Annual Report 2018–19, Government of India, 2020. . 2018. Available from: <http://coal.nic.in/sites/default/files/2019-11/chap11AnnualReport1819en.pdf>.
- 27) Report on Minimisation of Water Requirement in Coal Based Thermal Power. *CENTRAL ELECTRICITY AUTHORITY*. 2012. Available from: https://cea.nic.in/wp-content/uploads/2020/04/min_of_water_coal_power.pdf.
- 28) Sardar Sarovar Narmada Nigam Ltd . Dam and Reservoir . Available from: <https://sardarsarovardam.org/dam-reservoir.aspx>.
- 29) Pimentel D. Solar and Wind as Renewable Energy Systems: Benefits and Risks. Springer, Dordrecht. 2008;p. 3–4. Available from: <https://doi.org/10.1007/978-1-4020-8654-0>. doi:10.1007/978-1-4020-8654-0.
- 30) Michaelides EES. Alternative Energy Sources. and others, editor;Springer. 2012. Available from: <https://www.springer.com/gp/book/9783642209505>.
- 31) Mercury Contamination in Maine Fishes. 2020. Available from: <http://fishguideme.com/kevins-magazine-articles/mercury-contamination-in-marine-fishes/>.
- 32) Methane Management-A challenge. 2020. Available from: <https://www.unecce.org/energy/welcome/areas-of-work/methane-management/the-challenge.html>.
- 33) IAEA-TECDOC-892, Proceedings of an IAEA Advisory Group meeting/Workshop. Comparison of Energy Sources in terms of their full Energy Chain Emissions Factors of Greenhouse Gases. In: and others, editor. IAEA. 1996. Available from: https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/013/28013414.pdf.
- 34) Mama CN, Okafor FO. Siltation In Reservoirs. *Nigerian Journal of Technology*. 2011;30(1).
- 35) Environmental Impacts of Natural Gas. 2020. Available from: <https://www.ucsusa.org/resources/environmental-impacts-natural-gas#references>.
- 36) Natural Gas 1998 Issues and Trends. 2020. Available from: http://www.eia.doe.gov/oil_gas/natural_gas/analysis_publications/natural_gas_1998_issues_and_trends/it98.html.

- 37) Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, US EPA, 2011. . Available from: https://www.epa.gov/sites/default/files/documents/hf_study_plan_110211_final_508.pdf.
- 38) Global wind Energy Council. 2015. Available from: <http://www.gwec.net>.
- 39) Teach Engineering-STEM Curriculum for K-12. . Available from: <https://www.teachengineering.org>.
- 40) Why wind and solar power are such a challenge for energy grids. 2015. Available from: <https://www.vox.com/2015/6/19/8808545/wind-solar-grid-integration>.
- 41) Solar Radiation. . Available from: <https://ecglp.com/files/3514/0200/1304/2-Solar-Radiation.pdf>.
- 42) What is solar cell?. . Available from: <https://www.electrical4u.com/solar-cell/>.
- 43) Bielecki A, Ernst S, Skrodzka W, Wojnicki I. Concentrated Solar Power Plants with Molten Salt Storage: Economic Aspects and Perspectives in the European Union. *International Journal of Photoenergy*. 2019;2019:1–10. Available from: <https://dx.doi.org/10.1155/2019/8796814>. doi:10.1155/2019/8796814.
- 44) Concentrating Solar Power. . Available from: <https://www.seia.org/initiatives/concentrating-solar-power>.
- 45) . . Available from: <http://science.howstuffworks.com/environmental/green-science/thin-filmsolar-cell.htm>.
- 46) Wood C, Drewes K. *Vast Solar: improving performance and reducing cost and risk using high temperature modular arrays and sodium heat transfer fluid*. 2019. Available from: <https://www.semanticscholar.org/paper/Vast-Solar%3A-improving-performance-and-reducing-cost-Wood-Drewes/0d51d1a9a3d686d95a619d086639f79db33b3348>.
- 47) Ho CK. Review of avian mortality studies at concentrating solar power plants. Author(s). 2016. Available from: <https://doi.org/10.1063/1.4949164>.
- 48) World Uranium Mining Production. 2021. Available from: <https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx>.
- 49) Radiological Safety in Uranium Mining and Milling, Guidelines NO. AERB/FE-FCF/SG-2. 2007. Available from: <https://www.aerb.gov.in/images/PDF/CodesGuides/NuclearFacility/FuelCycleFacilities/4.pdf>.
- 50) Tripathi RM, Sahoo SK, Jha VN, Khan AH, Puranik VD. Assessment of environmental radioactivity at uranium mining, processing and tailings management facility at Jaduguda, India. *Applied Radiation and Isotopes*. 2008;66(11):1666–1670. Available from: <https://dx.doi.org/10.1016/j.apradiso.2007.12.019>. doi:10.1016/j.apradiso.2007.12.019.
- 51) Natarajan R. Reprocessing of spent nuclear fuel in India: Present challenges and future programme. *Progress in Nuclear Energy*. 2017;101:118–132. Available from: <https://dx.doi.org/10.1016/j.pnucene.2017.03.001>. doi:10.1016/j.pnucene.2017.03.001.
- 52) Wattal PK. Back end of Indian nuclear fuel cycle-A road to sustainability. *Progress in Nuclear Energy*. 2017;101:133–145. Available from: <https://dx.doi.org/10.1016/j.pnucene.2017.03.004>. doi:10.1016/j.pnucene.2017.03.004.
- 53) . . Available from: <https://world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it.aspx>.
- 54) Safety I, Standards. IAEA Safety Standards, Regulations for the Safe Transport of Radioactive Material 2018 Edition, International Atomic Energy Agency, Vienna, 2018. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1798_web.pdf.
- 55) Karkhanis PP, Agarwal K. Impact Testing of High-Level Waste Canisters. *BARC Newsletter*. 2016;p. 47110806–47110806. Available from: https://inis.iaea.org/search/search.aspx?orig_q=RN:47110806.
- 56) Transport of Radioactive Materials, 2021. . Available from: <https://world-nuclear.org/information-library/nuclear-fuel-cycle/transport-of-nuclear-materials/transport-of-radioactive-materials.aspx>.
- 57) International Advisory Committee report to the International Atomic Energy Agency, The International Chernobyl Report - An Overview. 1991. Available from: <https://www.iaea.org/publications/3756/the-international-chernobyl-project>.
- 58) JSTS Failure Data Base/ 100 selected cases. *Chernobyl Accident*. Available from: <http://www.sozogaku.com/fkd/en/hfen/HA1000644.pdf>.
- 59) Sources And Effects Of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation. *UNSCEAR 2000 REPORT*. 2000;I.
- 60) Three Mile Island, A report to the commissioners and to the public. 1980. Available from: <https://www.osti.gov/biblio/5395798-three-mile-island-report-commissioners-public-volume>.
- 61) Backgrounder to TMI-2 Accident. . Available from: <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.pdf>.
- 62) Institute of Nuclear Power Operations, USA, Special Report on Fukushima Daiichi (INPO 11-005), 2011. . Available from: http://hps.org/documents/inpo_fukushima_special_report.pdf.
- 63) Joseph Miller, Fukushima Dai-ichi Nuclear Power Station accident, EDA, 2011. 2011. Available from: <http://www.slideshare.net/jsmeda/fukushima-daiichi-nuclear-power-station-accident-april19-2011>.
- 64) Fear and stress outweigh Fukushima radiation risk, 2013. . Available from: <https://www.world-nuclear-news.org/Articles/Fear-and-stress-outweigh-Fukushima-radiation-risk>.
- 65) Background radiation. . Available from: <https://research.csu.edu.au/integrity-ethics-compliance/radiation/forms-templates-proformas/radiation-life-background>.
- 66) What is Background Radiation?. . Available from: http://www.world-nuclear.org/uploadedFiles/org/Features/Radiation/4_Background_Radiation%281%29.pdf.
- 67) Sources of Radiation. . Available from: <https://www.nrc.gov/about-nrc/radiation/around-us/sources.html>.
- 68) Radiation Exposure from Medical Diagnostic Imaging Procedures. . Available from: <https://hps.org/documents/meddiagnosticimaging.pdf>.
- 69) Radiation Exposure and Cancer. US NRC. . Available from: <https://www.nrc.gov/about-nrc/radiation/health-effects/rad-exposure-cancer.html>.
- 70) Conca J. World-Wide Risk From Radiation Very Small, 2016. . Available from: <https://www.forbes.com/sites/jamesconca/2016/06/24/radiation-poses-little-risk-to-the-world/?sh=5b7f30044e16>.
- 71) Understanding Cancer, 2016. American Association for Cancer Research. . Available from: https://www.onhealth.com/content/1/cancer_types_treatments.
- 72) Bajaj SS. Regulatory practices for nuclear power plants in India. *Sadhana*. 2013;38(5):1027–1050. Available from: <https://www.ias.ac.in/article/fulltext/sadh/038/05/1027-1050>.
- 73) Fritsche UR. Energy And Land Use. *International renewable energy Agency IRENA& UN Convention to Combat, desertification*, . 2017. Available from: http://inas.org/tl_files/inas/downloads/land/IINAS_2017_UNCCD-IRENA_Energy-Land_paper.pdf.
- 74) Uchiyama Y. Life cycle assessment of renewable energy generation technologies. *IEEE Transactions on Electrical and Electronic Engineering*. 2007;2(1):44–48. Available from: <https://dx.doi.org/10.1002/tee.20107>. doi:10.1002/tee.20107.
- 75) Neumeyer C, Goldston R. Dynamic EROI Assessment of the IPCC 21st Century Electricity Production Scenario. *Sustainability*. 2016;8(5):421–421. Available from: <https://dx.doi.org/10.3390/su8050421>.

- 76) Peter E, Hodgson E. Peter E Hodgson, Energy, The Environment and Climate Change, Imperial College Press, 2010. Imperial College Press. 2010. Available from: <https://www.imperial.ac.uk/environmental-policy/research/themes/energy-climate/>.
- 77) EROI – A Tool To Predict The Best Energy Mix, 2015. . Available from: <https://www.forbes.com/sites/jamesconca/2015/02/11/eroi-a-tool-to-predict-the-best-energy-mix/?sh=25f558fea027>.
- 78) Kessides N, Ioannis DC, Wade. Deriving an Improved Dynamic EROI to Provide Better Information for Energy Planners. *Sustainability*. 2016;3:2339–2357. Available from: <https://ideas.repec.org/a/gam/jsusta/v3y2011i12p2339-2357d15147.html>.
- 79) Meldrum J, Nettles-Anderson S, Heath G, Macknick J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters*. 2013;8(1):015031–015031. Available from: <https://dx.doi.org/10.1088/1748-9326/8/1/015031>.
- 80) Levelized Cost Of Energy, Levelized Cost Of Storage, and Levelized Cost Of Hydrogen. . Available from: <https://www.lazard.com/perspective/lcoe2020>.
- 81) Ueckerdt F, Hirth L, Luderer G, Edenhofer O. System LCOE: What are the costs of variable renewables? *Energy*. 2013;63:61–75. Available from: <https://dx.doi.org/10.1016/j.energy.2013.10.072>. doi:10.1016/j.energy.2013.10.072.
- 82) NEA (2005), “Projected Costs of Generating Electricity: 2005 update”, Nuclear Energy Agency and International Energy Agency.. 2005. Available from: https://www.oecd-neo.org/jcms/pl_14002/projected-costs-of-generating-electricity-2005-update.
- 83) Grover RB. Role of Nuclear Energy in India's Energy Mix. *IANCAS Bulletin*. 2006.
- 84) Kamerschen DR, Thompson HG. Nuclear and Fossil Fuel Steam Generation of Electricity: Differences and Similarities. *Southern Economic Journal*. 1993;60(1):14–14. Available from: <https://dx.doi.org/10.2307/1059927>. doi:10.2307/1059927.
- 85) Nuclear Electricity Generation: What Are the External Costs? OECD, NEA4372, Nuclear Energy Agency, 2003. . OECD. 2003. Available from: https://www.oecd-neo.org/jcms/pl_13756/nuclear-electricity-generation-what-are-the-external-costs?details=true.
- 86) Mishra UC. U.C.Mishra, Report No. IAEA.-R-2717-F, Relative radiation hazards of coal based and nuclear power plants, 1983.. 1983.
- 87) Wind Energy. . Available from: <https://mnre.gov.in/wind/current-status>.
- 88) Solar Energy. . Available from: <https://mnre.gov.in/solar/current-status/>.
- 89) Kumar R, Ojha K, Ahmadi MH, Raj R, Aliehyaei M, Ahmadi A, et al. A review status on alternative arrangements of power generation energy resources and reserve in India. *International Journal of Low-Carbon Technologies*. 2020;15(2):224–240. Available from: <https://dx.doi.org/10.1093/ijlct/ctz066>. doi:10.1093/ijlct/ctz066.
- 90) From a webinar, Reducing CO2 footprints of India's coal-based power sector. 2020. Available from: <https://www.youtube.com/watch?v=nqYNMl70zq0>.
- 91) Government of India: Department of Atomic Energy. . Available from: <https://dae.gov.in/node/133>.
- 92) Mohan A. Whose land is it anyway? Energy futures & land use in India. *Energy Policy*. 2017;110:257–262. Available from: <https://dx.doi.org/10.1016/j.enpol.2017.08.025>. doi:10.1016/j.enpol.2017.08.025.
- 93) Vishwanathan SS, Garg A. Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India. *Climatic Change*. 2020;162(4):1877–1891. Available from: <https://dx.doi.org/10.1007/s10584-019-02616-1>. doi:10.1007/s10584-019-02616-1.
- 94) . . Available from: <https://www.nrdc.org/experts/anjali-jaiswal/road-paris-indias-advancement-its-climate-ple>.
- 95) Mahadeva R, Iyer. The Saga of Atomic Energy in India- Why is Nuclear Power still Subcritical? Delhi. Authors Press. 2020.
- 96) Ministry of External Affairs: Government of India. . Available from: https://www.mea.gov.in/rajya-sabha.htm?dtl/27300/QUESTION_NO2812_FOREIGN_COUNTRIES_HAVING_NUCLEAR_PACT_WITH_INDIA.