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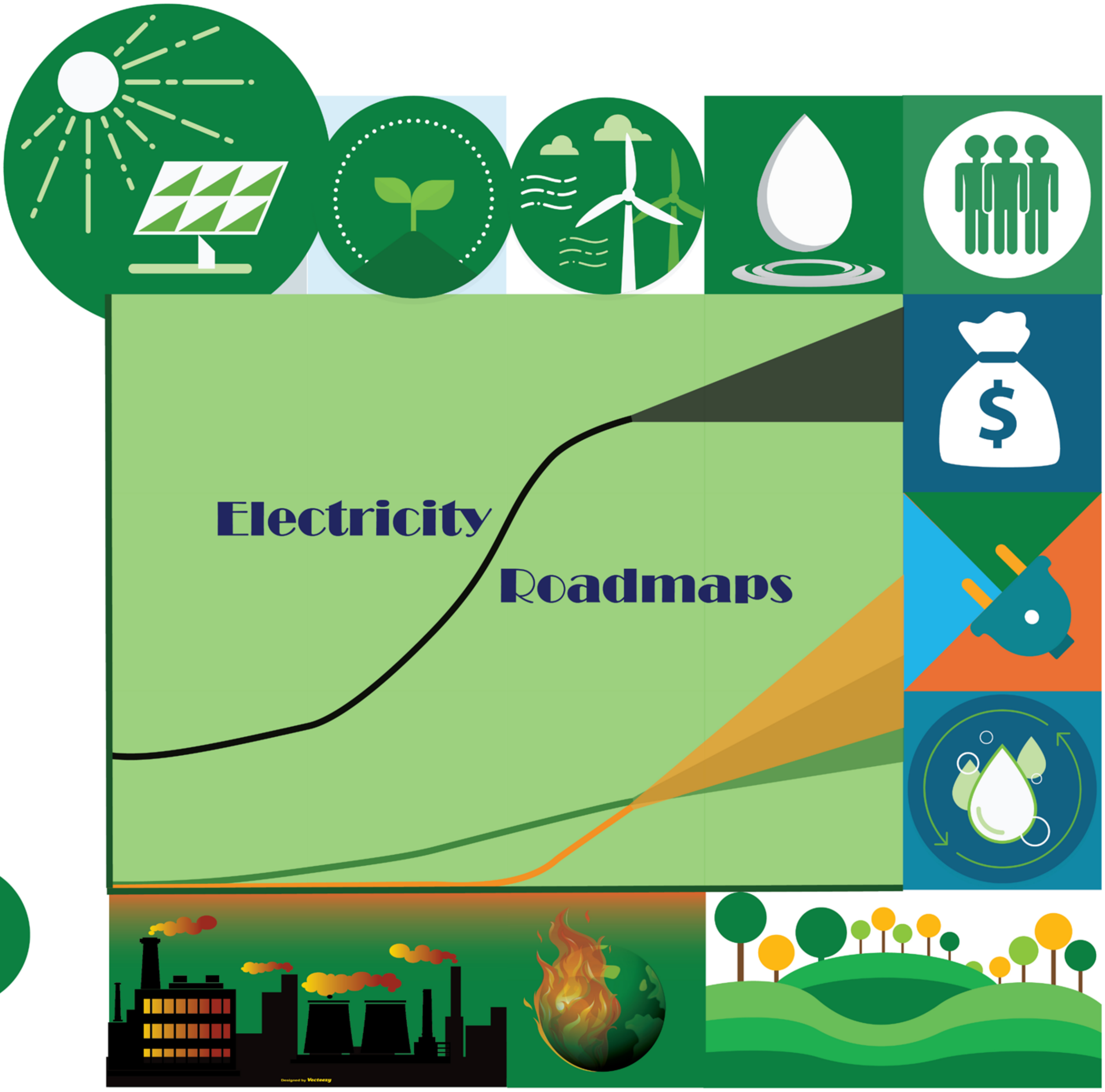
ELECTRICITY TRANSITION ROADMAPS

Comparative Evaluation of Long-Term Low Carbon Electricity Transition Roadmaps for India



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Electricity Transition Roadmaps

Comparative Evaluation of Long-Term Low Carbon Electricity Transition Roadmaps for India: A Supply Side Assessment

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Shakti Sustainable Energy Foundation seeks to facilitate India's transition to a sustainable energy future by aiding the design and implementation of policies in the following areas: clean power, energy efficiency, sustainable urban transport, climate change mitigation and clean energy finance.

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List of Abbreviations

SDGs: Sustainable developmental goals
CCS: Carbon capture and storage
RE: Renewable energies (solar and wind only, unless specified)
ORE / Other RE: other renewable energies (excluding solar and wind)
GHGs: Greenhouse gas emissions
PM10: Particulate Matter emissions (smaller than 10 µm)
LCOE: Levelized Cost of Electricity generation
LEAP: Long-range Energy Alternative Planning model
TIMES: The Integrated MARKAL (Market Allocation) model
MARKAL: Market Allocation model
CGE: Computational General Equilibrium model
(R): Reference roadmap scenarios
(A): Alternate roadmap scenarios
N: Number of studies (sample size)
Coal: Sub- and Super-critical coal power plants
Solar / Solar PV: Utility-scale ground mounted photovoltaic systems
Wind: Horizontal axis on-shore large wind turbines
Gas: Natural gas combined cycle power plants
Nuclear: Nuclear power plants
Hydro: Large hydro power stations with dams
Solar CSP: Concentrated solar thermal power

EXECUTIVE SUMMARY

Background

Low carbon electricity transition roadmaps for future power supply options are valuable tools for developing India's climate mitigation strategies. Electricity system modeling to understand future trajectories and developments of the power sector has become a norm to support the future energy policies of any nation. Various energy system models have been developed in recent years that have different capabilities which are better suited for different purposes. As a result, many modeling studies show significant differences in their predictions and projected future scenarios. Hence, harmonizing, comparing and interpreting the results of different modeling studies within a single framework becomes necessary as they all could share a common objective of modeling the future of India's power system for instance. Further, most of the future roadmaps are developed keeping climate mitigation as their utmost priority and often ignore other socio-environmental aspects of energy transition. Hence, there is a need to evaluate and quantify: (i) the key differences between the major electricity transition roadmaps and scenarios developed for India; (ii) the co-benefits and trade-offs of different electricity transition roadmaps from multiple sustainability perspectives (in addition to climate mitigation); (iii) benchmark India's transition roadmaps with other emerging and developed economies in the world.

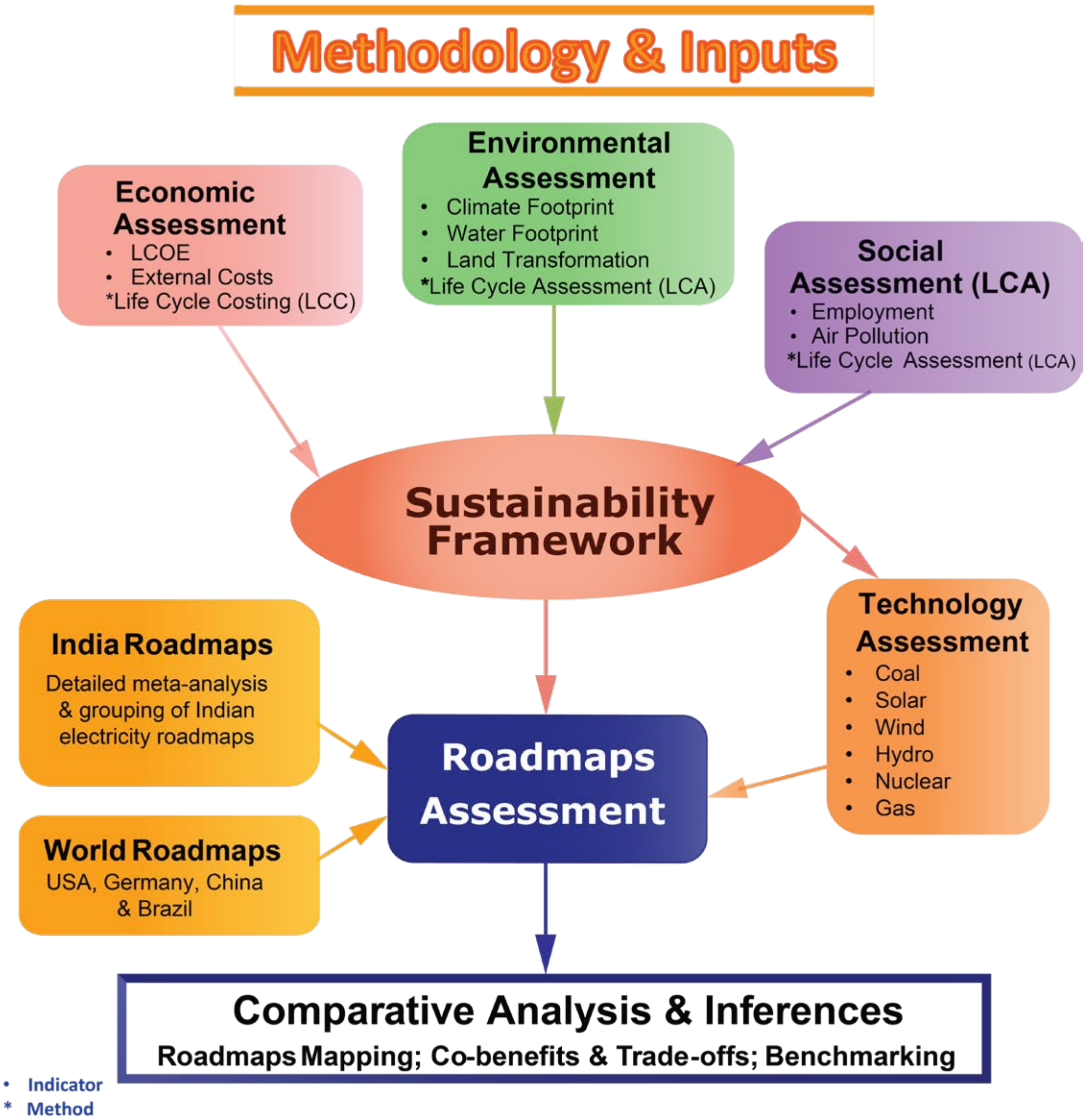
Objective

This study aims to provide detailed insights into the future electricity-mix anticipated by various India specific modeling studies in the last five years and intends to address the following energy policy relevant questions in an Indian context:

1. What kind of impacts could future electricity-mixes have on multiple sustainability indicators?
2. What are the projections for the major electricity sources in India's future roadmaps?
3. How much increase in renewable energy share is expected across the modeling studies?
4. What types of electricity system models are prevalent in India-specific modeling studies?
5. How do future Indian electricity-mix projections compare with other emerging and developed economies across the world?

Methodology

In this work, we conducted a comparative review of major low carbon electricity transition roadmaps developed specifically for India from a supply side perspective. Overall, we reviewed 16 India-specific modeling studies with a total of 41 roadmap scenarios; five studies from think tanks and academia each, four studies from international organizations and two studies from governmental or related agencies. We first harmonized the electricity generation-mix predictions for India in 2030 and 2050, and generically compared the electricity supply trends across various electricity modeling studies. A robust sustainability indicator-wise comparison on the performances of the electricity roadmaps was possible only for 2030 due to data availability issues and the short-term focus of most modeling studies in an Indian context. For robust comparison of electricity roadmaps, we adopted a bottom-up scenario analysis based approach wherein a series of indicators from environmental (climate footprint, water footprint, land transformation), economic (LCOE, external costs) and social (employment, air pollution) dimensions were chosen and integrated within our "Sustainability Framework" to assess the multi-dimensional aspects of electricity supply technologies (see graphical representation below). Then, the technology level impacts were aggregated to arrive at the cumulative impacts of India's low carbon electricity transition roadmaps. Lastly, we collected electricity supply data on low carbon electricity transition roadmaps for other emerging and developed economies (China, Brazil, the USA and Germany) from 11 international studies with a total of 27 roadmap scenarios. Through a short international comparative assessment, we provide glimpses on where the future electricity supply trends projected for India stand in comparison to other countries.



Methodology and Inputs used to assess India's low carbon electricity transition roadmaps.

Inferences and Conclusion

I. Generic Comparative Assessment of India's Roadmaps (comparing median values only)

- The median for alternate roadmap scenarios predict slight increases in coal power capacities during 2020 to 2030 and expect that the coal capacities will slightly drop afterwards and then stabilize around 2020 installed capacities (approx. 205 GW). Further, most roadmaps predict dramatic reductions for coal share in their annual electricity generation-mixes in the alternate scenarios: from over 72% in today's grid to 49% in 2030 to 21% in 2050.
- For nuclear power, the future predictions are very conservative and most alternate scenarios expect that nuclear capacities might stabilize around 17 GW to 20 GW in the coming decades; that is, nearly thrice as much increase in nuclear power capacity as of today (7 GW in 2020). However, the predictions for natural gas based power plants are promising: 45 GW in 2030 to 115 GW in 2050 (compared with 25 GW in 2020); this might be because of their flexible role in balancing and maintaining the grid stability during peak loads and also during non-availability of renewable energy sources in the future power grid, among other reasons.
- For solar power, most alternate scenarios project an ambitious rise in solar capacity by 2030 and 2050 in comparison to today's installed capacity; for example, the median values for alternate scenarios in 2030 and 2050 are higher by a factor of 5 and 15 in comparison to today's solar capacity installations (35 GW), respectively. The same trend holds true for wind power projections, except that their capacity projections are not as dramatic as for solar power. Nevertheless, the median values for alternate scenarios predict 130 GW and 290 GW of wind power capacities by 2030 and 2050, respectively; that is, an increase in the total wind power capacity by a factor of 3 to 8 in comparison to today's wind power capacity (38 GW). The RE share (solar and wind only) in annual electricity generation is expected to rise from 8% in 2020 to 23% in 2030 to 45% in 2050 in alternate scenarios, and the RE share in total power capacity is projected to rise from 20% in 2020 to 39% in 2030 to 59% in 2050 in alternate scenarios. Further, the majority of roadmap scenarios expect large hydro to stabilize after reaching around 70 GW in the coming decades, from 46 GW in 2020.
- Lastly, the predictions for other renewable energies mainly include bioenergy (primarily) and micro/small hydro based electricity generation, and the roadmap scenarios expect higher contributions from these renewable energy sources in the future electricity-mix. However, the possible contributions from prospective renewable energy technologies are ignored or highly underrated in the present modeling studies.

II. Low Carbon Electricity Transition Roadmaps: Benefits & Trade-offs

- Our comparative assessment of India's future low carbon electricity transition roadmaps finds that the scenarios with a very high share of renewables (solar PV and wind) and lower absolute coal power generation perform not only well in terms of climate footprint, but they could have dramatic co-benefits in terms of water footprint, air pollution, external costs and employment generation indicators. The opposite is true with respect to coal dominated roadmap scenarios. The reason for a strong dependence of the roadmap scenarios on mainly coal, solar and wind electricity sources is because coal power has significant impacts on other sustainability indicators (in addition to climate change) when compared to renewables. For instance, it is estimated that coal emits 36 to 68 times more GHG emissions, consumes 10 to 400 times more fresh water resources and emits 13 to 38 times more particulate matter emissions in comparison to wind and solar, respectively. Hence, the external costs for coal power generation that account for some of the above mentioned environmental impacts indicate that coal is a very expensive electricity source from a socio-environmental perspective and suggests that the external costs for coal power could be 26 to 36 times higher than for wind and solar, respectively. Thus, it becomes evident that the impacts of electricity roadmaps increase 10s of times for every unit of coal power generated in their electricity generation-mix and likewise could decrease 10s of times for every unit of coal power being replaced by renewables.

- The mean system costs for the roadmaps with very high renewables are optimal in comparison to coal dominated roadmaps. The cost savings resulting from the lower LCOE of renewables (in comparison to coal power) and the significantly avoided climate damage costs associated with coal (e.g., carbon costs) in future electricity markets could be utilized to build a strong support infrastructure for a very high penetration of renewable energies in India's future power grid.
- The employment indicator favors the roadmaps with higher absolute renewable power generation contribution in the total electricity-mix, particularly solar power as it would create 5 times more jobs than coal for the same amount of electricity generation.
- Coal power accounts for nearly 92% of the total cumulative GHG emissions during 2020 to 2030 (comparing median values). Hence, we highlight that reducing the dependence on coal power generation more ambitiously – e.g., adopting the best performing roadmap scenarios instead of the pathway suggested by the median roadmap - could yield considerable "emission space" for GHGs from other sectors in India, for example heavy metal industries and other essential industries wherein there are often no alternatives for emission reductions (in the short run). Further, we underscore again that a shift towards renewables could help the country to reduce GHG emissions by 36 to 68 times for every unit of coal electricity being replaced.

III. Electricity-Climate-Water Nexus

- We recommend a radical shift in modeling future electricity roadmaps for India wherein the water footprint should be given its due place and must be considered as one of the key criteria, along with climate change and cost optimization. If direct integration of water criteria into the existing models is difficult in the short run, then we suggest that the projected low carbon roadmap scenarios should be re-evaluated for freshwater consumption optimization through scenario based bottom-up approaches (like this study). We further caution the policy makers that ignoring the water footprint indicator during electricity system modeling and policy design could also favor sub-optimal clean technologies that might not become practically scaled-up on-the-ground in future India owing to the strong influence from water scarcity issues. Moreover, we underscore that a responsible action towards conserving India's freshwater resources will certainly benefit the country directly; unlike climate mitigation efforts that often need concerted action across the globe and whose benefits are often indirect and circuitous.
- Moreover, we underscore that accounting for water footprint in electricity modeling and energy policy studies not only helps in fine-tuning and filtering the climate friendly technology-mix to meet on-the-ground India-specific requirements, but could also greatly support in directing the development of India's future electricity sector towards water conservation and efficient water utilization in the coming era of water scarcity and global warming.

IV. Electricity Modeling in India

- Although the electricity models used in India-specific studies ranged from simple excel based simulation type models to large scale simulation and optimization models to integrated models based on computational general equilibrium, we observed that the open source modeling tools have not yet found their place in India's modeling community. We call for attention from energy modelers in the country to the application of open source based tools and data sets in modeling India's future electricity system.
- In general, we found that the modeling granularity, data and assumptions used for projecting 2030 scenarios are more reliable than 2050 scenario projections, and also that most of the India-specific modeling studies have a short-term focus on prospective electricity and storage technologies. This could be because of the lack of Indian-specific detailed future technological studies on different electricity sources and prospective technology types till 2050. In addition, we encountered serious data availability issues (India-specific) while quantifying the technological impacts on the different sustainability indicators chosen in this study. We certainly recommend more policy oriented research in this direction.

V. Benchmarking India's Roadmaps

- Benchmarking India's electricity transition roadmaps with other emerging and developed economies highlights that the alternate scenarios for India's future expect ambitious reductions in the coal share and significant escalations in the RE share in comparison to other countries as well as to India's present status-quo. Further, the median projection for India's RE share by 2030 (23%) is second only to Germany (55%) and India outperforms all the other three countries that were studied.
- Lastly, we observed that India is lagging behind other countries, especially when compared to developed economies (Germany and the USA), in terms of the development of open source based electricity modeling tools and their applications in an Indian context.

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1. INTRODUCTION

Low carbon electricity transition roadmaps for future power supply options are valuable tools for developing India's climate mitigation strategies. Electricity system modeling to understand future trajectories and developments of the power sector has become a norm to support the future energy policies of any nation. Given the complexity of interactions between the electricity sector and socio-economic and environmental dimensions of a society, modeling Indian power system and developing future scenarios to understand its evolution is the necessary exercise that has to be undertaken; so as to foresee the future challenges and hence take necessary actions beforehand. Moreover, electricity system models can greatly assist the policy makers to steer the development of power system towards pre-defined future policy goals. However, the uncertainties about the future electricity demand, electricity supply options, costs and future advancements of different technologies complicate the electricity system modeling task [1]. While initial modeling studies focused on low cost optimization and energy security aspects, the recent studies are strongly driven by global climate change policy instruments and the need to achieve significant greenhouse gas reductions by the 2030 or the middle of 21st Century. Given its complexity, the electricity sector has encountered a series of challenges in recent years (in addition to global warming) that include water availability, affordability and reliability of electricity supply infrastructure, air and water pollution, land transformation and other socio-economic issues. Hence, there is a necessity for fair development of the electricity sector towards meeting multiple sustainable developmental goals (SDGs) with minimal impact on the environment and our surroundings.

There is a necessity for fair development of the electricity sector towards meeting multiple SDGs with minimal impact on the environment and our surroundings.

Various energy system models have been developed in the recent years that have different capabilities and are better suited for different purposes: (a) optimization models covering the entire energy system that generate future normative energy scenarios; (b) simulation models providing future forecasts for entire energy system; (c) exclusive power system and electricity market models for generating future scenarios/predictions or for operational decisions and business planning; and (d) qualitative mixed methods models for providing narrative scenarios [2]. As a result, many modeling studies show significant differences in their predictions and projected future scenarios. Hence, harmonizing, comparing and interpreting the results of different modeling studies within a single framework becomes necessary as they all could share a common objective of modeling the future of India's power system for instance. Further, most of the future roadmaps are developed keeping climate mitigation as their utmost priority and often ignore other socio-environmental aspects of energy transition. Hence, there is a need to evaluate and quantify: (i) the key differences between the major electricity transition roadmaps and scenarios developed for India; (ii) the co-benefits and trade-offs of different electricity transition roadmaps from multiple sustainability perspectives (in addition to climate mitigation); (iii) benchmark India's transition roadmaps with other emerging and developed economies in the world.

This work can greatly aid in quantitatively assessing the co-benefits and trade-offs of low carbon electricity transition roadmaps developed for India.

In this work, we conduct a comparative review of major low carbon electricity transition roadmaps developed specifically for India from the supply side perspective. We harmonize the electricity generation-mix predictions for 2030/2050 and compare the electricity supply trends projected for India across various electricity modeling studies. Further, we highlight the best and the poorest performing roadmap scenarios for 2030 and estimate the cumulative impacts of different electricity-mix scenarios from 2020 to 2030 on multiple sustainability indicators: climate footprint, water footprint, land transformation, air pollution, levelized cost of electricity generation, external costs and employment generation. Finally, we benchmark India's electricity supply trends with other emerging (China and Brazil) and developed (USA and Germany) economies. In a nutshell, our work can greatly aid in assessing the co-benefits and trade-offs of low carbon electricity transition roadmaps developed for India (quantitatively), and also might help in foreseeing the unintended consequences of climate action on other ecosystem and human services oriented sustainability indicators, if any. Furthermore, the results of our study can assist in integrating climate mitigation efforts with sustainable developmental goals (SDGs) and help policy makers in developing integrated energy policies oriented towards the long-term sustainable development of India.

1.1. Indian Electricity Sector

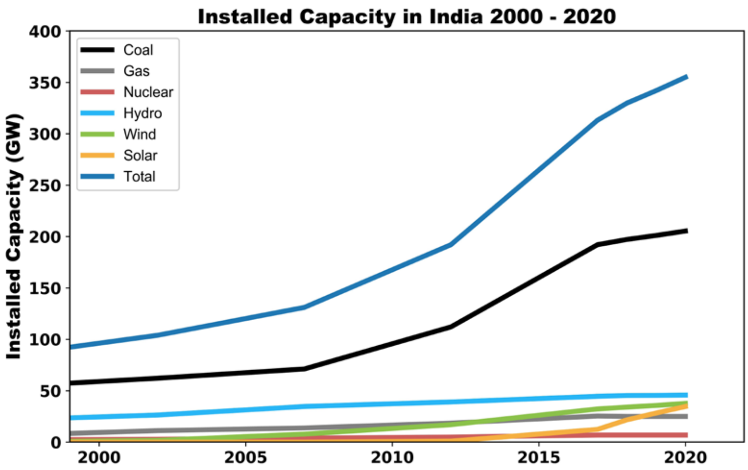
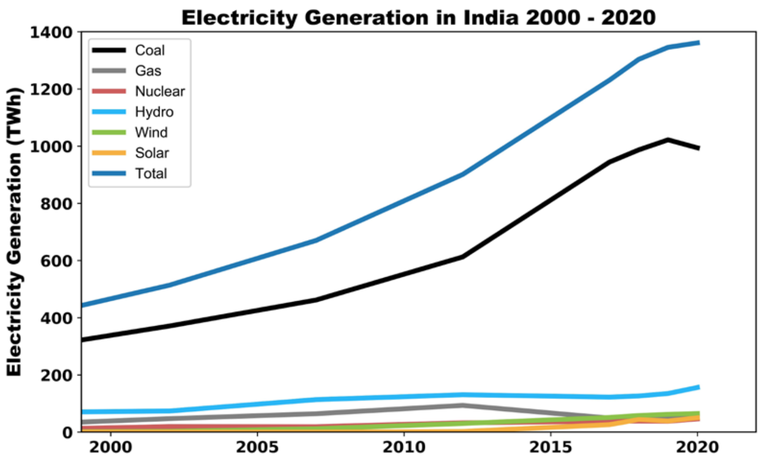
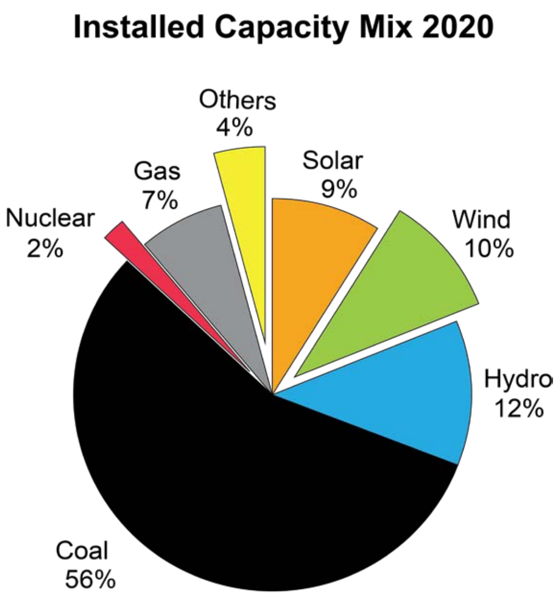
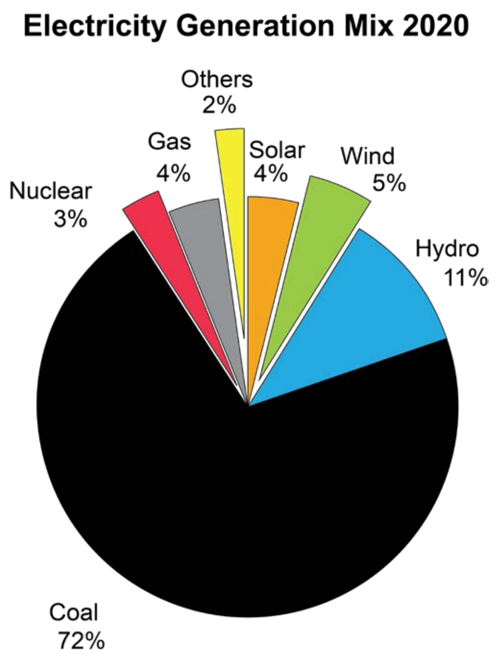


Figure 1: The historic growth of different power sources in Indian electricity sector from 2000 to 2020.







The Pie charts provide the breakdowns for different power sources in India's electricity-mix in 2019-2020.

Source: [5-8]

India's economic development is predominantly driven by fossil fuel based energy sources, and the economy is projected to grow rapidly for the next few decades [3]; correspondingly, the electricity sector in the country is expected to grow several folds between 2010 and 2050 [4]. Coal power has dominated the Indian electricity sector so far (see Figure 1), and more than 72% of the total electricity generation came from coal in 2019-2020 [5]. Figure 1 shows the historic growth of different power sources in Indian electricity sector from 2000 to 2020 for both installed capacity and electricity generation [6,7]. The Pie charts provide the breakdowns for different power sources in India's electricity-mix in 2019-2020 [5,8]. To decouple the electricity sector from rising greenhouse gas emissions (GHGs), the Indian government has already started a series of initiatives and national missions. For instance, India's renewable energy target of 175 GW by 2022 is one of the most ambitious renewable energy programs across the world; India has pledged in the "Paris agreement" at the COP21 to reduce its GDP emission intensity by 33-35% by 2030 (in comparison to 2005 levels), and to meet at least 40% of its power capacities via non-fossil fuel sources by 2030. Further, the Prime Minister's Council envisions eight multifaceted national missions to deal with the challenges of climate change as part of the National Action Plan on Climate Change (NAPCC), including special focus on solar energy and energy efficiency – among others [9]. Furthermore, we underscore that India is one of the few countries deemed to have a 2-degrees compatible Nationally Determined Contributions (NDCs) [10,11]. Because of all these initiatives and increasing market competitiveness of renewable energies, the share of coal in the electricity-mix of the country is going-down since the last few years (see Figure 1). For instance, the share of coal in India's electricity generation-mix reduced from 77% in 2015-16 to 72% in 2019-20, whereas the share of new renewable energies increased from 6% to 10% during the same time period [5,8]. Consequently, most of the low carbon electricity transition roadmaps for India envision significantly higher growth rates for renewable energies in the coming decades, although in varying proportions.

This study aims to provide detailed insights into the future electricity-mix anticipated by various India specific modeling studies in the last five years.

This study aims to provide detailed insights into the future electricity-mix anticipated by various India specific modeling studies in the last five years and intends to address the following energy policy salient questions in an Indian context:

1. What kind of impacts could future electricity-mixes have on multiple sustainability indicators?
2. What are the projections for the major electricity sources in India's transition roadmaps?
3. How much increase in renewable energy share is expected across the modeling studies?
4. What types of electricity system models are prevalent in India specific modeling studies?
5. How do future Indian electricity-mix projections compare with other emerging and developed economies across the world?

2. METHODOLOGY AND APPROACH

2.1. Sustainability Framework

A Sustainability Framework that is inclusive of economic, environmental and social dimensions was developed to evaluate India's low carbon electricity transition roadmaps. A series of indicators from economic (LCOE, External costs), social (employment, air pollution) and environmental (climate footprint, water footprint, land transformation) dimensions were chosen and integrated within this framework to assess the multi-dimensional aspects of electricity supply technologies and low carbon transition roadmaps. **Figure 2** shows the schematic of the methodology and the sustainability framework developed in this policy research study. We first conducted technology level assessments and then evaluated the low carbon electricity transition roadmap scenarios from a bottom-up perspective; that is, technology level impacts were aggregated to arrive at cumulative impacts of roadmap scenarios.

We assess and compare the key low carbon electricity transition roadmaps to identify their co-benefits and trade-offs.

A brief description of the sustainability indicators along with the justification for their choice is provided below.

Environmental Dimension

a) Climate Footprint

Given the exponential growth of electricity sector, decarbonising the electricity system is of utmost importance to meet the India's Nationally Determined Contribution (NDC) targets. Thus, climate footprint as an indicator that accounts for life cycle greenhouse gas emissions (GHGs) from electricity sources measures their decarbonisation potential (expressed in "kg CO_2-eq. /MWh").

b) Water Footprint

There is a strong relationship and interdependency between water and energy. Water plays an important role in the life cycle of electricity sources; for instance, water is used during energy fuel cycle operation (extraction, processing and transportation), power plant manufacturing and operation of power plant utilities, waste disposal and decommissioning stages. Thus, understanding the water-energy nexus will help decision makers to enhance their knowledge about water risks before adding a power project to the grid. We account for life cycle water consumption of electricity sources (i.e., water lost) in this study (expressed in "m^3/MWh").

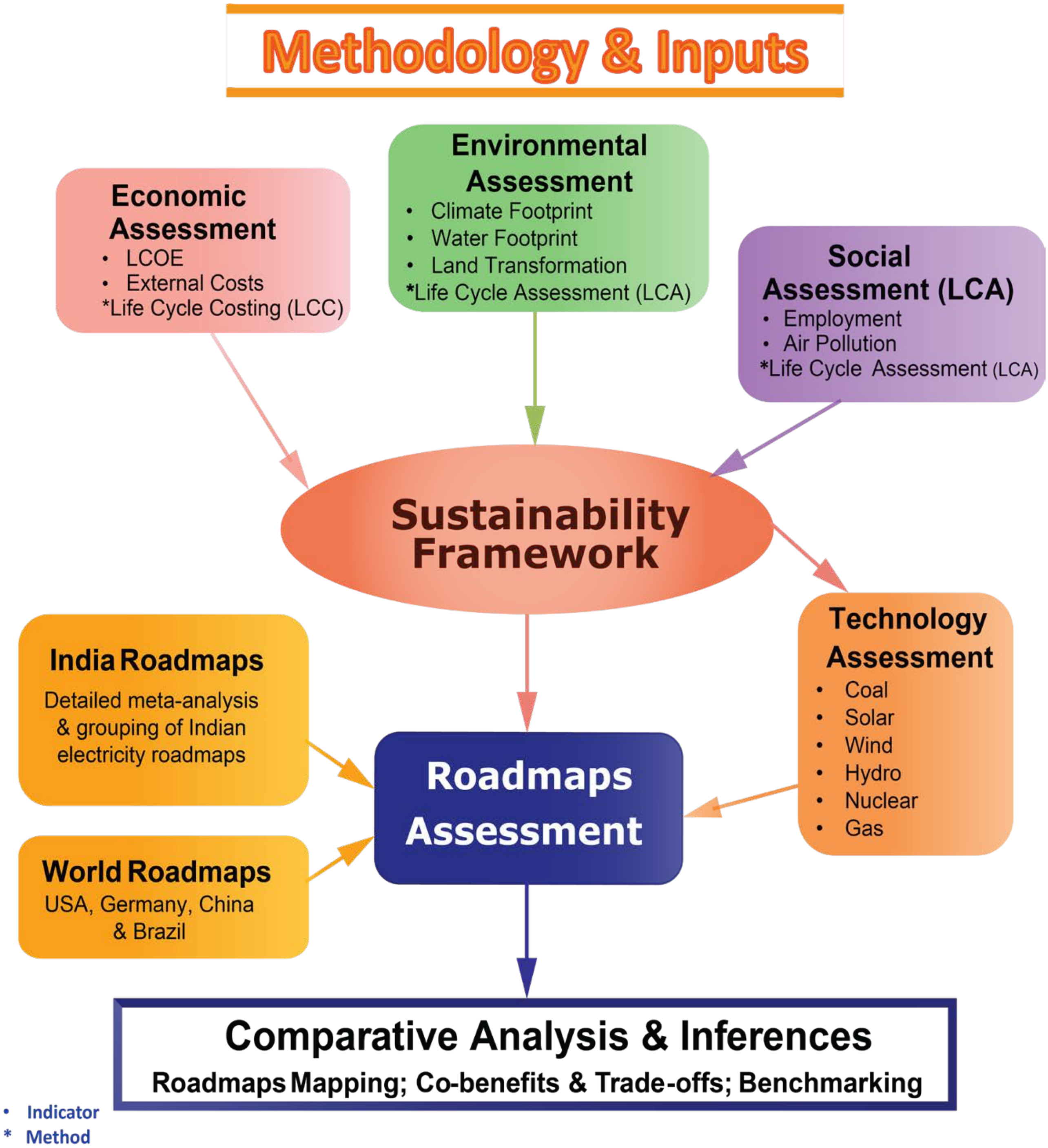


Figure 2: Methodology and Inputs used to assess and benchmark India's low carbon electricity transition roadmaps.

c) Land Transformation

Land is one of the primary components of our biosphere and plays a vital role in maintaining the ecological sustainability. Thus, land footprint represents a major component in sustainability assessment, and we consider land transformation as an indicator to measure the impacts of electricity sources on land. Land transformation includes, but is not limited to, transformed land area for setting up the power plant, mining fuel, fuel transportation, waste disposal and provision of space around the plant. It also accounts for indirect land transformations, such as the land area that goes into upstream processes and land degradation due to pollutants and effluents from the fuel and material cycles, among others. In this study, land transformation is expressed as the ratio of life-cycle land area transformed by an electricity source to its lifetime electricity generation (expressed in "m^2/GWh").

Economic Dimension

a) Levelized Cost of Electricity (LCOE)

The cost aspects play a major role in the deployment of electricity generation technologies and highly influence the power system planning and operations. The life cycle costs of electricity generation account for capital costs, maintenance and operation costs, fuel costs and project financing, among others across the lifetime of a power plant. It is generally expressed as levelized cost of electricity generation, which is a ratio between the overall costs of electricity generation discounted to present values and the lifetime electricity delivered by a power plant (expressed in "INR/kWh").

Electricity sources cause various negative impacts on air, water, land and socio-economic aspects across their life cycle value chains.

b) External Costs

Electricity sources cause various negative impacts on air, water, land and socio-economic aspects (e.g., health impacts, infrastructure and livelihood impacts, agriculture crop loss, energy security issues, and additional infrastructure requirements) across their life cycle value chains. "External costs" intend to quantify these externalities that are not internalized within the current regulatory setup. This study accounts external costs as an indication of potential impacts from electricity sources (expressed in "INR/kWh") that are not captured in their market costs (e.g., LCOE).

Social Dimension

a) Air Pollution

Fourteen of the world's 20 most air polluted cities are located in India [12], and this issue has raised local and international pressures on Indian decision makers in recent years. Further, the impact of power generation on air pollution and hence on human health has been substantial in India, especially because of coal power accounting for more than 70% of electricity supply in the country [13]. Thus, it is apparent that new energy policies must account for the impact of electricity generation on regional air quality (expressed in "kg PM_{10}eq. /MWh").

b) Employment Generation
There is a direct relation between the energy use, economic development and employment growth of a country. Hence, it becomes of the utmost importance to evaluate the impact of different electricity sources on the employment generation in the emerging economy like India. In this study, we account for jobs created across the life cycle value chains of the electricity sources as a metric to measure their employment potential (expressed in "Job-Years/GWh").

2.2. Technology Assessment

A meta-analysis of all the major electricity sources relevant to India's future low carbon electricity transition roadmaps was undertaken and their impacts on the chosen sustainability indicators were quantified. We used life cycle costing (LCOE) and life cycle assessment (LCA) methodologies to quantify the impacts of different technological value chains across their lifetimes on the chosen sustainability indicators (see **Box 1**).

More than 80 studies/reports were shortlisted for the technological meta-analysis after the initial screening and preliminary review of the available literature. Out of these, 50 studies were selected based on the data transparency and consistency, credibility of the data sources and their relevance to the scope of this study. Based on these 50 studies, the impacts of the chosen electricity sources on various sustainability indicators were quantified. However, we underscore that most of the detailed data (esp. upstream data for LCA) comes from global studies due to non-availability of India specific data. **Table 1** shows the technology relevant assumptions with respect to different electricity generation sources considered in this study. We conducted the technology assessments for sub-technology types as well (e.g., solar CSP, wind offshore and coal CCS), but we realized later that most of the roadmap studies in India focus mainly on the generic technology types (mentioned in Table 1); hence, we chose these technology types as the representative ones to quantify the impacts of the future low carbon electricity transition roadmaps in India. The results of this work, that is, quantification and harmonization of the impacts of different electricity sources on the chosen sustainability indicators with respect to a common functional unit (i.e., per unit of electricity) are shown in **Figure 3**. The detailed data and sources used in quantifying and harmonizing the technological impacts are documented in **Tables 1A-7A** in the Supporting Information[1].

We use life cycle methodologies (LCA) to quantify the impacts of different technological value chains on the sustainability indicators.

1. Supporting Information is provided as a separate document attached to this report.

Table 1: Technological assumptions for different electricity sources.

Electricity Source	Technology Type
Coal	Sub- and Super-critical coal power plants (mix)
Solar	Utility-scale ground mounted photovoltaic systems (mix of crystalline and thin film technologies)
Wind	Horizontal axis on-shore large wind turbines
Hydro	Large hydro power stations with dams
Nuclear	Nuclear power plants (preferably Pressurized Water Reactors)
Gas	Natural gas combined cycle power plants

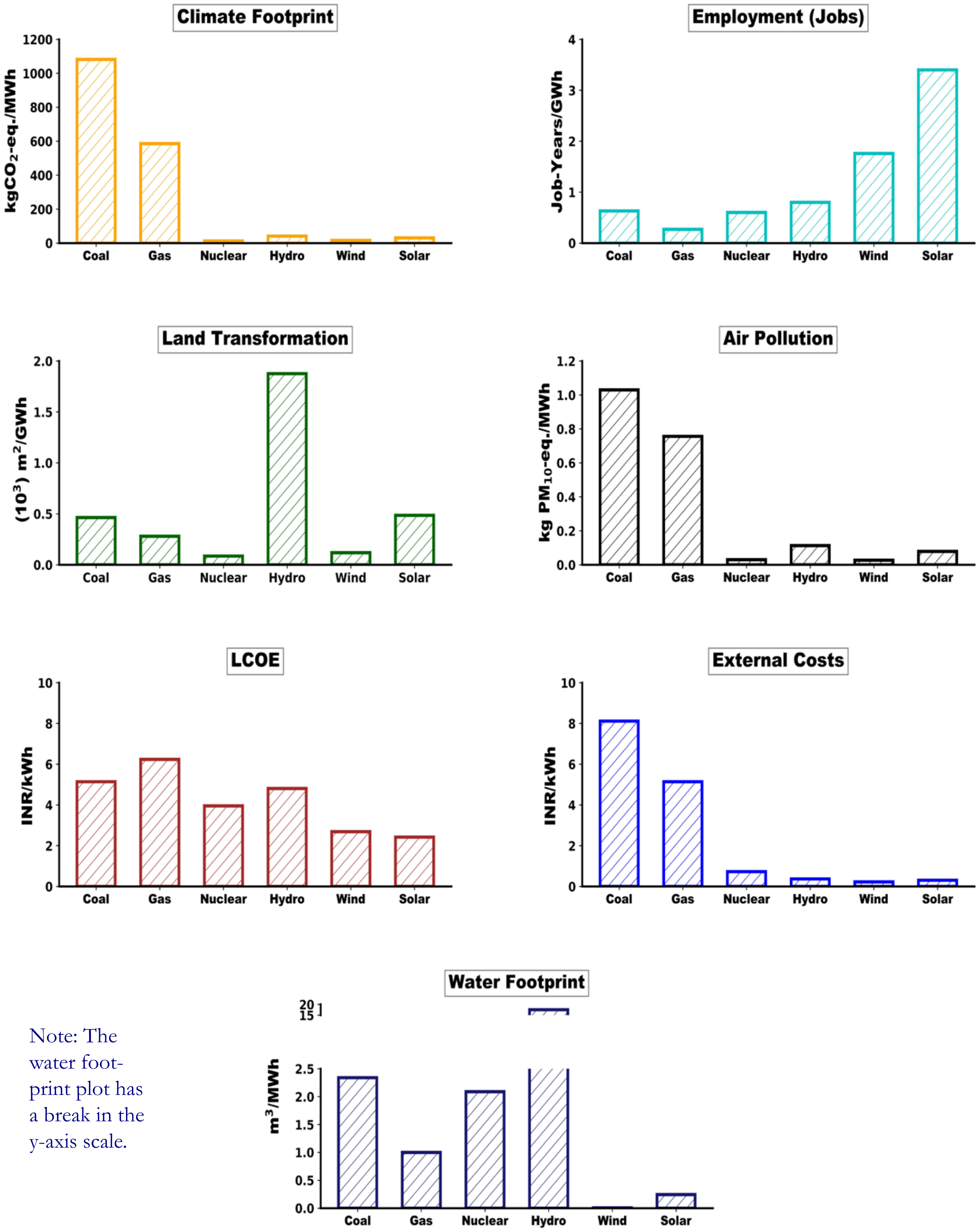
See "Supporting Information" document for more details on our assumptions and data.

BOX 1 : Life Cycle Assessment and Costing Methodologies

Life Cycle Assessment (LCA) is a comprehensive assessment methodology that accounts for the compilation and evaluation of all the resources and potential environmental impacts associated with a technological system's lifecycle, that is, right from its extraction through the use phase to the final disposal of the technology, including recycling part when possible. The life cycle perspective is very useful in preventing problem shifting, for example, from one stage of the lifecycle to another, from one substance to another, from one country to another and from one environmental problem to the other. Because of this capability of LCA to examine and address the linkages and interactions between different components of the entire technological system, it is considered as a valuable support tool in integrating sustainability into the technology design and innovation, and also in framing the environmental policies. LCA is already a backbone of many recent environmental policies in Europe, Japan and many other industrialized countries, and is picking up slowly in the emerging economies (e.g., china). The United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) launched an International Partnership in 2002 which is called the Life Cycle Initiative. The aim of this partnership is to put life cycle thinking into practice along with improving the supporting tools by creating better data and indicators.

On the other hand, Life cycle costing which is often referred as levelized cost of electricity generation (LCOE) accounts for all the capital and operational expenditure of building and operating a power plant across its expected lifetime in relation to its lifetime electricity generation. The costs related to electricity transmission and distribution, and socio-environmental externalities of power generation are generally excluded from this metric. It is for this reason, we account for an additional indicator called "external costs" in our study (just for indicative purpose) that attempts to include the costs related to effects on human health, local environment and global warming, among others.
Sources: [14,15]; https://www.lifecycleinitiative.org/

LCA is already a backbone of many recent environmental policies in Europe, Japan and many other industrialized countries.



Note: The water foot-print plot has a break in the y-axis scale.

Figure 3: Impacts of different electricity sources on multiple sustainability indicators.

2.3. Roadmaps Assessment

An extensive meta-analysis of existing low carbon electricity transition roadmaps for India 2030/2050 was undertaken. After preliminary review of the available scientific literature and India's energy policy landscape, around 60 studies/reports were identified. However, to filter-out the dated reports and modeling tools/methodologies, only studies undertaken after 2010 and that provide proper documentation of their methodology and roadmap scenario data in a consistent and transparent manner were considered for in-depth analysis. Hence, an in-depth analysis and data collection was possible for only 28 of the studies. Figure 1A (in Supporting Information) shows the format used for detailed data collection from the individual modeling studies to conduct our meta-analysis. After collecting detailed data, a second level filtering was done and 16 studies (with a total of 41 roadmap scenarios; see Table 2) were finally chosen for our comparative assessment based on the following parameters: publication year (2015 and afterwards; with the exception of LCSIG2014 and IRADe2014), India-specific studies (rather than global studies), direct or indirect reference or use by other prominent stakeholders in India (e.g., NITI Aayog, Shakti Sustainable Energy Foundation or other prominent Indian think tanks), studies that modeled future roadmaps on their own (rather than studies that conducted statistical analysis on other modeling studies or depended on the modeling results from other studies), the latest and most relevant study that suit the above parameters (if a modeling group has published a series of studies).

16 India specific modeling studies with a total of 41 roadmap scenarios were finally chosen for our comparative assessment.

During the data collection and meta-analysis phase, it was observed that most of the studies have projected electricity roadmaps for India till 2030 only (see Figure 6). Moreover, there is a lack of inclusiveness of prospective electricity and storage technologies, high granular modeling is conducted primarily for short timelines (e.g., 2030) rather than 2050, and data availability on future performances of electricity sources in an Indian context is very limited, especially with respect to the diverse sustainability indicators chosen in this study. Hence, we conducted our roadmaps comparative assessment in two levels:

1. A generic comparison of electricity supply and demand projections for 2030 and 2050 scenarios;
2. A robust sustainability indicator-wise comparison on the performances of the six major electricity sources in India's 2030 electricity roadmap scenarios – both annual (2030) and cumulative impacts (2020-2030) were assessed.

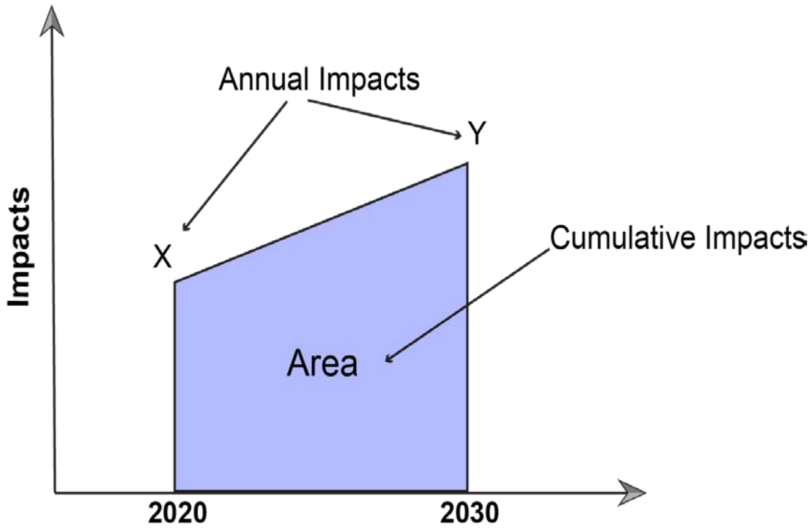


Figure 4: Schematic illustration of our approach to calculate the cumulative impacts from annual values.

We benchmark India's future electricity supply trends with other emerging and developed economies (China, Brazil, the USA and Germany).

The six major electricity sources considered in all the roadmap scenarios are coal, gas, nuclear, hydro, wind and solar. For better comparison across studies and roadmap scenarios, we distinguish between reference and alternate scenarios in our comparative analyses. Further, we use simple straight line escalation to quantify the cumulative impacts during 2020 to 2030 from annual impacts presented in the modeling studies (see **Figure 4**). In addition, we collected electricity supply data on low carbon electricity transition roadmaps for other emerging and developed economies (China, Brazil, the USA and Germany) from 11 international studies with a total of 27 roadmap scenarios. Through a short international comparative assessment, we provide glimpses on where the future electricity supply trends projected for India stand in comparison to other countries.

Finally, we assessed and compared the key alternative low carbon transition roadmap scenarios from environmental, economic and social perspectives via the developed sustainability framework to deduce overarching implications and identify their **co-benefits** and **trade-offs**.

3. KEY ROADMAPS FOR INDIA'S LOW CARBON ELECTRICITY TRANSITION

3.1. Key Modeling Studies and Roadmaps

The complete list of modeling studies reviewed in our work is presented in **Table 2**, along with the details on modeled scenarios selected from each study for our comparative analysis. Overall, we reviewed 16 modeling studies with a total of 41 scenarios; five studies from think tanks and academia each, four studies from international organizations and two studies from governmental or its related agencies (see **Figure 5**). As some studies provided numerous scenarios, while others provided only 2 or 3 scenarios, we put the upper limit of 3 scenarios per modeling study (one reference and two alternate scenarios) to maintain the homogeneity of the comparative results. We nominated a reference scenario for each study, and chose the current trajectory or business-as-usual based scenarios as the reference for the studies that did not explicitly provide the references scenarios. For alternate scenarios, we preferably chose one intermediate scenario and one ambitious scenario whenever the studies provided more than two alternate scenarios. As a result, we ended-up with a total of 16 reference scenarios and 25 alternative scenarios for our comparative analysis. A brief description for all the 16 modeling studies, their methodologies and results are provided in the **Supporting Information** for further reference.

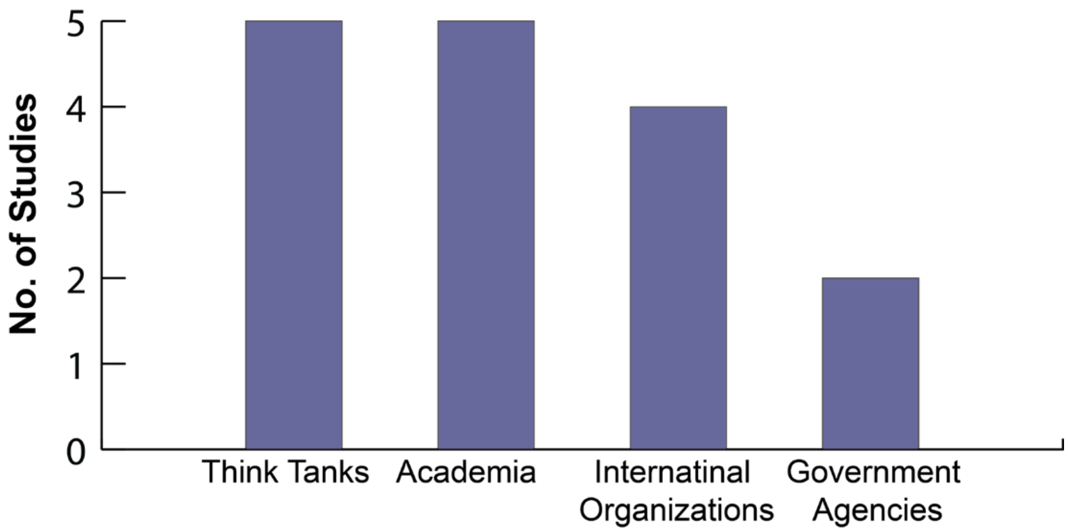


Figure 5: Categorization of the modeling studies.

Table 2: Electricity modeling studies assessed in our work.

Abbreviation	Study Name & Year	Primary Institution / Authors	Timeline	Scenarios (selected for analysis)
CPI2019	Developing a roadmap to a flexible, low-carbon Indian electricity system: interim findings, 2019 [16]	Climate Policy Initiative	2017 - 2030	Thermal Flexibility - Current Trajectory Scenario (**R**), Balanced Flexibility - Current Policy Scenario (**B-CP**), Balanced Flexibility -High RE Scenario (**B-RE**)
CSTEP2015	Quality of Life for All: A Sustainable Development Framework for India's Climate Policy, 2015 [17]	Centre for Study of Science, Technology and Policy	2012 - 2030	Business-as-Usual Scenario (**R**), Sustainable Development Scenario (**SD**)
DDPP2015	Pathways to deep decarbonization in India, 2015 [4]	Deep Decarbonization Pathways Project, IIM Ahmedabad	2005 - 2050	Conventional Scenario (**R**), Sustainable Scenario (**S**)
Greenpeace2015	Energy [r]evolution, A sustainable World Energy Outlook, 2015 [18]	Greenpeace International	2012 - 2050	Reference Scenario (**R**), Energy [R]evolution Scenario (**E[R]**), Advanced Energy [**R**] evolution Scenario (**AE[R]**)
Gulagi2017	The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India, 2017 [19]	Ashish Gulagi, Dmitrii Bogdanov & Christian Breyer	2015 - 2050	Power Scenario (**R**), Integrated Scenario (**I**)
ICRIER2016	A More Sustainable Energy Strategy for India, 2016 [20]	Indian Council for Research on International Economic Relations	2012 - 2047	Business-As-Usual Scenario (**R**), Low-carbon Scenario (**LC**)
IEA2015	India energy outlook, 2015 [21]	International Energy Agency	2013 - 2040	New Policy Scenario (**R**), India Vision Case (**IV**)
IEA2019	World Energy Outlook, 2019 [22]	International Energy Agency	2018 - 2040	Current Policies Scenario (**R**), Stated Policies scenario (**SP**), Sustainable Development Scenario (**SD**)

Table 2: Electricity modeling studies assessed in our work.

Abbreviation	Study Name & Year	Primary Institution / Authors	Timeline	Scenarios (selected for analysis)
IESS2015	India Energy Security Scenarios 2047, 2015 [23]	NITI Aayog, Government of India	2012 - 2047	Determined effort scenario - Level 2 scenario **(R)**, Maximum Energy Security scenario (**ES**), Maximum Renewable Energy scenario (**RE**)
IRADe2014	Low Carbon Development Pathways for a sustainable India, 2014 [24]	Integrated Research and Action for Development (IRADe)	2005 - 2050	Dynamics-As-usual Scenario (**R**), Visionary Development Scenario (**VD**), Low-carbon Development Scenario 2 (**LC2**)
LCSIG2014	Expert group on 'low carbon strategies for inclusive growth' (LCSIG), 2014 [25]	Planning Commission, Government of India	2007 - 2030	Baseline Inclusive Growth (**R**) , Low Carbon Inclusive Growth (**LC**)
Singh2018	Evaluating India's climate targets: the implications of economy-wide and sector specific policies, 2018 [26]	Arun Singh, Niven Winchester & Valerie J. Karplus	2011 - 2030	Reference Scenario (**R**), Emissions-intensity Scenario (**EI**), Non-Fossil Scenario (**NF**)
TERI2019	Exploring Electricity Supply-Mix Scenarios to 2030, 2019 [27]	The Energy and Resources Institute	2018 - 2030	Current Policy Scenario (**CP**), Current Trajectory Scenario (**R**), High Renewable Energy Scenario (**RE**)
TERI-WWF2013	The Energy Report- India, 100% Renewable Energy by 2050, 2013 [28]	The Energy and Resources Institute	2018 - 2051	Reference Scenario (**R**), Renewable Energy Scenario (**RE**)
Tiewsoh2019	Electricity Generation in India: Present State, Future Outlook and Policy Implications, 2019 [29]	Lari Shanlanh Tiewsoh, Jakub Jirasek & Martin Sivek	2015 - 2030	Energy Savings with High Renewables and Gas (**ES+HRE**), High Growth with High Renewables and Gas (**HG+HRE**), High Growth with Low Renewables and Gas (**R**)
Vishwanathan2020	Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India, 2020 [30]	Saritha S. Vishwanathan & Amit Garg	2010 - 2050	Business-As-Usual Scenario (**R**), NDC Scenario (**NDC**), 2 deg. early action - high budget (**2C-H**)

3.2. Electricity Modeling in India: Model Types and Description

The different models and methodologies used in the India specific key electricity modeling studies are briefly described in **Table 3**. The electricity models range from simple excel based simulation type models (e.g., IESS2015 and scenario based approaches in TERI2019) to large scale simulation and optimization models (e.g., WEM in IEA2019, LEAP in Tiewsoh2019) to integrated models based on computational general equilibrium (e.g., TIMES in CSTEP2015, MARKAL in TERI-WWF2013). Further, the models can also be categorized based on their approach: top-down (e.g., TIMES/MARKAL), bottom-up (Mesap/PlaNet in Greenpeace2015, AIM in Vishwanathan2020, LUT model in Gulagi2017) and hybrid models (SIM in DDPP2015, LCG model in LCSIG2014). However, it is observed that the open source modeling tools have not yet found their place in India's electricity modeling community.

Table 3: A brief description and summary of different model types used in modeling India's future roadmaps.

No.	Study	Model / Methodology
1	CPI2019	PLEXOS model; Optimization and simulation type (details not provided)
2	CSTEP2015	TIMES - The Integrated MARKAL (Market Allocation) EFOM (Energy Flow Optimization Model) system; Constrained optimization market equilibrium model
3	DDPP2015	Soft-linked Integrated Modeling system (SIM) - involving Global CGE model and ANSWER MARKAL model; Computational general equilibrium (top-down approach) & market simulation (bottom-up approach)
4	Greenpeace2015	Mesap/PlaNet (Modular Energy System Analysis and Planning Environment/Planning Network); Simulation type model using bottom-up technology driven approach
5	Gulagi2017	Lappeenranta University of Technology-LUT Energy System Transition modeling tool (LUT model); Model based on linear optimization with hourly resolution for an entire year of the energy system parameters
6	ICRIER2016	India Energy Security Scenarios (IESS), version 2.0 (web/excel); Simple excel based simulation model
7	IEA2015	World Energy Model (WEM) developed by IEA; large scale simulation model
8	IEA2019	World Energy Model (WEM) developed by IEA; large scale simulation model

No.	Study	Model / Methodology
9	IESS2015	India Energy Security Scenarios - IESS is a bottom -up model; Economic demand was modeled for various demand sectors; As per the economic model, the need for electricity in different sectors was projected; Sectoral demands were aggregated to get the total electricity demand in a given year; Simple simulation type model
10	IRADe2014	IRADe macroeconomic model using General Algebraic Modeling System (GAMS) tool; Dynamic multi-sectoral, inter-temporal, linear programming model based on input-output framework; Input-output matrix used is based on Social Accounting Matrix for India 2003-04
11	LCSIG2014	Low Carbon Growth (LCG) Model; Demand supply equilibrium model with multi-sectoral dynamic optimization; This model is a combination of the bottom-up and top-down approach; executed using GAMS
12	Singh2018	Mixed Complementarity Problem (MCP) model based on Mathematical Programming System for General Equilibrium Modeling (MPSGE) and General Algebraic Modeling System (GAMS) Language; executed using PATH solver; Multi-sector applied general equilibrium model type
13	TERI2019	Scenario-based approach; Supply scenarios were prepared by considering electricity demand growth of 6.0% year-on-year to 2030, with grid demand reaching 2040 TWh; Simple simulation type model
14	TERI-WWF2013	MARKAL (Market Allocation); Bottom-up dynamic linear programming model - depicts demand and supply sides of the energy systems
15	Tiewsoh2019	LEAP (Long-range Energy Alternative Planning) model; optimization type
16	Vishwanathan2020	Asia-Pacific Integrated Model (AIM); a bottom-up optimization model, captures the techno-economic perspective at the national level with sectoral granularity

3.3 Model Timelines & Technology Types

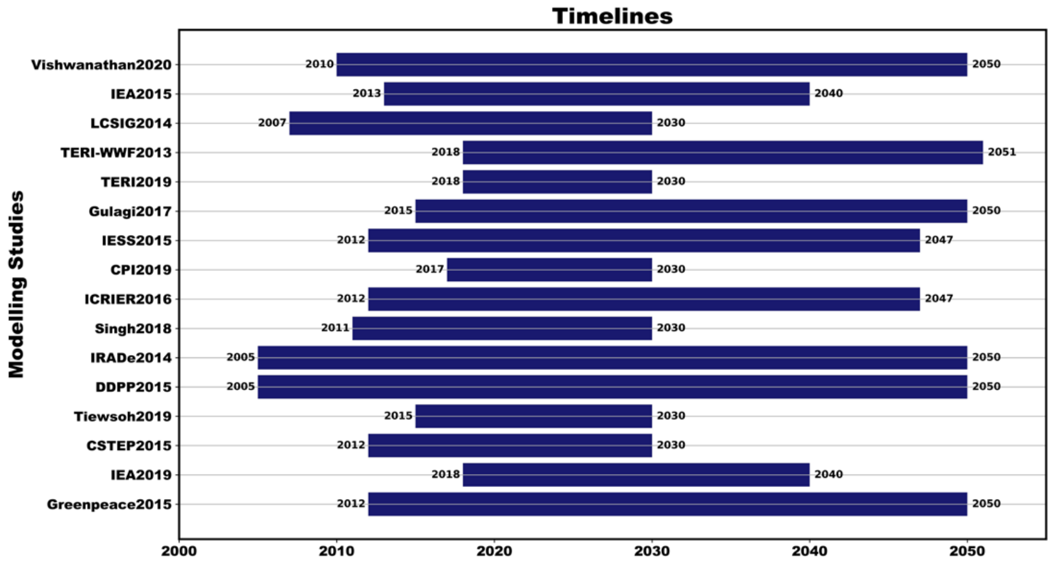


Figure 6: Timelines of the India specific key electricity modeling studies.

It is observed that most of the modeling studies have a timeline till 2030 and only eight of the total number of selected studies project electricity roadmaps until 2050 (see **Figure 6**). Further, the electricity technologies modeled in the majority of studies are generic types and mainly account for the technologies that are already successful or reached market maturity today (e.g., Solar PV and Wind Onshore). Only a few modeling studies account for prospective technologies, but even these studies limit their scope only to already successfully demonstrated technologies, such as wind offshore, solar CSP and carbon capture and storage (CCS) technologies, providing very conservative future projections for these technologies.

Most of the India specific modeling studies have a short-term focus (till 2030 only).

The electricity and storage technology types modeled in the different studies are presented in pictorial form below (Figure 7). It can be observed that, out of 16 modeling studies, only 5 studies account for solar CSP, 3 studies for wind offshore and 2 studies for coal-based carbon capture and storage (CCS). In addition, the scope of other renewables (e.g., geothermal, ocean, hydro and waste to energy) is often discussed qualitatively rather than quantitatively in the studies that consider these options. The same argument holds true for the storage technologies in most of the studies, except that Gulagi2017 and CPI2019 made an initial attempt to present a prospective quantitative assessment of possible storage technologies (in particular, pumped hydro and battery storage) in future Indian electricity scenarios. Further, although bioenergy and diesel (or oil) based electricity sources are often discussed and provided with quantitative future projections in most studies, their contributions in the total electricity generation varied significantly across the studies, from studies completely ignoring these sources to studies projecting considerable contributions in the future electricity-mix of India. In general, we observed that the modeling granularity, data and assumptions used for projecting 2030 scenarios are more reliable than 2050 scenario projections because of short term focus on prospective electricity and storage technologies (and relevant energy policies) in most of the India specific modeling studies. Consequently, due to lack of the inclusiveness of prospective electricity and storage technologies, high granularity modeling for short timelines (e.g., 2030 but not for 2050), and data availability issues on future performances of electricity sources in the Indian context (especially with respect to the diverse set of sustainability indicators chosen in this study), we conducted our comparative assessment in two levels:

1. A generic comparison of electricity supply and demand projections for 2030 and 2050 scenarios
2. A detailed sustainability indicator-wise comparison on the performances of the six major electricity sources in India's 2030 electricity roadmap scenarios– both annual and cumulative impacts (2020-2030) assessment was carried out.

Data availability on the future impacts of electricity sources and prospective technologies is very limited in the Indian context.

Study	Coal	Coal-CCS	Nuclear	Hydro	Wind-Onshore	Wind-Offshore	Solar-PV	Solar-CSP	Gas	Gas-CCS	Oil/ Diesel	Bioenergy	Small/ Micro-Hydro	Any other Renewables	Storage
Greenpeace2015	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	NO	Geothermal / Ocean / Hydrogen	NO
IEA2019	YES	NO	YES	YES	YES	NO	YES	YES	YES	NO	YES	YES	NO	Geothermal	NO
CSTEP2015	YES	NO	YES	YES	YES	NO	YES	YES	YES	NO	YES	YES	NO	NO	NO
Tiewsoh2019	YES	NO	YES	YES	NO	NO	YES	NO	YES	NO	NO	NO	NO	NO	NO
DDPP2015	YES	YES	YES	YES	YES	NO	YES	NO	YES	NO	NO	YES	NO	NO	NO
IRADe2014	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	YES	NO	NO	Solar Thermal and PV Storage (Batteries)
Singh2018	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	NO	NO	NO	NO	NO
ICRIER2016	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	NO	NO	NO	Not Specified	NO
CPI2019	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	YES	NO	NO	Pumped Hydro / Battery Storage
IESS2015	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES	YES	Waste to Energy	Not clear
Gulagi2017	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	YES	NO	Geothermal	Compressed Air, Batteries, Pumped- Hydro, Thermal Storage
TERI2019	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	NO	YES	YES	NO	NO
TERI-WWF2013	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO	NO	Bioenergy, Small-Hydro and others together	NO
LCSIG2014	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	NO	YES	NO	Not specified	NO
IEA2015	YES	NO	YES	YES	NO	NO	YES	NO	YES	NO	YES	YES	NO	Not specified	NO
Vishwanathan2020	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	YES	NO	Not specified	NO

Figure 7: The electricity and storage technology types modeled in the different modeling studies. YES NO

4. GENERIC COMPARATIVE ASSESSMENT OF INDIA'S ROADMAPS

4.1. Electricity Demand

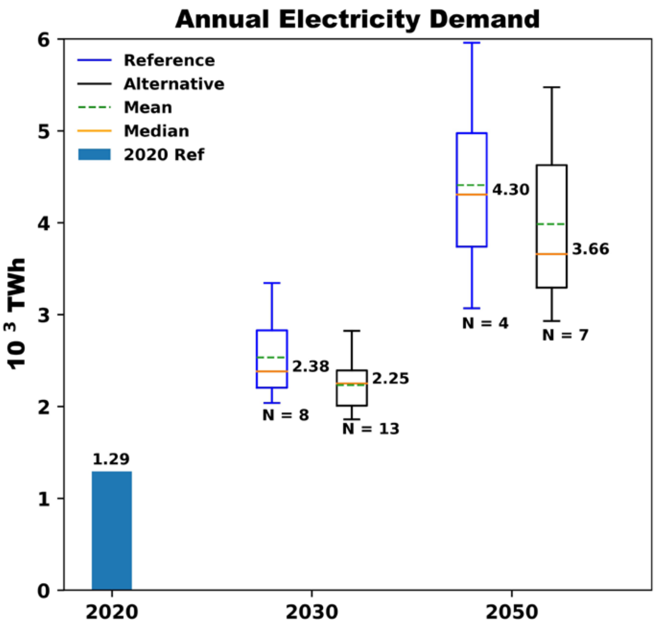


Figure 8: Electricity demand projections for 2030 and 2050. Note: the whiskers show the 10th and 90th percentile values.

The overall electricity demand for India in 2019 – 2020 was 1291 TWh [5]. The annual overall electricity demand estimations for 2030 varied from 2036 TWh (Vishwanathan2020) to 3343 TWh (CSTEP2015) with a median value of 2380 TWh (DDPP2015 and IEA2019) in reference scenarios and from 1857 TWh (DDPP2015) to 3000 TWh (Tiewsoh2019-HG+HRE) with a median value of 2256 TWh (IEA2015) in alternate scenarios. For 2050, the demand estimations varied from 3068 TWh (Vishwanathan2020) to 5960 TWh (DDPP2015) with a median of 4304 TWh (Greepeace2015 and IEA2015) in reference scenarios and from 2928 TWh (Vishwanathan2020) to 5473 TWh (Greepeace2015) with a median of 3657 TWh (IESS2015) in alternate scenarios. It can be observed that the modeling studies project higher electricity demand for reference scenarios in comparison to alternate scenarios (see **Figure 8**). This is because of the assumptions for the enforcement of higher demand efficiency and electricity conservation measures in alternate scenarios than in reference scenarios. It should be noted that all modeling studies did not provide explicit electricity demand estimations for their scenarios and hence the number of studies (N) quoted in demand projections vary from the total number of studies assessed in this work.

4.2. Electricity Generation and Installed Capacity

The total installed power capacity in India reached 370 GW in 2020 and the electricity generated during the period 2019 – 2020 was 1385 TWh, including both conventional and new renewable energy sources. The annual electricity generation projections vary from 2254 TWh (DDPP2015-S) to 4917 TWh (IRADe2014-R) for 2030 and from 3508 TWh (Vishwanathan2020-2C-H) to 13,629 TWh (IRADe2014-VD) for 2050, including both reference and alternate scenarios. Correspondingly, the power capacity projections vary from 524 GW (LCSIG2014-R) to 1390 GW (Gulagi2017-I) for 2030 and from 1014 GW (IESS2015-R) to 4818 GW (Gulagi2017-I) for 2050. Our statistical analysis on annual electricity generation trends shows that the median values for reference and alternate scenarios are 2960 TWh and 2855 TWh in 2030, and 6020 TWh and 5464 TWh in 2050, respectively (see **Figure 9**).

The RE share in annual electricity generation is expected to rise from 8% in 2020 to 23% in 2030 to 45% in 2050 in alternate scenarios.

It can be noted that the alternate scenarios show a slightly lower electricity generation trend in comparison to reference scenarios because of the lower demand projections in alternate scenarios due to effective implementation of electricity conservation measures as pointed out in an earlier section (4.1). In contrast, the power capacity projections show an inverse trend, that is, the median values for alternate scenarios (789 GW in 2030 and 1896 GW in 2050) are higher than for reference scenarios (765 GW in 2030 and 1548 GW in 2050). This is because of the predictions for higher shares of solar and wind electricity sources in the alternate scenarios than in the reference scenarios, wherein coal and conventional electricity sources retain the majority share often. The renewable energy (RE) share and coal share plots in **Figure 9** validate this point. The RE share in annual electricity generation is expected to rise from 8% in 2020 to 23% in 2030 to 45% in 2050 in alternate scenarios, and in total power capacity it is projected to rise from 19% in 2020 to 39% in 2030 to 59% in 2050 in alternate scenarios. However, the reference scenarios project lower shares for RE than the alternate scenarios. Nevertheless, it is underscored that both reference and alternate scenarios predict increasing shares for RE and decreasing shares for coal in the electricity sector over the time period 2020 to 2050. It could further be observed that most of the roadmaps predict dramatic reductions for coal share in annual electricity generation-mix in alternate scenarios: from over 72% in today's grid to 49% in 2030 to 21% in 2050 (comparing just median values).

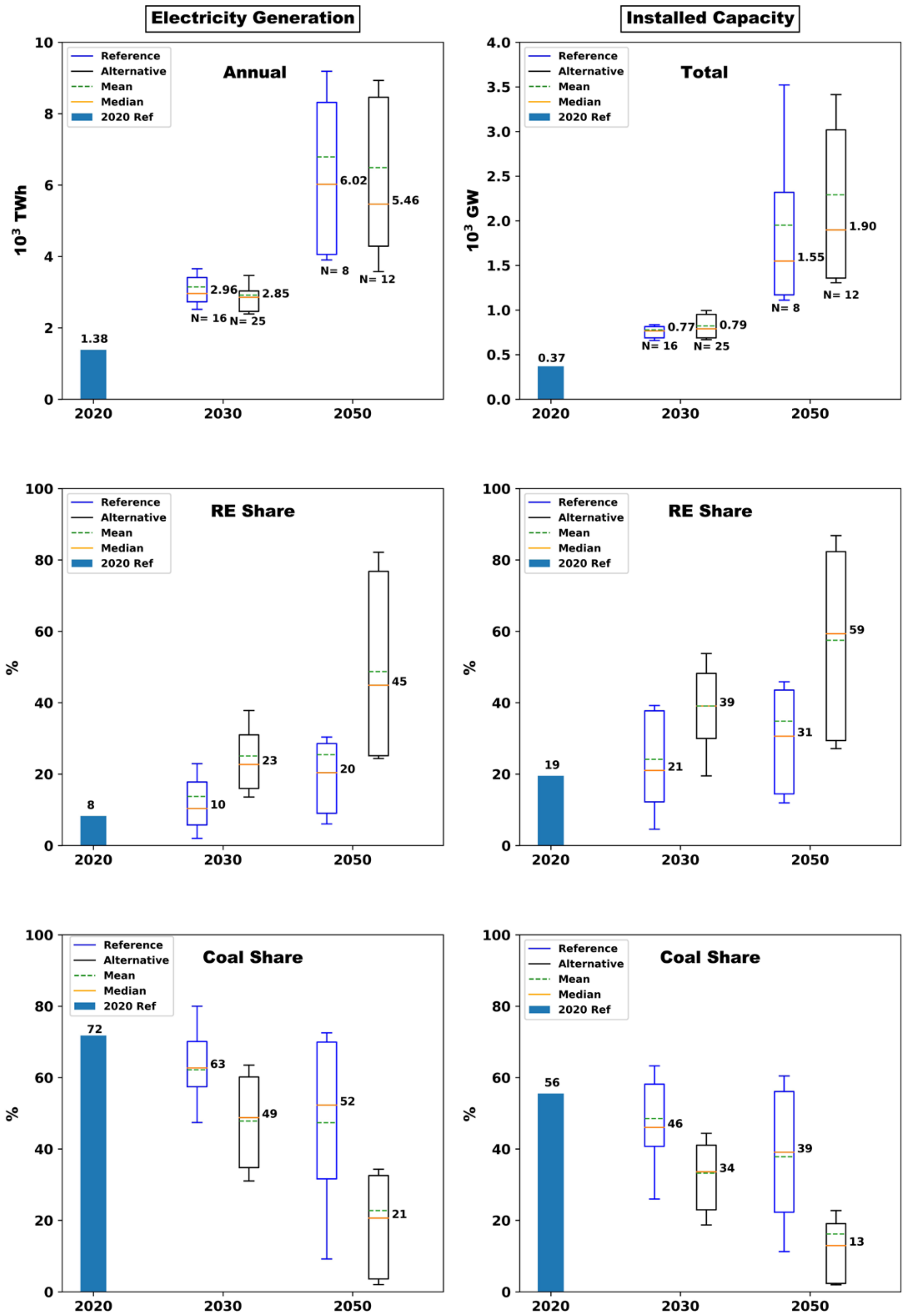


Figure 9: The total electricity generation and power capacity trends projected for 2030 and 2050.

Note: (a) The numbers of studies (N) remain the same for all electricity supply trends; (b) RE share includes the shares of solar and wind electricity sources only – other RE and conventional large hydro are excluded for better clarity and consistency across the studies.

4.3. Roadmap Projections for different Electricity Sources

The future electricity generation and power capacity trends projected for different types of electricity sources by various modeling studies are statistically summarized in **Figure 10** and **Figure 11**. For coal power, the majority of future roadmaps in their reference scenarios predict an increase in capacity additions till 2030 and then foresee lower incremental growth rates between 2030 to 2050 (reaching 417 GW in 2050); whereas the alternate scenarios predict a slight increase in coal capacities between 2020 to 2030 (reaching 228 GW in 2030) and expect that the coal capacities could slightly drop afterwards and then stabilize around 2020 levels of installed capacities (around 205 GW). For nuclear power, the future predictions are very conservative and most alternate scenarios expect that nuclear capacities might stabilize around 17 GW - 20 GW in the coming decades; that is, nearly thrice as much increase in the nuclear capacity as of today (7 GW in 2020). However, the predictions for natural gas-based power plants are promising: 45 GW – 66 GW in 2030 to 115 GW – 163 GW in 2050 (compare with 25 GW in 2020); this might be because of their flexible role in balancing and maintaining grid stability during peak loads and also during non-availability of intermittent renewable energy sources, among others. But, the alternate scenarios project lower gas power capacities for India than the reference scenarios. In summary, the alternate scenarios predict lower power capacities for all the conventional electricity sources in comparison to the reference scenarios.

The alternate scenarios predict lower power capacities for all the conventional electricity sources in comparison to the reference scenarios.

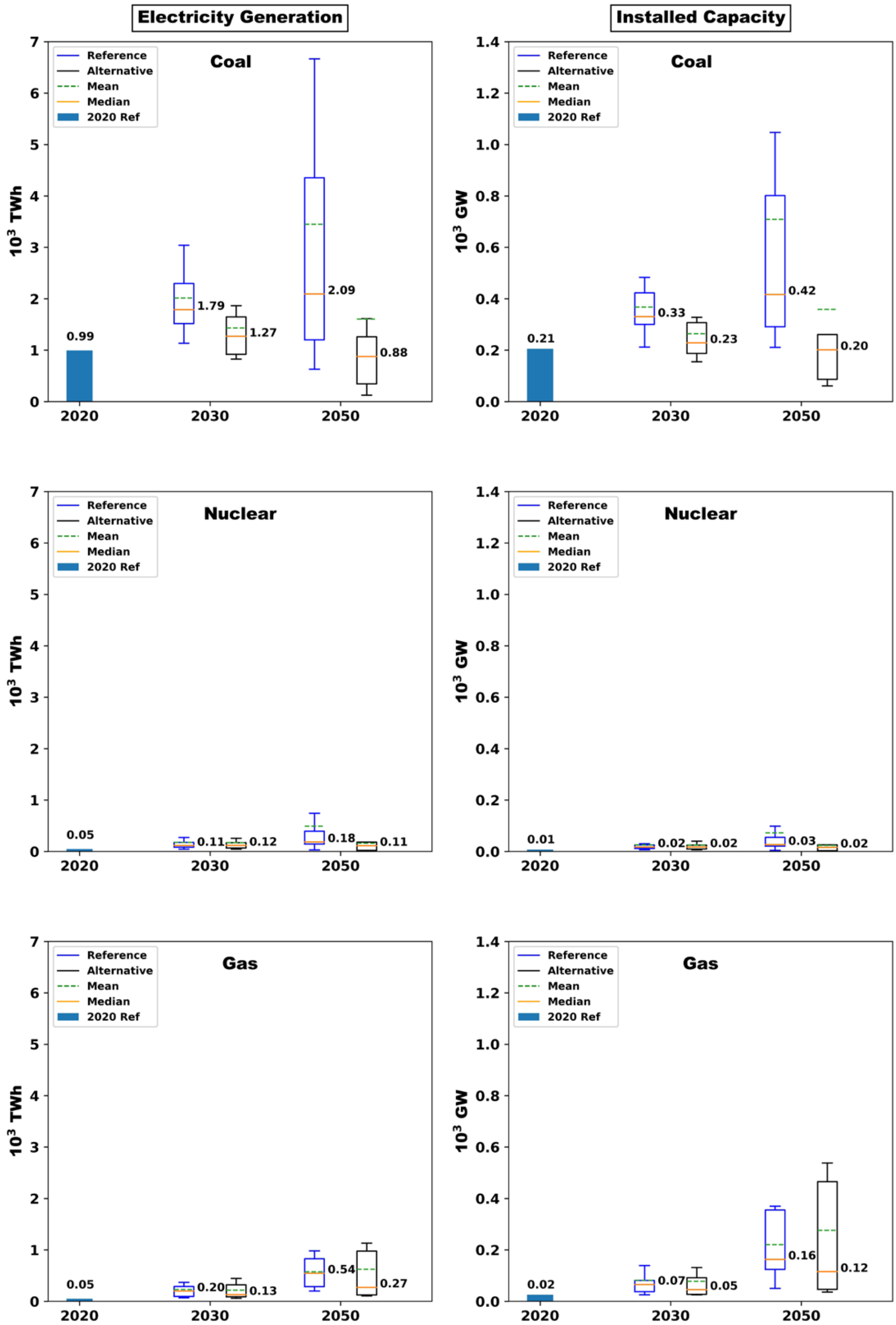


Figure 10: Electricity generation and power capacity projections for conventional electricity sources (excluding large hydro).

On the other hand, the future roadmaps predict a very significant growth for solar and wind power capacities (see **Figure 11**). For solar power, both reference and alternate scenarios predict significant increases in capacity additions until 2050. However, most alternate scenarios project an ambitious rise in solar capacity in comparison to the reference scenarios; for instance, the median values for alternate scenarios for 2030 (190 GW) and 2050 (540 GW) are more than double in comparison to their corresponding median values for reference scenarios (90 GW and 210 GW respectively). It is underscored that these capacity additions are significant as they call for a dramatic increase in the solar power capacity by 2030 and 2050 in comparison to today's installed capacity; for example, the median values for alternate scenarios in 2030 and 2050 are higher by a factor of 5 and 15 respectively, in comparison to today's solar capacity installations (35 GW). The same trends hold true for wind power projections, except that their capacity projections are not as dramatic as for solar power. Nevertheless, the median values for alternate scenarios predict 130 GW and 290 GW of wind power capacity by 2030 and 2050; that is, an increase in the total capacity additions by a factor of 3 and 8 respectively, in comparison to today's wind power capacity (38 GW). Further, the majority of roadmap scenarios expect large hydro to stabilize after reaching around 70 GW in the coming decades (from 46 GW in 2020). Lastly, the predictions for other renewable energies mainly include bioenergy (primarily) and micro/small hydro based electricity generation, and the alternate scenarios expect higher contribution from these renewable energy sources in the future electricity-mix. However, as indicated earlier, the possible contributions from prospective renewable energy technologies (e.g., wind-offshore, solar CSP/CPV and new technological interventions) tend to be ignored or highly underrated in the present India specific modeling studies.

The alternate scenarios predict a dramatic increase in the solar power capacity by 2030 (5 times) and 2050 (15 times) in comparison to current installed capacity.

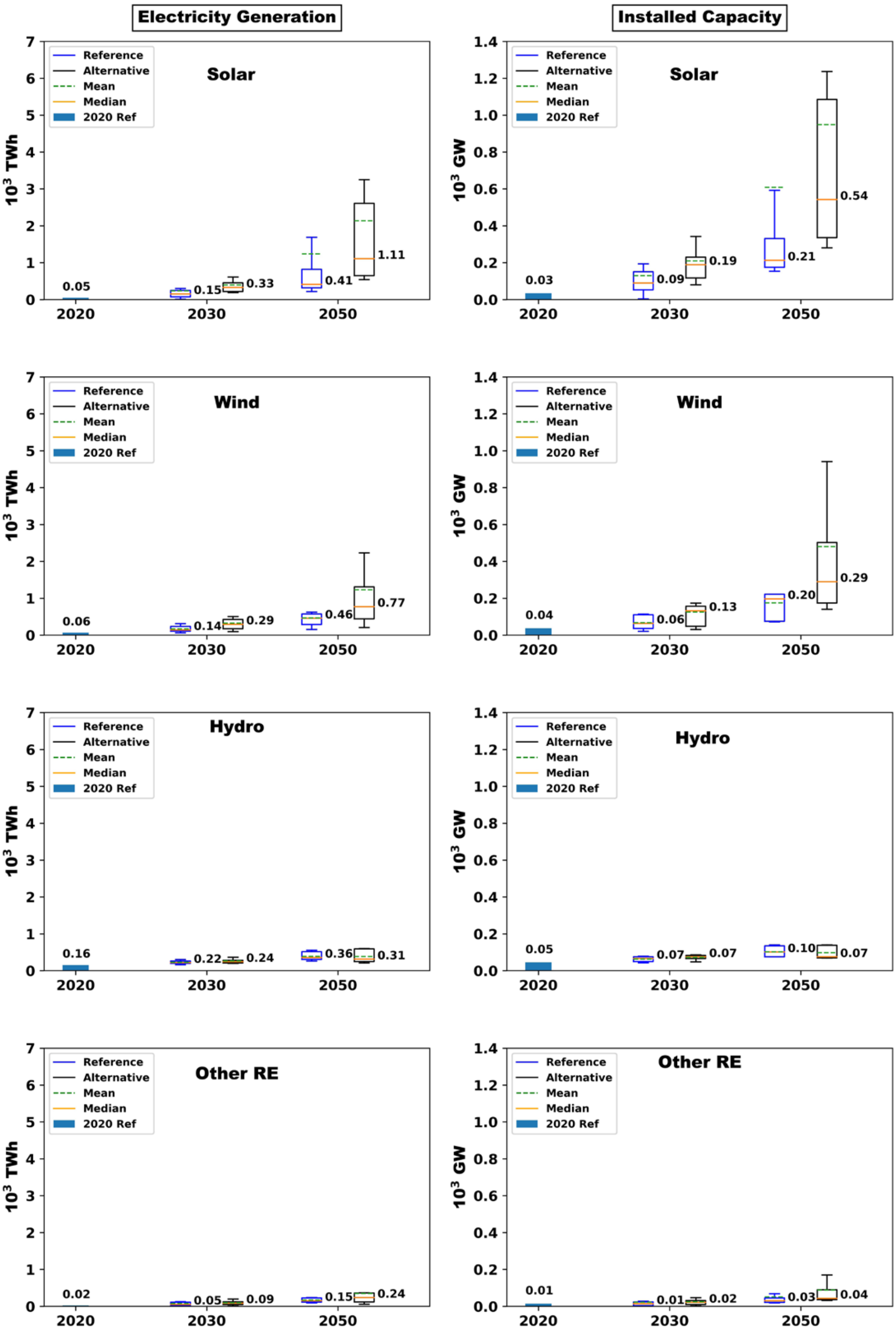


Figure 11: Electricity generation and power capacity projections for renewable energy sources.

Photo by Pete Wright on Unsplash

5. LOW CARBON ELECTRICITY ROADMAPS: BENEFITS & TRADE-OFFS

In this section, we conduct a robust comparative assessment between all the 16 modeling studies with a total of 41 roadmap scenarios. For better comparison across studies and roadmap scenarios, we distinguish between reference and alternate scenarios in our comparative analyses. Firstly, the electricity generation-mix projections for 2030 across all the modeling studies are presented, with individual break-ups for the six major electricity sources considered in all the roadmap scenarios (coal, gas, nuclear, hydro, wind and solar). Secondly, we estimate the cumulative impacts of these six electricity sources during the coming decade (2020 to 2030) by assuming simple straight-line escalation between their impacts from 2020 (present value) to their impacts in 2030 (as estimated in different roadmap scenarios; 41 in total). Lastly, we present the impacts of these six electricity sources on the seven indicators chosen in our sustainability framework (described in **Section 2.1**). A brief outline of our comapartive study presented in this section is provided below:

The impacts of the major six electricity sources that constitute all the roadmap scenarios are quantified with respect to the seven sustainability indicators.

- Contribution of major electricity Sources in the future electricity genera tion-mix (coal, gas, nuclear, hydro, wind and solar)
  - » Annual in 2030
  - » Cumulative during 2020 – 2030
- Impacts of these six electricity sources on multiple sustainability indicators (annual / cumulative)
  - » Climate Footprint
  - » Water Footprint
  - » Land Transformation
  - » Air Pollution
  - » Levelized Cost of Electricity (LCOE)
  - » External Costs
  - » Employment Generation (Jobs)

5.1. Electricity Generation

The electricity generation-mix for 2030 predicted by the modeling studies are presented visually in **Figure 12** (alternate scenarios) and **Figure 13** (reference scenarios). Most of the scenarios expect the share of coal power generation to continue to dominate the electricity generation-mix in the (R) reference scenarios (57% - 70%; 25:75 percentiles) and decrease in the (A) alternate scenarios (35% - 60%; 25:75 percentiles). In contrast, the RE share (solar and wind) is expected to increase from 8% to 22% (25:75 percentiles) in the reference scenarios and from 22% to 33% (25:75 percentiles) in the alternate scenarios.

Comparing alternate scenarios (**Figure 12**), it can be observed that DDPP2015 (S), Vishwanathan2020 (2C-H) and TERI2019 (RE) are the top three scenarios projecting the lowest total electricity generation in 2030; In contrast, IRADe2014 (VD), Tiewsoh2019 (HG+HRE) and Gulagi2017 (I) are the bottom three scenarios predicting the highest total electricity generation.

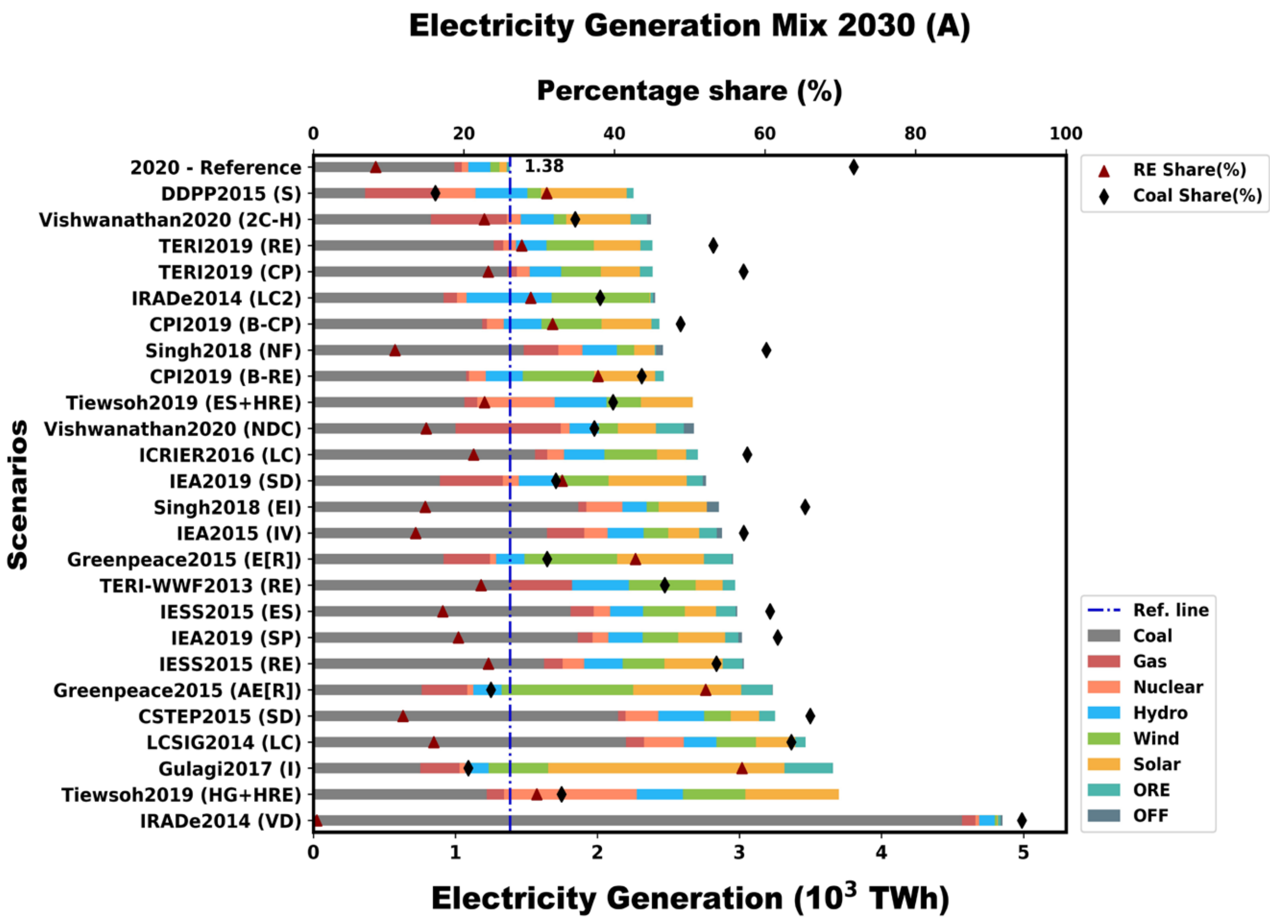


Figure 12: Electricity generation-mix 2030 (alternate scenarios).

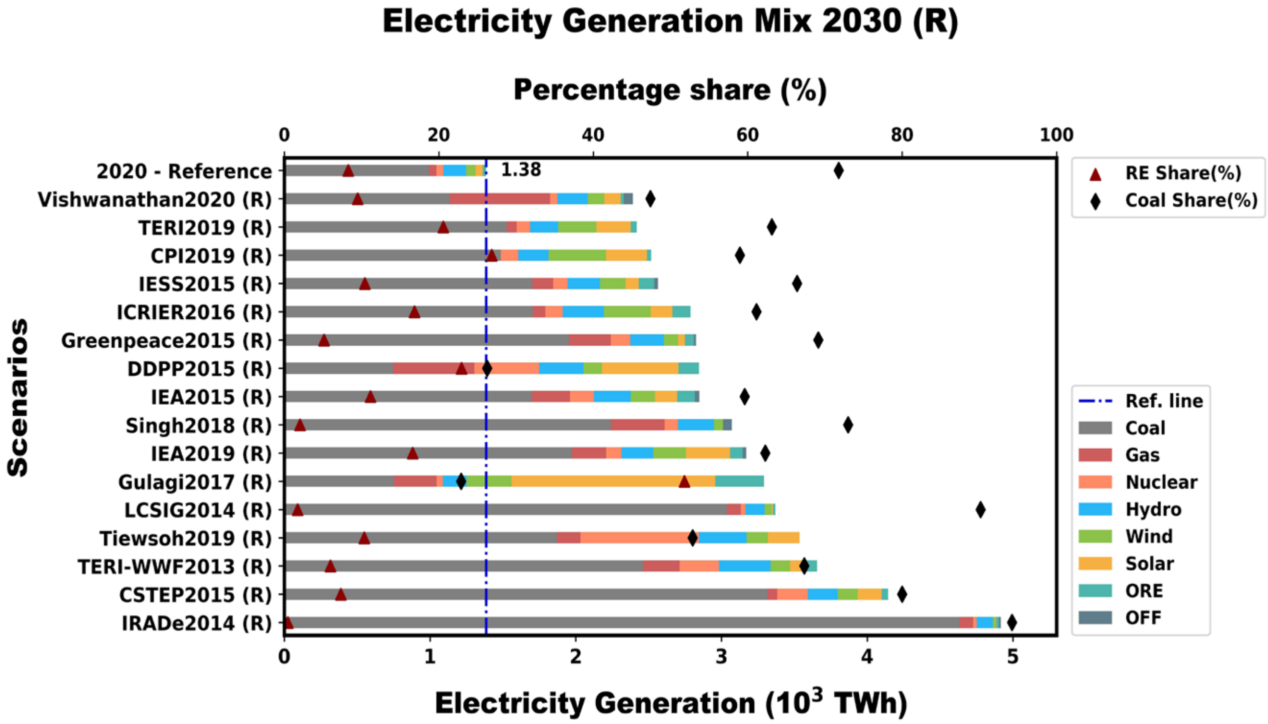


Figure 13: Electricity generation-mix 2030 (reference scenarios).

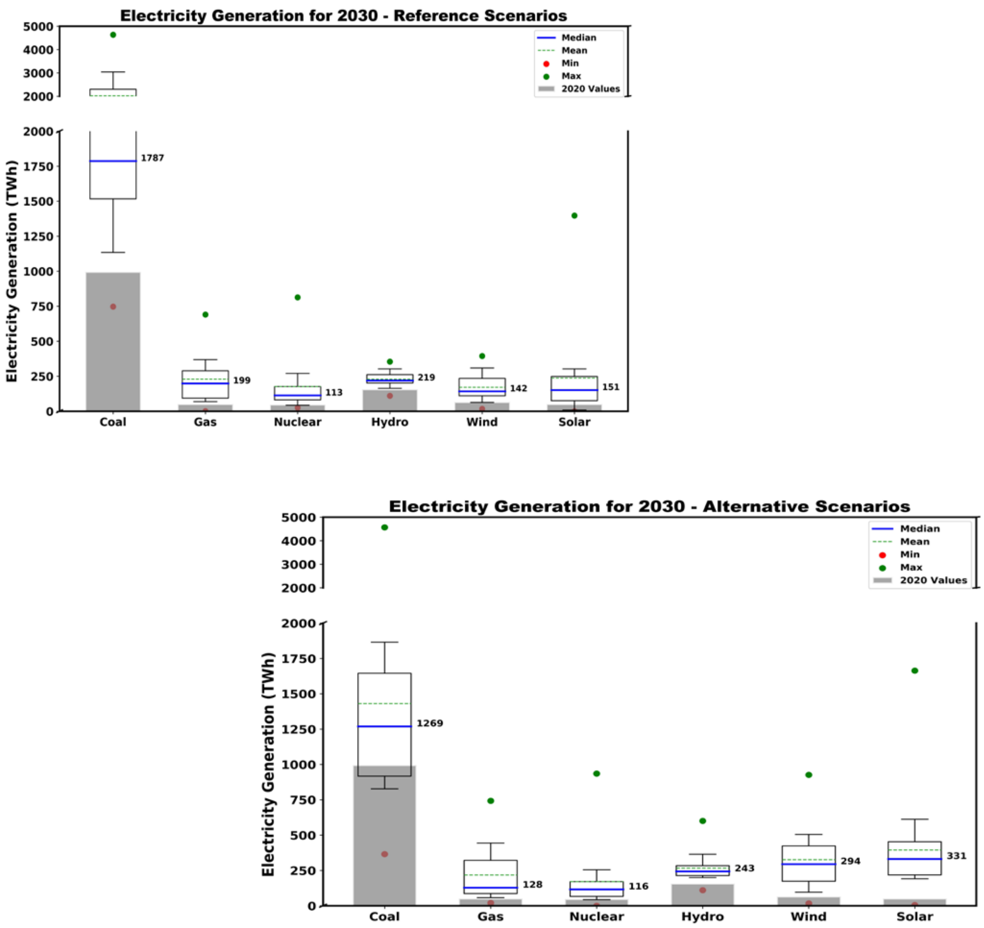
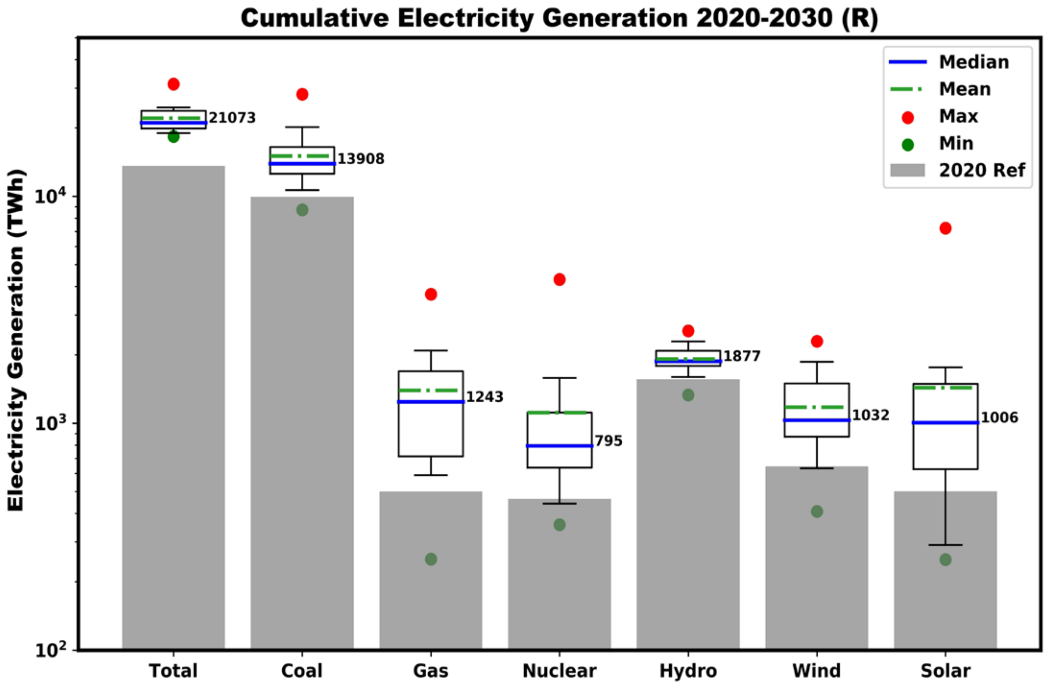


Figure 14: Annual Electricity generation from different sources in 2030.

Figure 14 and **Figure 15** shows the annual and cumulative electricity generation from different electricity sources during 2020 to 2030 in India. For reference scenarios, the median values for the annual electricity generation are 1787, 199, 113, 219, 142 and 151 TWh for coal, gas, nuclear, hydro, wind and solar in 2030, with a cumulative generation of 13908, 1243, 795, 1877, 1032 and 1006 TWh during 2020 to 2030, respectively. For alternate scenarios, the median values for the annual electricity generation are 1269, 128, 116, 243, 294 and 331 TWh for coal, gas, nuclear, hydro, wind and solar in 2030, with a cumulative generation of 11316, 890, 813, 1995, 1794 and 1906 TWh during 2020 to 2030, respectively. It can be observed that the alternate scenarios expect a dramatic capacity growth for solar and wind electricity sources and a decline in coal generation capacity in comparison to reference scenarios. However, it is underscored that the median values for coal power generation in both reference and alternate scenarios do not hint at declining coal power capacity in comparison to 2020 installations, but rather expect capacity growth in the coming years (during 2020 to 2030).



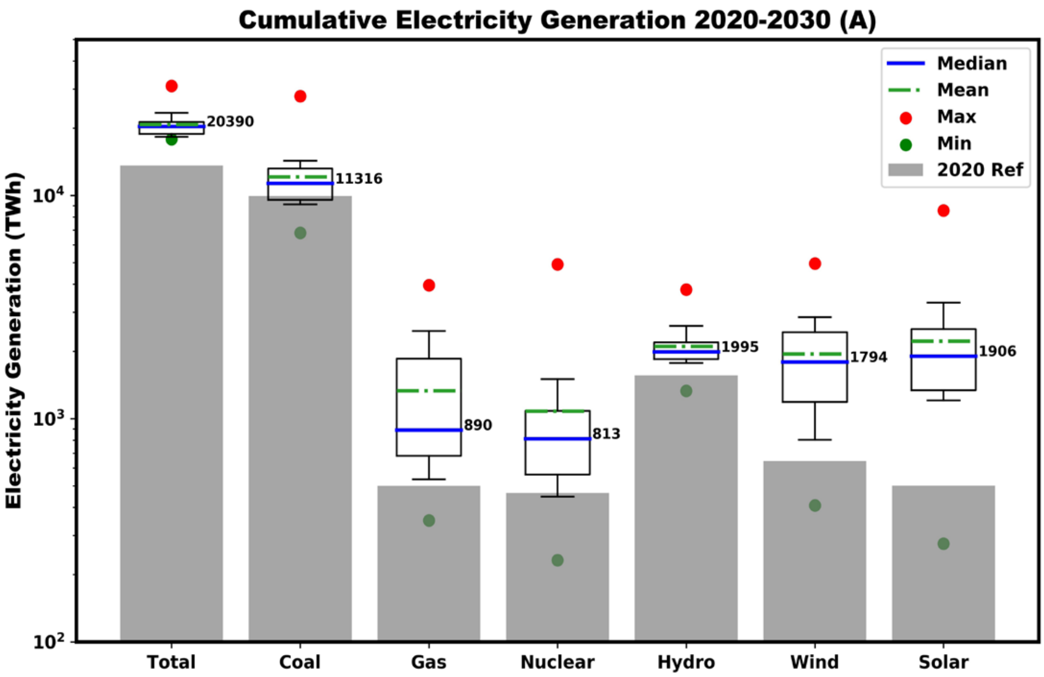


Figure 15: Cumulative electricity generation from different power sources during 2020 to 2030.
Note: (R) – Reference Scenarios; (A) – Alternate Scenarios; this plot has a logarithmic scale.

5.2. Climate Footprint

The total climate footprints for different electricity generation-mixes predicted by alternate and reference scenarios are shown in **Figure 16** and **Figure 17**. It can be observed that the climate impacts are dominated by coal power in all the roadmaps, with a minor contribution from gas power generation. The impacts from all other electricity sources are negligible in the total contributions even though some electricity sources (e.g., solar and wind) contribute significantly in the total electricity generation by 2030; particularly in most of the alternate scenarios (see **Section 5.1**).

Comparing alternate scenarios (**Figure 16**), it can be observed that DDPP2015 (S), Gulagi2017 (I) and Greenpeace2015 (AE[R]) are the top three scenarios having the lowest climate footprints in 2030; In contrast, IRADe2014 (VD), LCSIG2014 (LC) and CSTEP2015 (SD) are the bottom three scenarios having the highest climate footprints. Further, it is underscored that the top three best performing roadmaps envisage that the climate footprint from India's electricity sector in 2030 could be lower than in 2020.

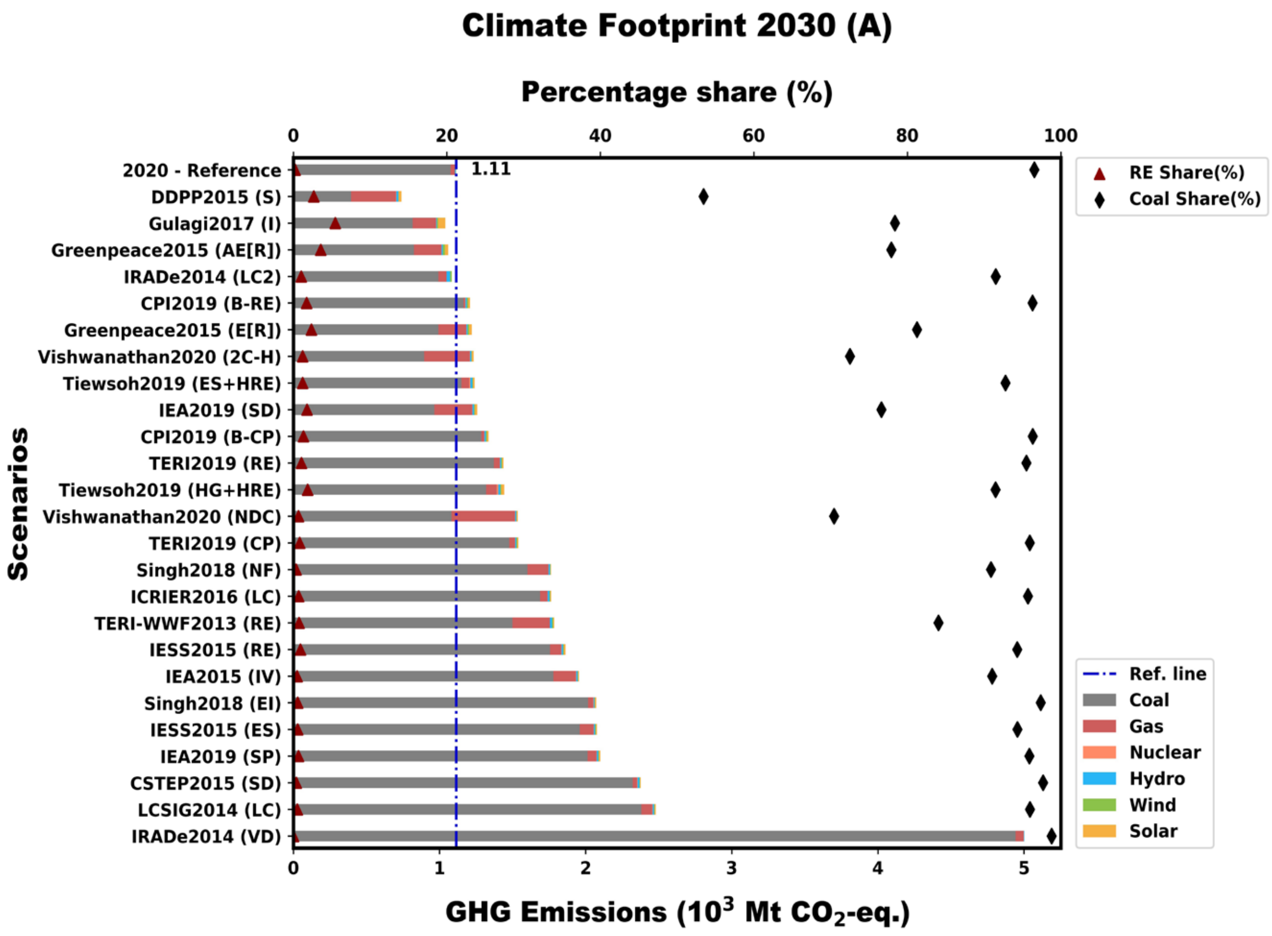


Figure 16: Climate Footprint 2030 (alternate scenarios).

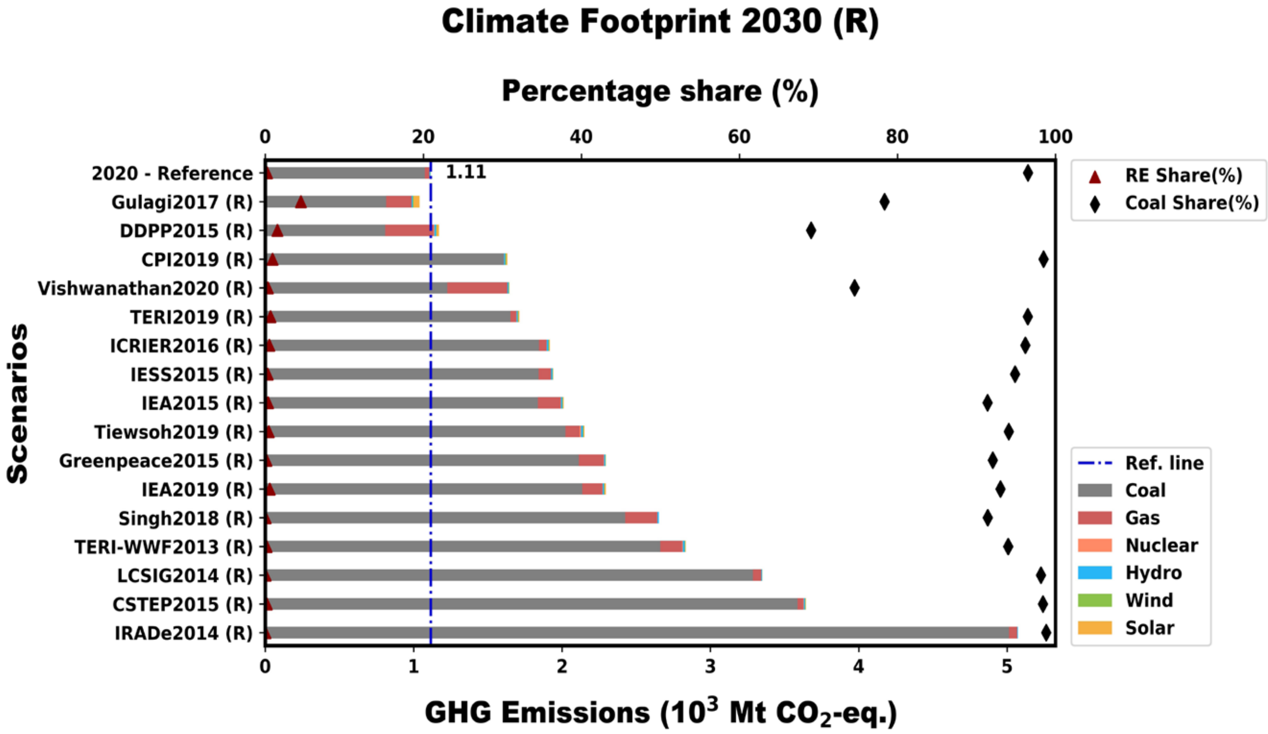
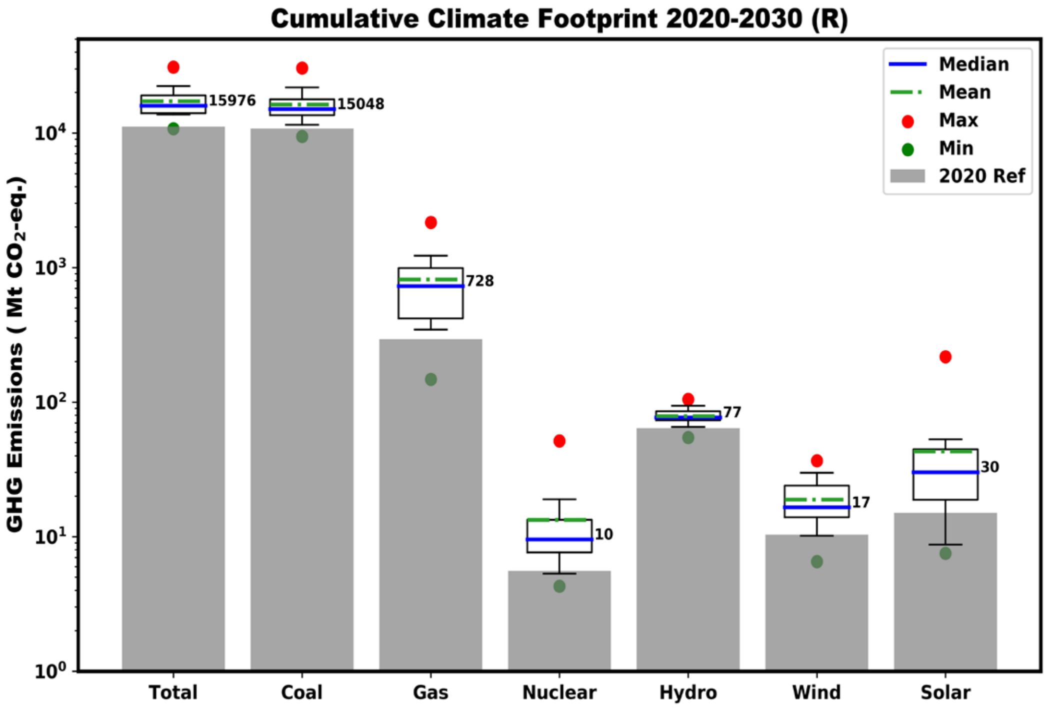


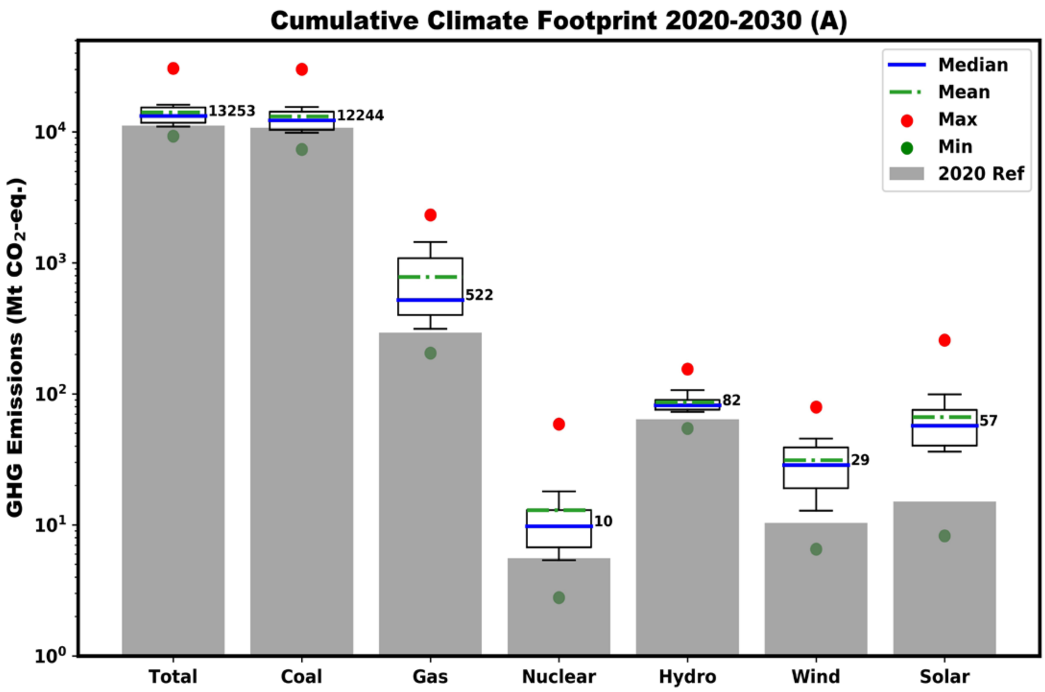
Figure 17: Climate Footprint 2030 (reference scenarios).

Figure 18 shows the cumulative climate footprints from different electricity sources during 2020 to 2030 in India. For reference scenarios, the median values for the cumulative climate footprints (2020-2030) are 15976, 15048, 728, 10, 77, 17 and 30 Mt CO_2-eq. GHG emissions for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. For alternate scenarios, the median values for the cumulative climate footprints (2020-2030) are 13253, 12244, 522, 10, 82, 29 and 57 Mt CO_2-eq. GHG emissions for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. Although solar and wind contribute significantly in some of the roadmap scenarios in terms of total electricity generation, their impacts on climate footprint are negligible due to the fact that their life cycle GHG emissions are 36 to 68 times lower in comparison to coal power emissions in India (see **Figure 3**).

Comparing the cumulative median value for total climate footprint (15976 Mt CO_2-eq.) in the reference scenario with the best performing alternate roadmap scenario (DDPP2015-S: 9268 Mt CO_2-eq.), it can be foreseen that following the DDPP2015 (S) roadmap could save around 6708 Mt CO_2-eq. GHG emissions during 2020 to 2030 (only) that is roughly equivalent to 2 years of overall GHG emissions from the whole of India (assuming 3.3 Gt per annum [31]). As noted earlier, we underscore again that the coal power generation significantly contributes to the climate impacts arising from India.

Figure 18: Cumulative climate footprints from different electricity sources during 2020 to 2030.
Note: this plot has a logarithmic scale.





5.3. Water Footprint

The total water footprints for different electricity generation-mixes predicted by alternate and reference scenarios are shown in **Figure 19** and **Figure 20**. It can be observed that the water footprint impacts are dominated by hydro and coal power in all the roadmaps, with minor contributions from nuclear and gas power generation (due to their lower shares in electricity-mix). The impacts from solar and wind electricity sources are negligible in the total contributions even though these electricity sources contribute significantly in total electricity generation by 2030 in most of the alternate scenarios (see Section 5.1).

Comparing alternate scenarios of all the modeling studies (**Figure 19**), it can be observed that Gulagi2017 (I), Greenpeace2015 (AE[R]) and Greenpeace2015 (E[R]) are the top three modeling studies having the lowest water footprints in 2030; In contrast, IRADe2014 (LC2), IRADe2014 (VD) and CSTEP2015 (SD) are the bottom three studies having the highest water footprints.

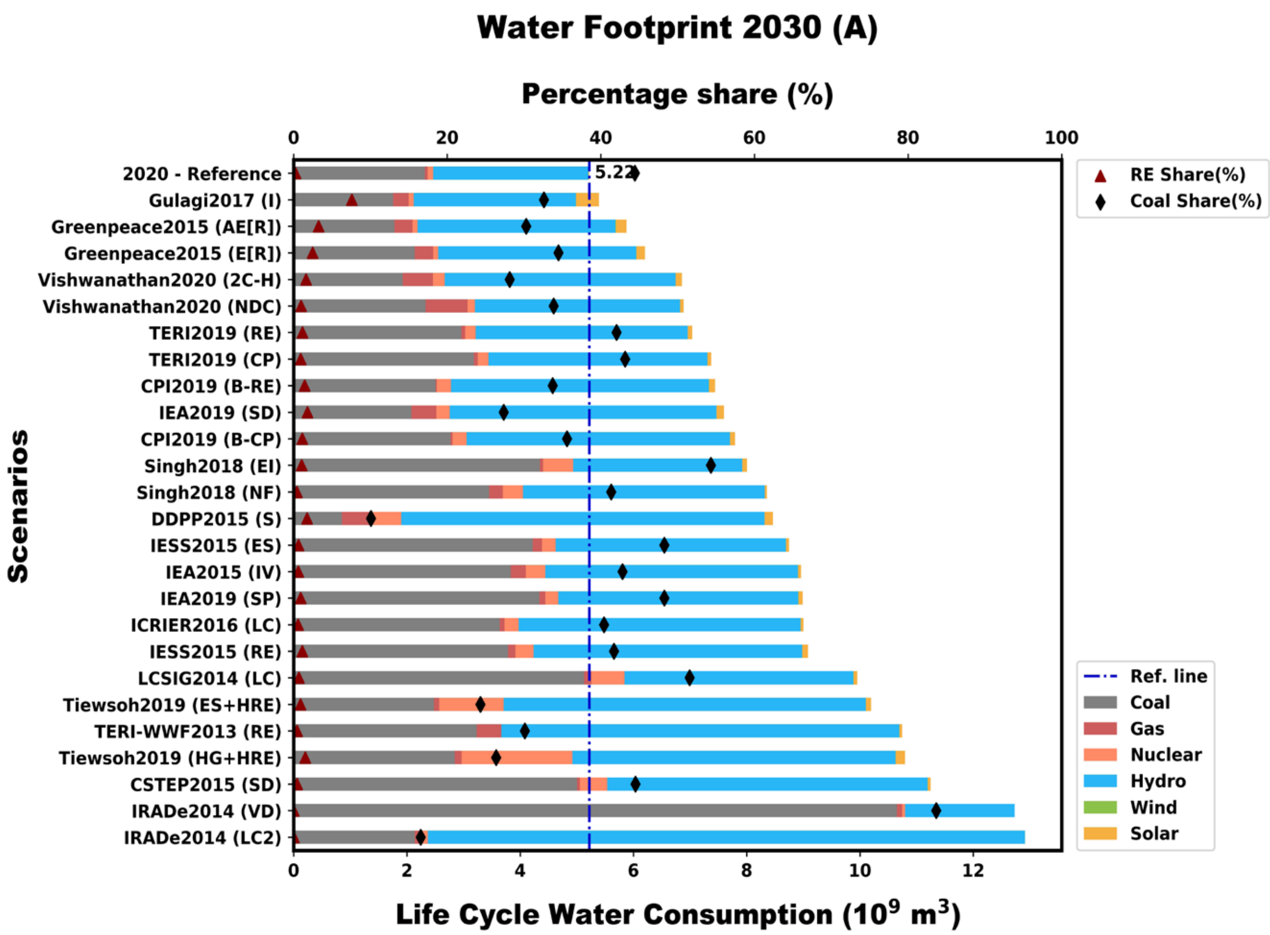


Figure 19: Water Footprint 2030 (alternate scenarios).

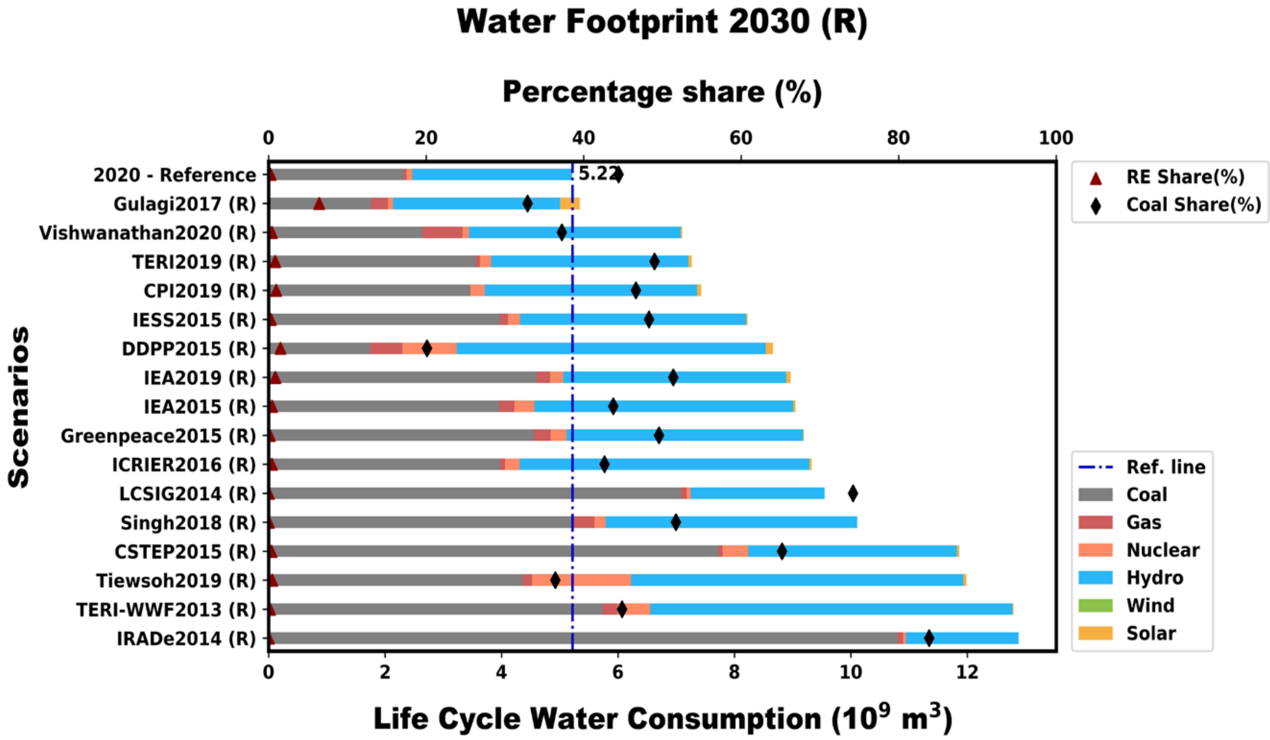


Figure 20: Water Footprint 2030 (reference scenarios).

Figure 21 shows the cumulative water footprints from different electricity sources during 2020 to 2030. For reference scenarios, the median values for the cumulative water footprints (2020-2030) are 71693, 32432, 1240, 1660, 32980, 6 and 246 (10^6) m^3 for total, coal, gas, nuclear, hydro, wind and solar electricity generation across their life cycle value chains, respectively. For alternate scenarios, the median values for the cumulative climate footprints (2020-2030) are 68411, 26389, 888, 1697, 35048, 10 and 465 (10^6) m^3 for total, coal, gas, nuclear, hydro, wind and solar electricity generation across their life cycle value chains, respectively. It should be noted that the life cycle water consumption indicator accounts for the consumption of fresh water resources only and ignores the consumption of sea water resources that can be significant for some electricity sources, especially nuclear power generation. Although the share for hydro power is much lower in comparison to coal in most of the electricity generation scenarios, the cumulative water footprint of hydro is more than coal; this is because hydro consumes nearly 7.5 times more water than coal. On the other hand, the insignificant contribution of solar (PV) and wind in the total water footprint is because these electricity sources are highly water efficient and consume nearly 10 to 400 times less water resources in comparison to coal power generation (see **Figure 3**).

Comparing the cumulative median values for total water footprint in the reference scenario (71693 (10^6) m^3) with the best performing alternate roadmap scenario (Gulagi2017-I: 53060 (10^6) m^3), it can be noted that embracing the Gulagi2017 (I) roadmap could save around 18633 (10^6) m^3 fresh water resources in the country during 2020 to 2030.

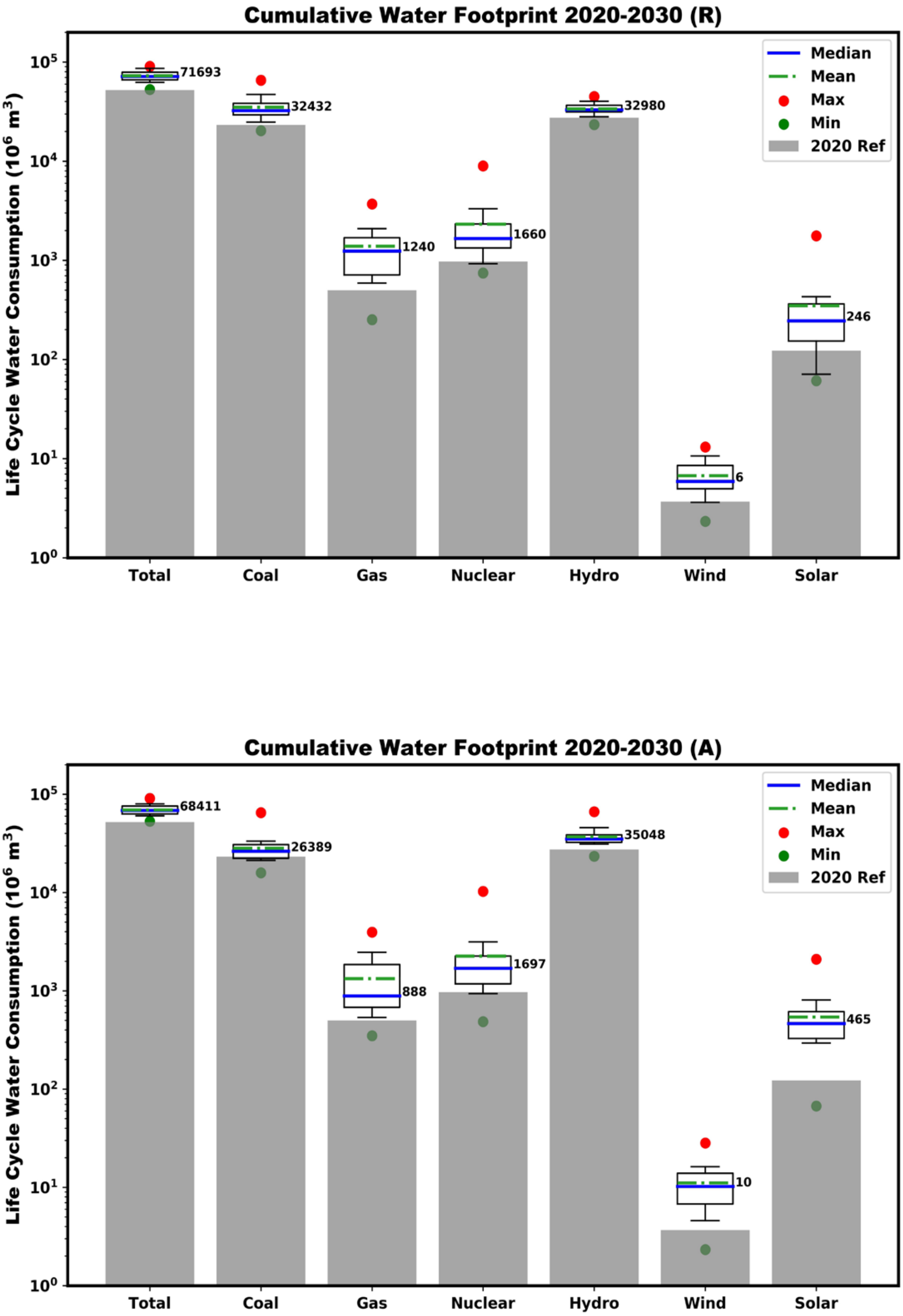


Figure 21: Cumulative water footprints from different electricity sources during 2020 to 2030.
Note: This plot has a logarithmic scale.

5.4. Land Transformation

The total land transformations for different electricity generation-mixes predicted by alternate and reference scenarios are shown in **Figure 22** and **Figure 23**. It can be observed that the land transformation impacts are dominated by coal and hydro in most of the roadmap scenarios, and solar power also contributes significantly in the roadmaps that predict higher solar share in their electricity generation-mix; but, wind and nuclear have minimal impacts on land transformation. It should be noted that the reason for significant impacts from coal power generation in most of the scenarios is because we account for life cycle land transformation in our study: coal transforms significant land area during mining, which is often totally ignored in mainstream policy studies. This highlights one of the major benefits of life cycle thinking, that is, it can give a comprehensive overview of the technological impacts across their life cycle value chains, in contrast with mainstream thinking that often takes into account the impacts arising at the operation phase only and totally ignores upstream and downstream impacts arising from power generation technologies.

Comparing alternate scenarios of all the modeling studies (**Figure 22**), it can be observed that Vishwanathan2020 (2C-H), Vishwanathan2020 (NDC) and TERI2019 (RE) are the top three modeling studies having the lowest land transformation in 2030; In contrast, IRADe2014 (VD), CSTEP2015 (SD) and LCSIG2014 (LC) are the bottom three studies having the highest land transformation.

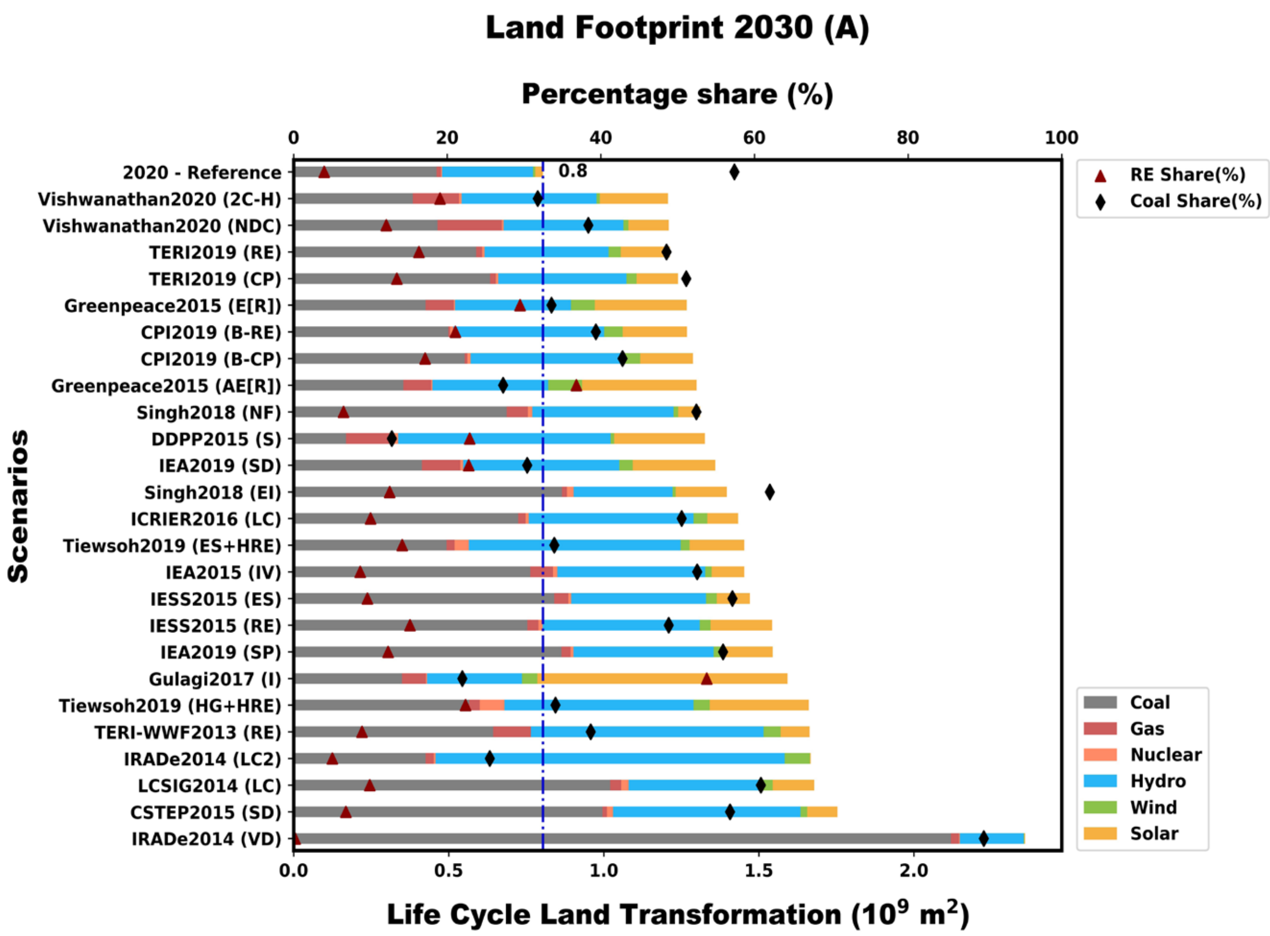


Figure 22: Land Transformation 2030 (alternate scenarios).

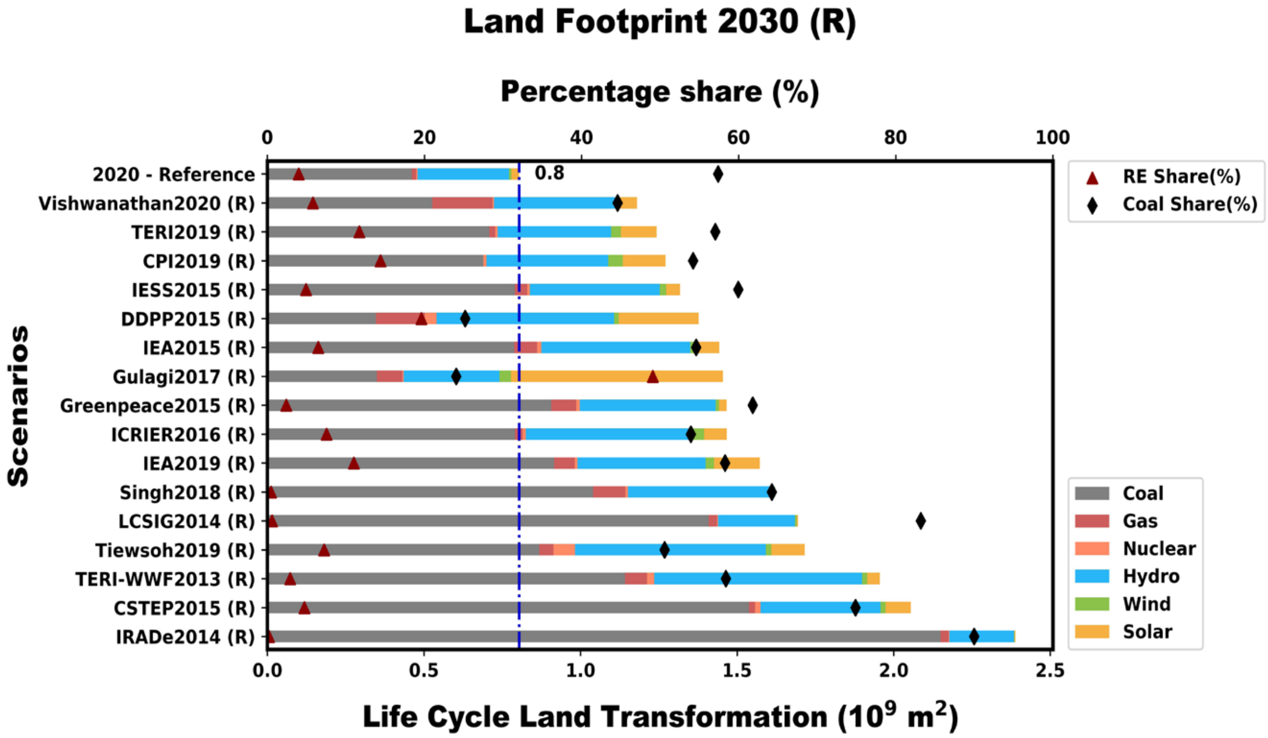


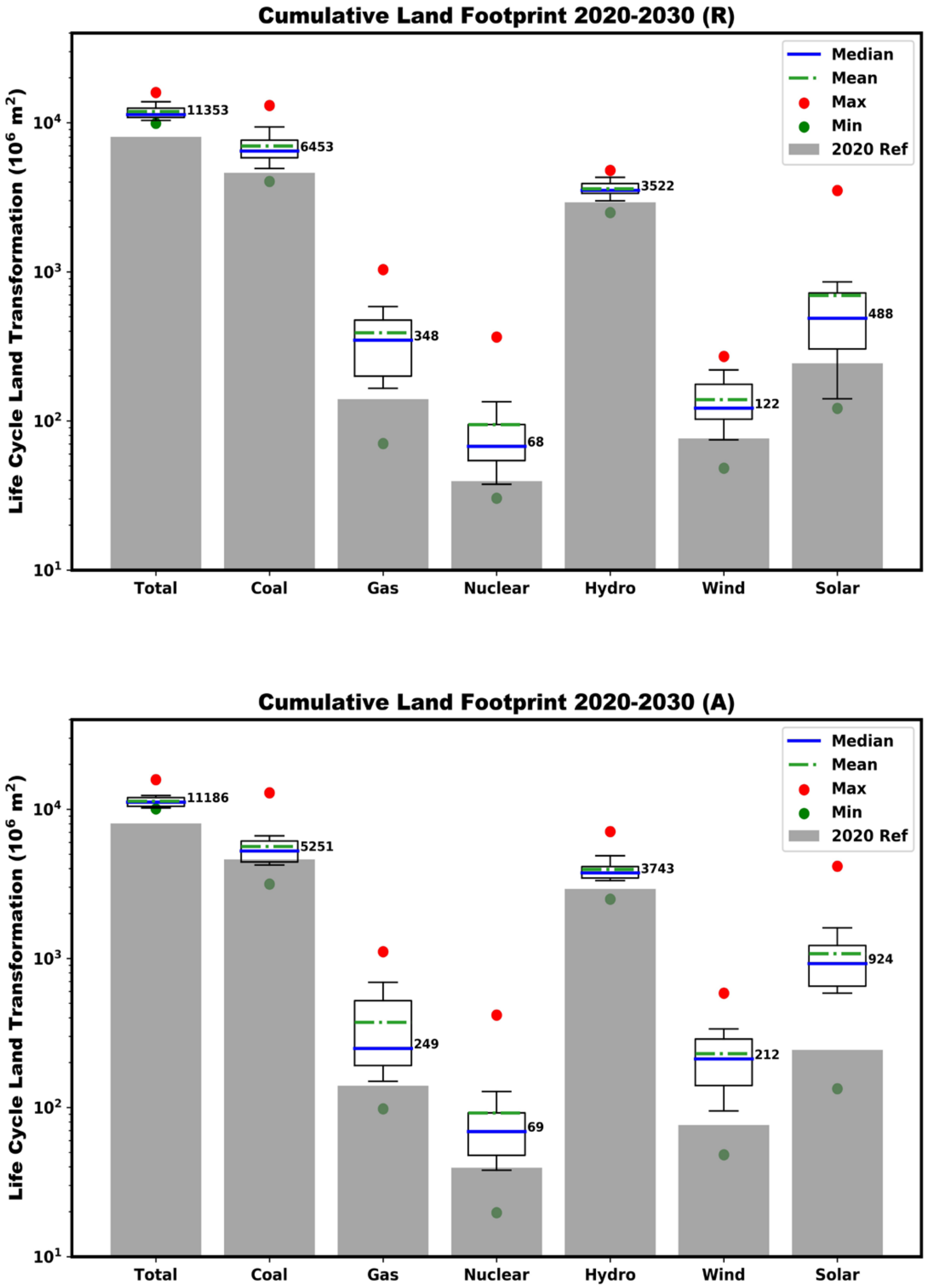
Figure 23: Land Transformation 2030 (reference scenarios).

Figure 24 shows the cumulative land transformations from different electricity sources during 2020 to 2030. For reference scenarios, the median values for the cumulative land transformation (2020-2030) are 11353, 6453, 348, 68, 3522, 122 and 488 (10^6) m^2 for total, coal, gas, nuclear, hydro, wind and solar electricity generation across their life cycle value chains, respectively. For alternate scenarios, the median values for the cumulative climate footprints (2020-2030) are 11186, 5251, 249, 69, 3743, 212 and 924 (10^6) m^2 for total, coal, gas, nuclear, hydro, wind and solar electricity generation across their life cycle value chains, respectively. Although the share of hydro is much lower in comparison to coal in most of the roadmap scenarios, the cumulative land transformations for hydro are comparable to coal; this is because hydro transforms nearly 4 times more land than coal. On the other hand, the lower contribution of solar in the total land transformation is because the share of solar is considerably lower than coal in most scenarios and also due to the fact that the land footprint of solar is comparable to coal when seen from life cycle perspective, unlike the popular belief (see **Figure 3**).

Comparing the cumulative median value for total land transformation in the reference scenario (11353 (10^6) m^2) with the best performing alternate roadmap scenario (Vishwanathan2020 2C-H: 10055 (10^6) m^2), it can be noted that embracing the Vishwanathan2020 (2C-H) roadmap could save around 1298 (10^6) m^2 land area from being transformed during 2020 to 2030 (only) that is equivalent to 2 times the land area of Mumbai (603 (10^6) m^2).

Figure 24: Cumulative land transformations from different electricity sources during 2020 to 2030.

Note: this plot has a logarithmic scale.



5.5. Air Pollution

The total impacts on air pollution from different electricity generation-mixes predicted by reference and alternate scenarios are shown in **Figure 25** and **Figure 26**. It can be observed that the air pollution impacts are dominated by coal power in all the roadmaps, with a minor contribution from gas power generation. The impacts from all other electricity sources are negligible in the total contributions even though these electricity sources together contribute considerably in total electricity generation by 2030 in most of the scenarios (see **Section 5.1**).

Comparing alternate scenarios (**Figure 25**), it can be observed that DDPP2015 (S), IRADe2014 (LC2) and Greenpeace2015 (AE[R]) are the top three scenarios having the lowest air pollution impacts in 2030; In contrast, IRADe2014 (VD), LCSIG2014 (LC) and CSTEP2015 (SD) are the bottom three scenarios having the highest air pollution impacts. Further, it is underscored that the top three best performing roadmaps predict that the air pollution impacts from India's electricity sector in 2030 could be lower or comparable to 2020 levels.

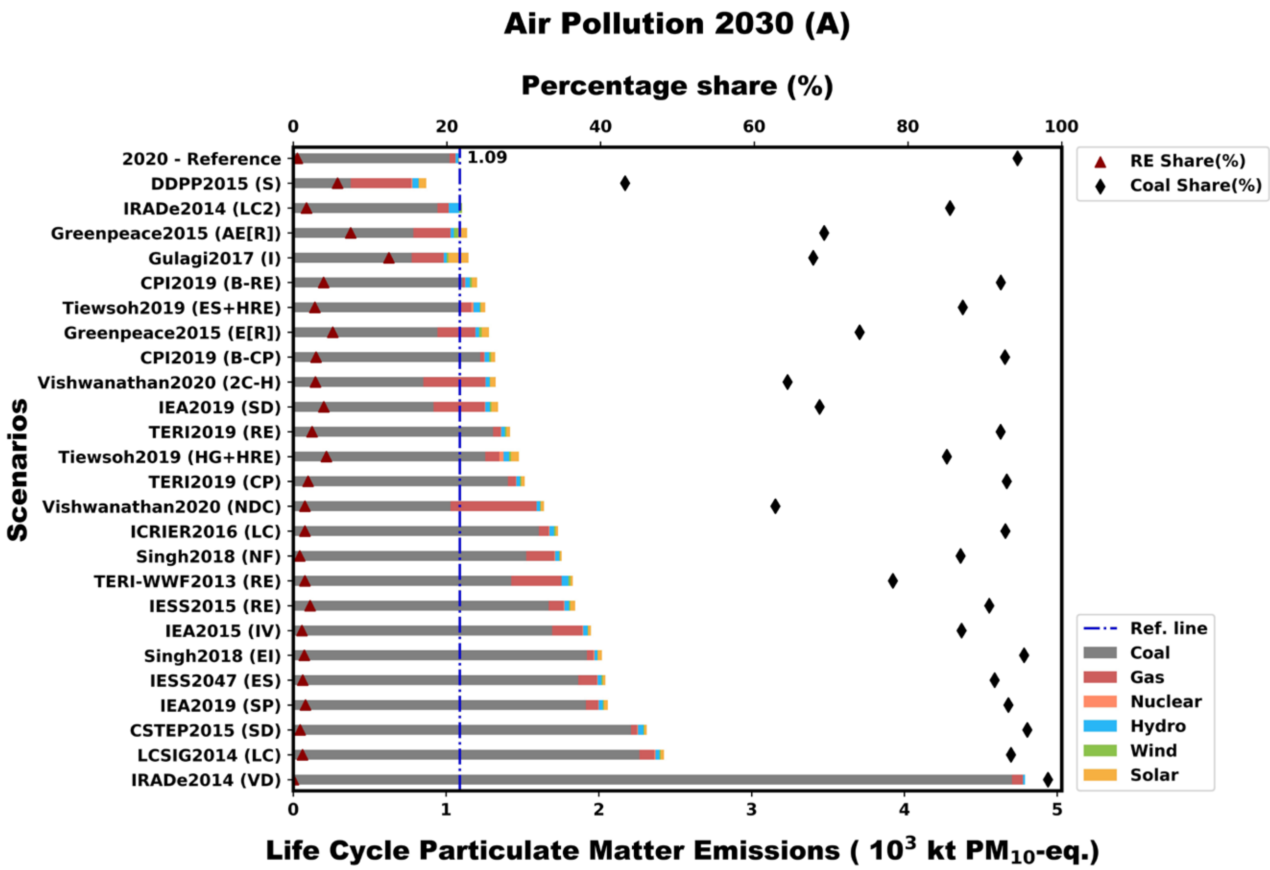


Figure 25: Air Pollution 2030 (alternate scenarios).

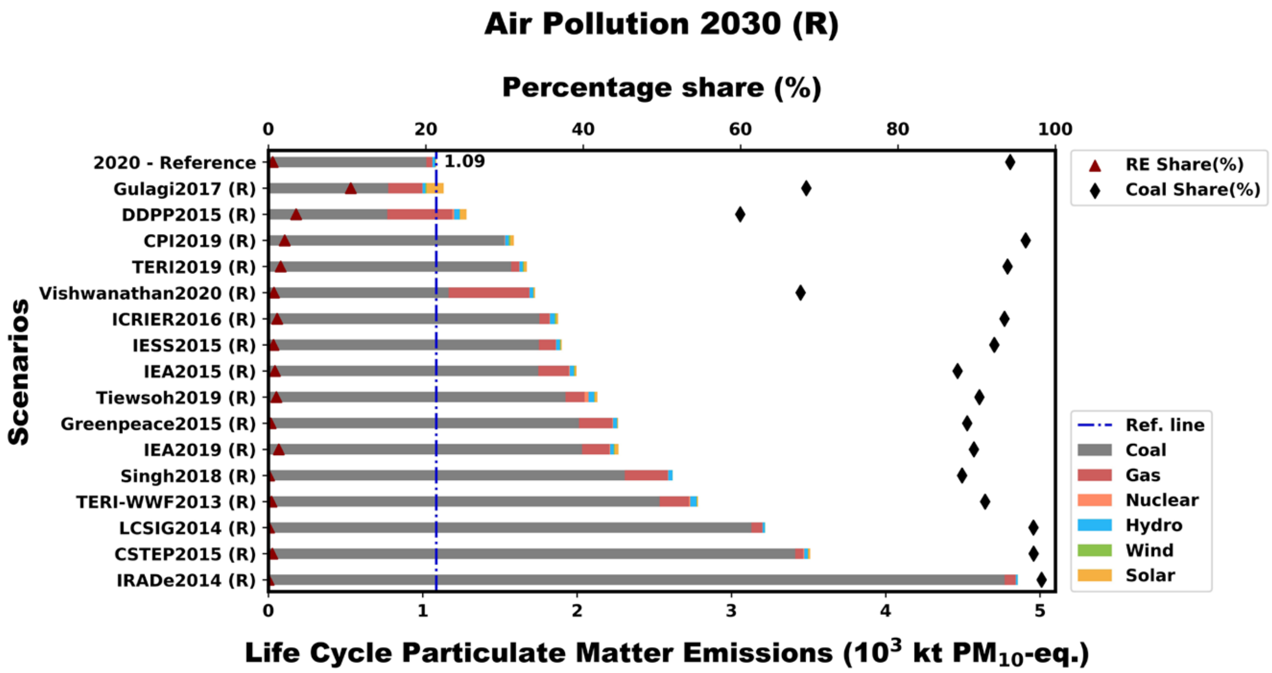


Figure 26: Air Pollution 2030 (reference scenarios).

Figure 27 shows the cumulative air pollution impacts from different electricity sources during 2020 to 2030. For reference scenarios, the median values for the cumulative air pollution impacts (2020-2030) are 15756, 14325, 941, 24, 212, 28 and 79 kt PM_{10}-eq. particulate matter emissions for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. For alternate scenarios, the median values for the cumulative air pollution impacts (2020-2030) are 13004, 11655, 674, 24, 225, 48 and 151 kt PM_{10}-eq. particulate matter emissions for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. Although solar and wind contribute significantly in most of the alternate road-map scenarios in terms of total electricity generation, their air pollution impacts are negligible because their life cycle emissions are 13 to 38 times lower in comparison to coal power emissions in India (see **Figure 3**). It should be noted here that we optimistically assume that the coal power plant fleet in India could have a lower emission factor in the coming years (1030 mg PM_{10}-eq./kWh; [32]) in comparison to today's power plants (3125 mg PM_{10}-eq./kWh; [33]). Hence, the particulate emissions from coal power fleet might increase by a factor of 3 if we assume instead that the emissions from coal power plants in 2030 remain the same as of today.

Comparing the cumulative median value for total air pollution (15756 kt PM_{10}-eq.) in the reference scenario with the best performing alternate roadmap scenario (DDPP2015-S: 9788 kt PM_{10}-eq.), it can be anticipated that embracing the DDPP2015 (S) roadmap could save around 5968 kt PM_{10}-eq. particulate matter emissions during 2020 to 2030. As noted earlier, we underscore again that the air pollution impacts in India's electricity sector are primarily resulting from coal power plants.

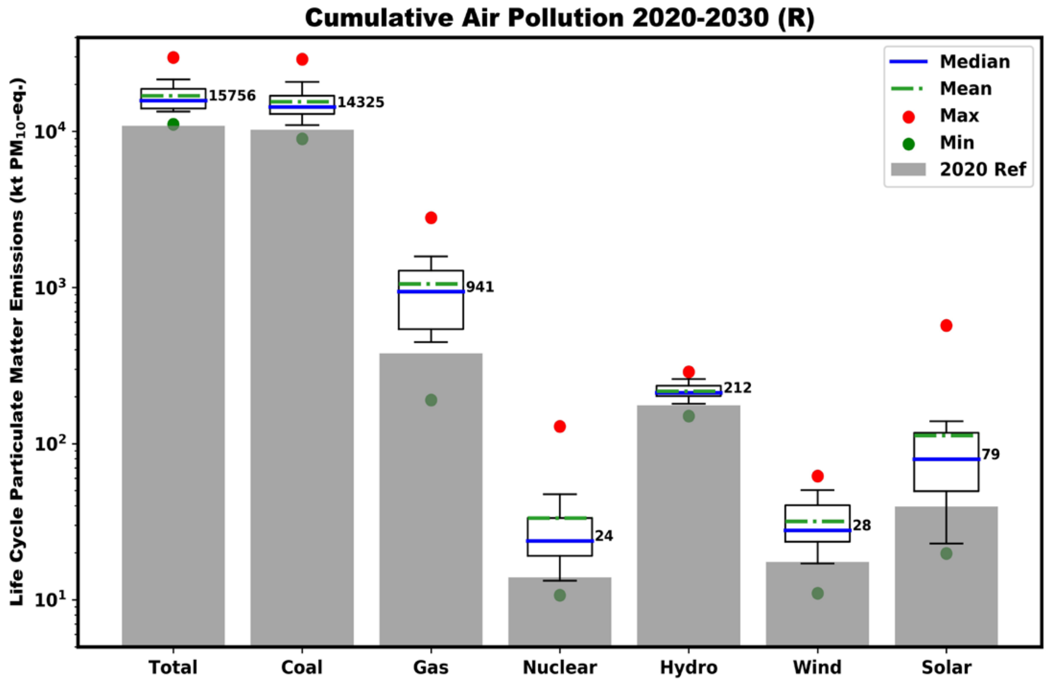
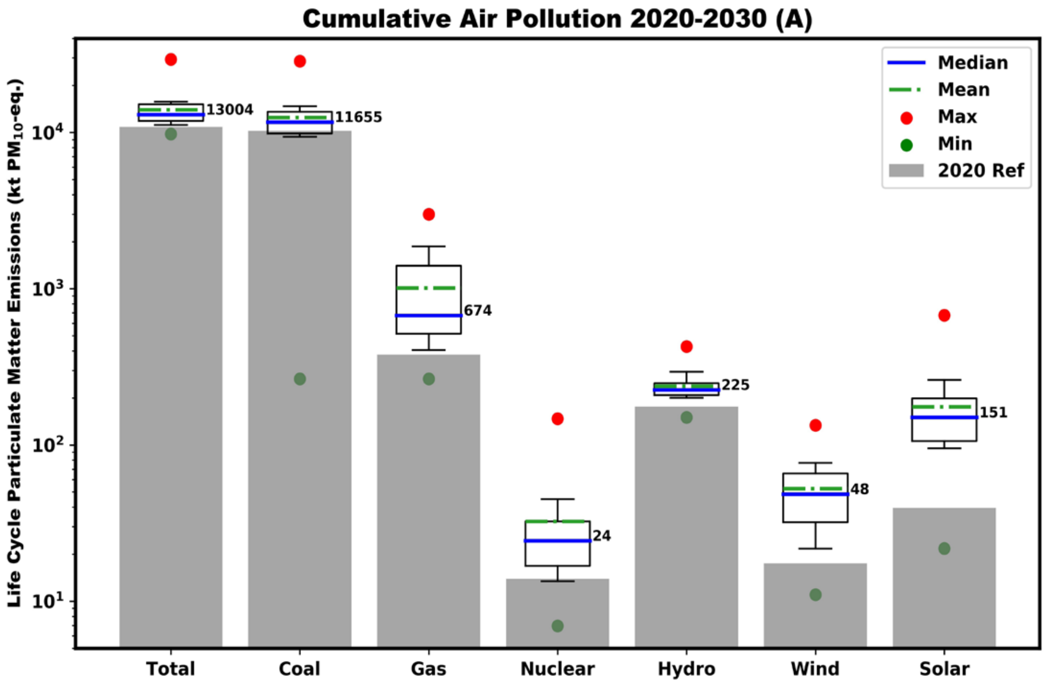


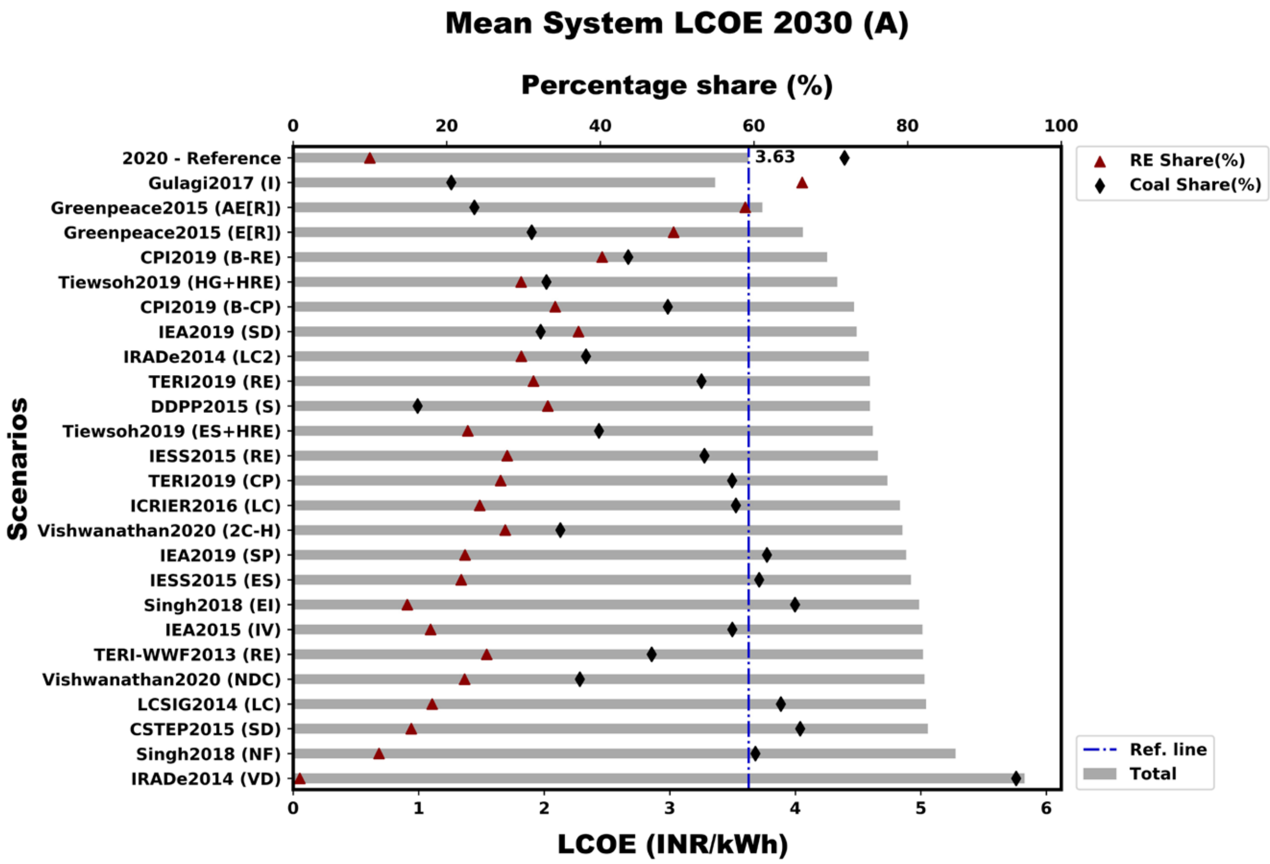
Figure 27: Cumulative air pollution impacts from different electricity sources during 2020 to 2030. Note: this plot has a logarithmic scale.



5.6. Levelized Cost of Electricity Generation (LCOE)

The mean system LCOE for electricity generation-mixes is calculated by normalizing the LCOE of individual electricity sources to their expected contribution in the total electricity generation-mix in 2030 and then aggregating the normalized LCOE values. However, the costs of electricity transmission and support infrastructure (e.g., storage and balancing reserves, among others) are not accounted in this parameter due to lack of data availability. The mean system LCOE for different electricity generation-mixes predicted by reference and alternate scenarios are shown in **Figure 28**. It can be observed that the mean system LCOE is inversely proportional to the share of solar and wind sources in the 2030 electricity-mix; the higher the share of renewables (RE share), the lower the mean system LCOE. This is because of the cost competitiveness of renewables in comparison to coal power in recent years, and this trend is expected to further continue in the coming decades.

Comparing alternate scenarios of all the modeling studies (**Figure 28**), it can be observed that Gulagi2017 (I), Greenpeace2015 (AE[R]) and Greenpeace2015 (E[R]) are the top three modeling studies having the lowest mean system LCOE in 2030; In contrast, IRADe2014 (VD), Singh2018 (NF) and CSTEP2015 (SD) are the bottom three studies with the highest mean system LCOE. Further, Gulagi2017 (I) scenario highlights that a dramatic shift towards renewables might reduce the system LCOE in 2030 in comparison to today's LCOE. However, the effect of storage and ancillary services on the mean system LCOE is yet to be quantified in future works.



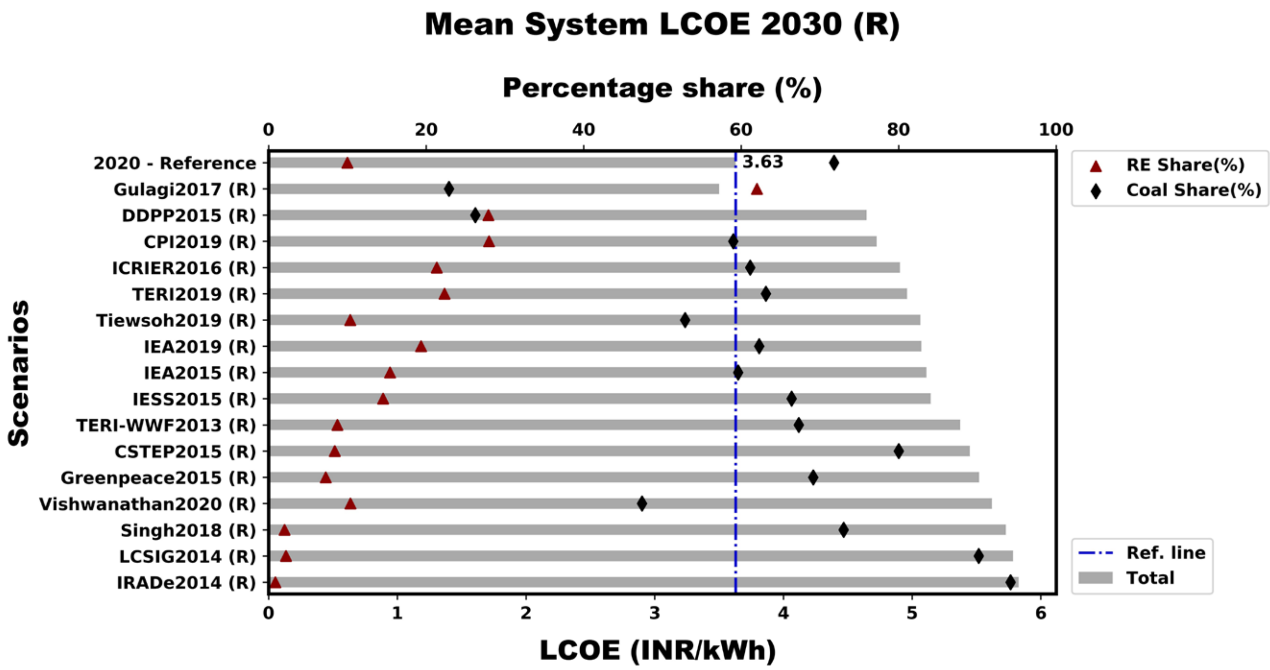


Figure 28: Mean System LCOE 2030 for alternate (A) and reference (R) scenarios.

5.7. External Costs

The external costs for different electricity generation-mixes predicted by alternate and reference scenarios are shown in **Figure 29** and **Figure 30**. It can be observed that the external costs for electricity generation-mixes are dominated by coal power in all the roadmaps, with a minor contribution coming from gas power generation. The external costs from all other electricity sources are negligible in the total contributions even though these electricity sources together contribute considerably in total electricity generation-mix by 2030 in most of the alternate scenarios (see **Section 5.1**)

Comparing alternate scenarios (**Figure 29**), it can be observed that DDPP2015 (S), Gulagi2017 (I) and IRADe2014 (LC2) are the top three scenarios having the lowest external costs in 2030; In contrast, IRADe2014 (VD), LCSIG2014 (LC) and CSTEP2015 (SD) are the bottom three scenarios having the highest external costs. Further, it is underscored that the top three best performing roadmaps predict that the external costs from India's electricity sector in 2030 could be lower or comparable to 2020 levels.

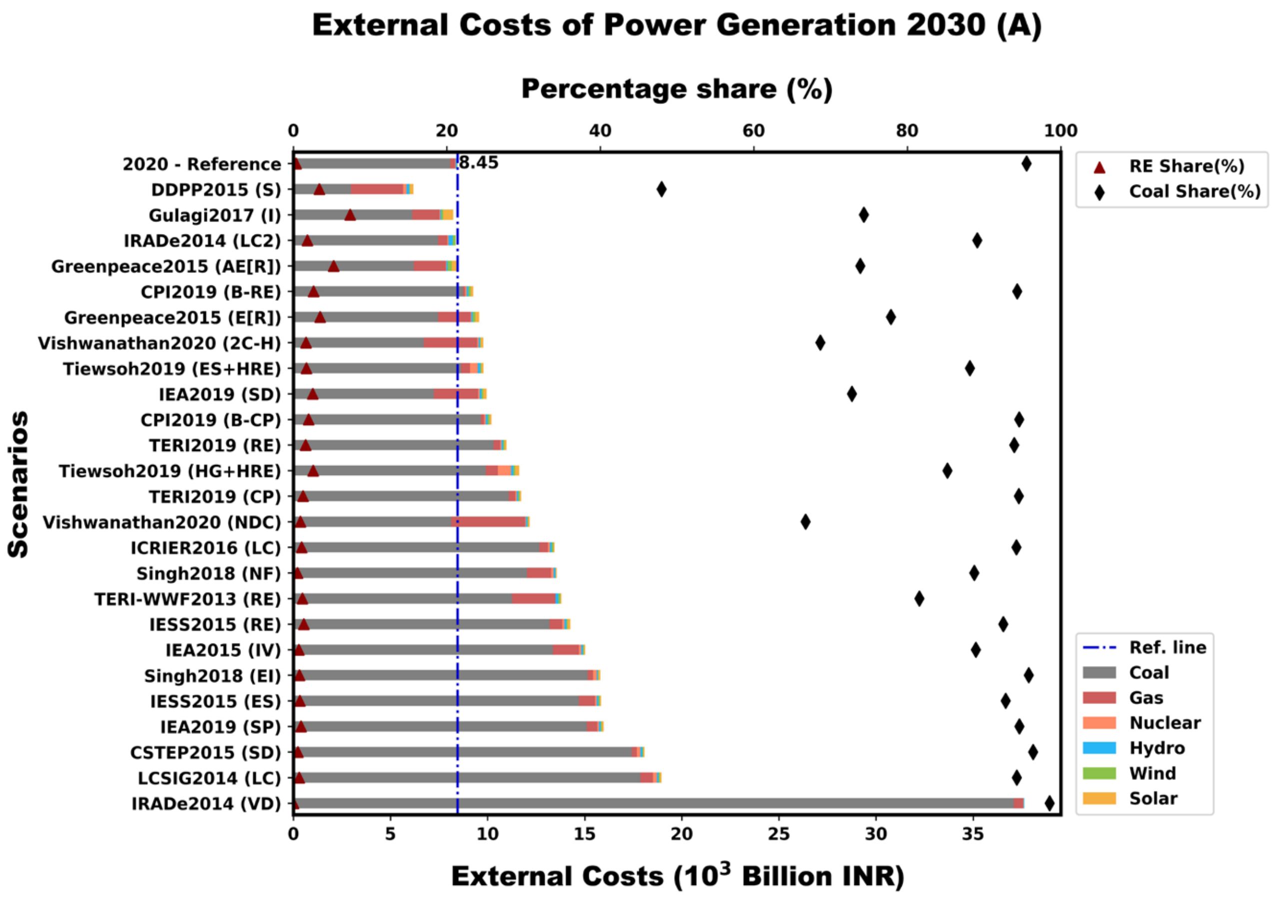


Figure 29: External Costs of Power Generation 2030 (alternate scenarios).

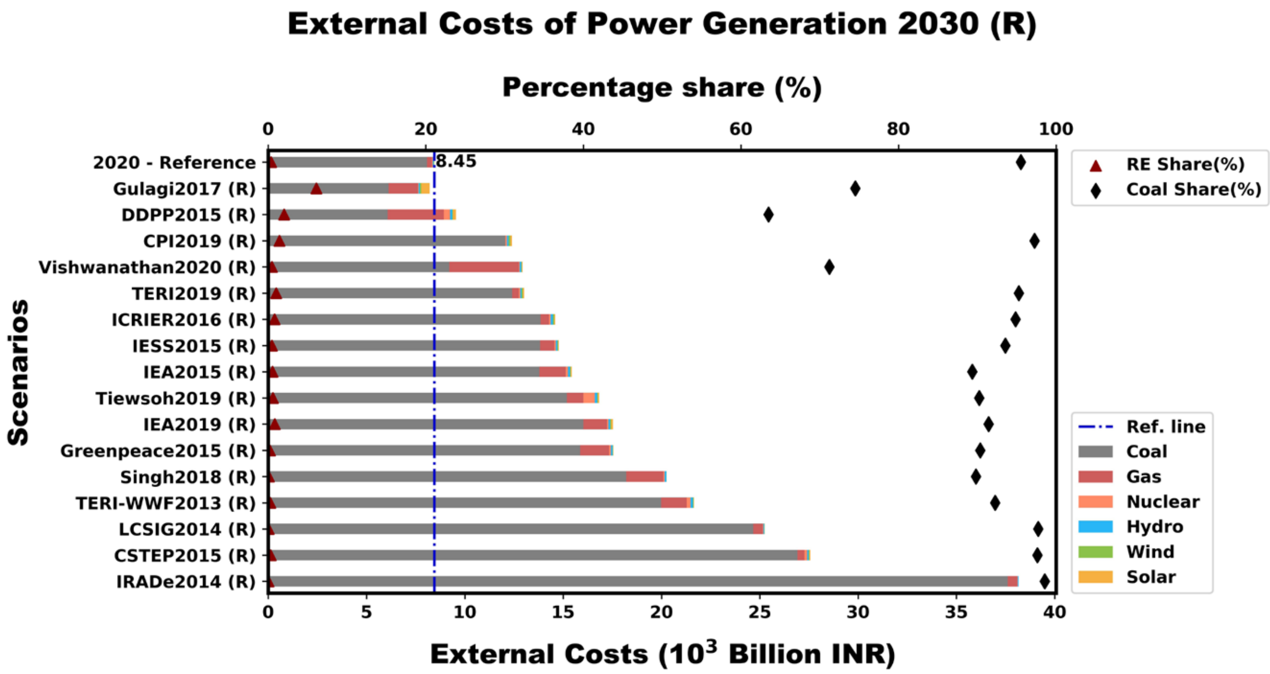
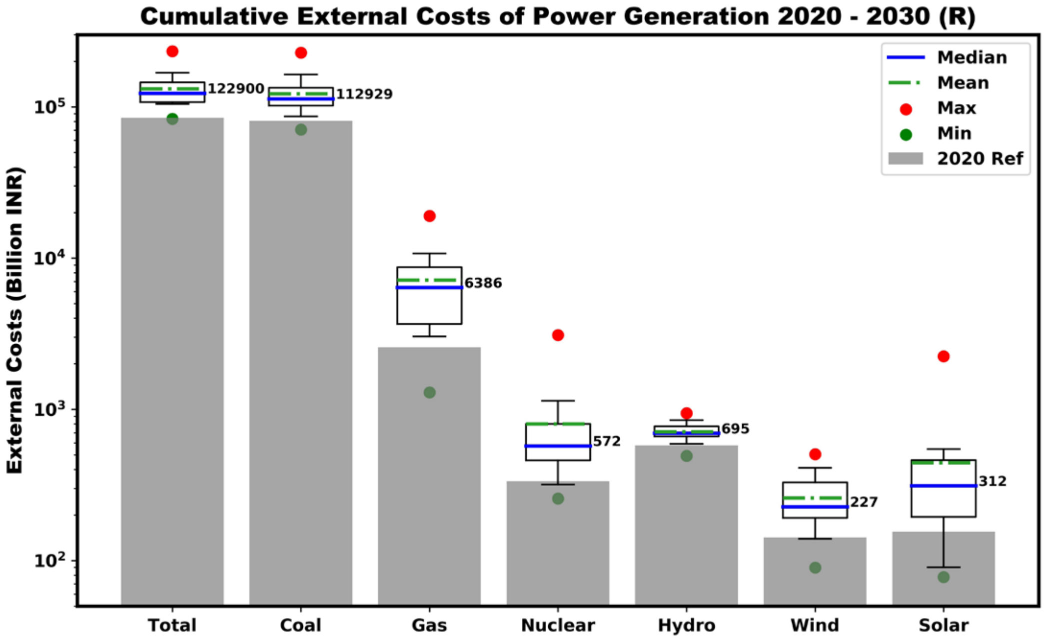


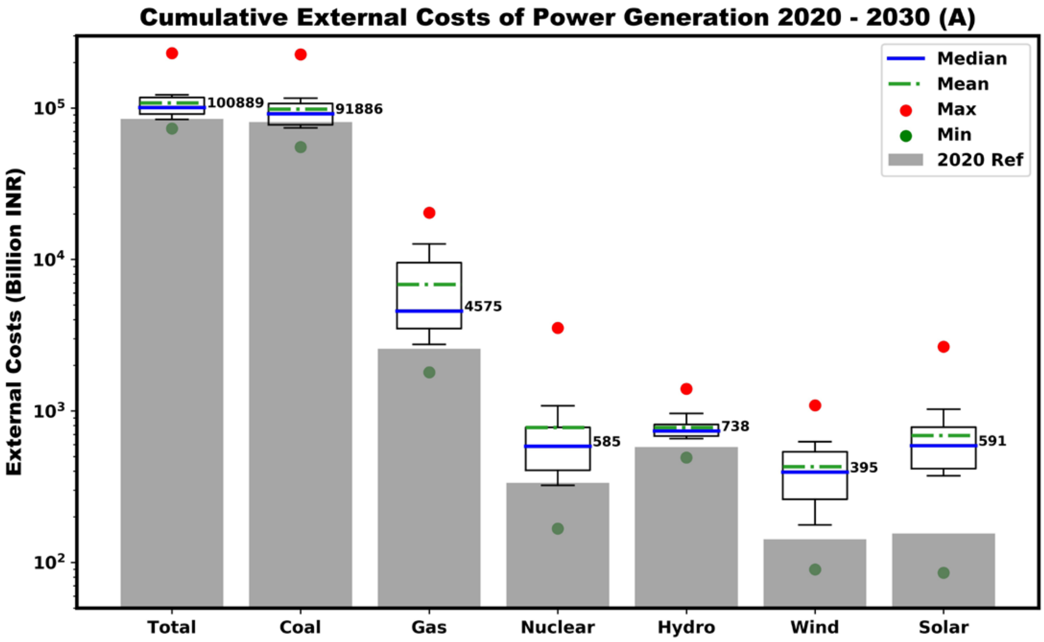
Figure 30: External Costs of Power Generation 2030 (reference scenarios).

Figure 31 shows the cumulative external costs from different electricity sources during 2020 to 2030. For reference scenarios, the median values for the cumulative external costs (2020-2030) are 122900, 112929, 6386, 572, 695, 227 and 312 billion INR for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. For alternate scenarios, the median values for the cumulative external costs (2020-2030) are 100889, 91886, 4575, 585, 738, 395 and 591 billion INR for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. Although solar and wind contribute significantly in the alternate roadmap scenarios in terms of total electricity generation, their external costs are negligible because these electricity sources have 26 to 36 times lower external costs in comparison to coal power generation (see **Figure 3**). Further, we underscore that the inclusion of external costs increase the levelized costs of coal power generation by a factor of 2.5. However, it should be noted here that the external cost estimates in this study are of a preliminary type and hence should be treated with caution. These estimates can be considered as indicative for a more detailed research in future works.

Comparing the cumulative median value for total external costs in the reference scenario (INR 122900 billion) with the best performing alternate roadmap scenario (DDPP2015-S: INR 73144 billion), it can be anticipated that embracing the DDPP2015 (S) roadmap could save approximately INR 49756 billion during 2020 to 2030 (only). This amount can be diverted towards building a strong support infrastructure for high penetration of renewable energies in the India's power grid in the next decades.

Figure 31: Cumulative external costs from different electricity sources during 2020 to 2030.
Note: this plot has a logarithmic scale.





5.8. Employment Generation

The employment generation potential for different electricity generation-mixes predicted by alternate and reference scenarios are shown in **Figure 32** and **Figure 33**. It can be observed that solar and wind electricity sources generate a significantly higher number of jobs across their life cycle value chains in comparison to other power sources. Further, it becomes evident that the performance of roadmap scenarios in employment indicator is directly proportional to the RE share in their electricity generation-mixes. However, the jobs created from coal power generation are much lower, given its significant share in almost all the roadmap scenarios (see **Section 5.1**). It should be noted here that, unlike other indicators in our sustainability framework, employment generation is a positive indicator; hence the higher the value, the better it is for the roadmap scenario.

Comparing alternate scenarios (**Figure 32**), it can be observed that Gulagi2017 (I), Greenpeace2015 (AE[R]) and Tiewsoh2019 (HG+HRE) are the top three scenarios having the highest employment generation in 2030; In contrast, Singh2018 (NF), Vishwanathan2020 (NDC) and IRADe2014 (LC2) are the bottom three scenarios having the lowest employment generation potential.

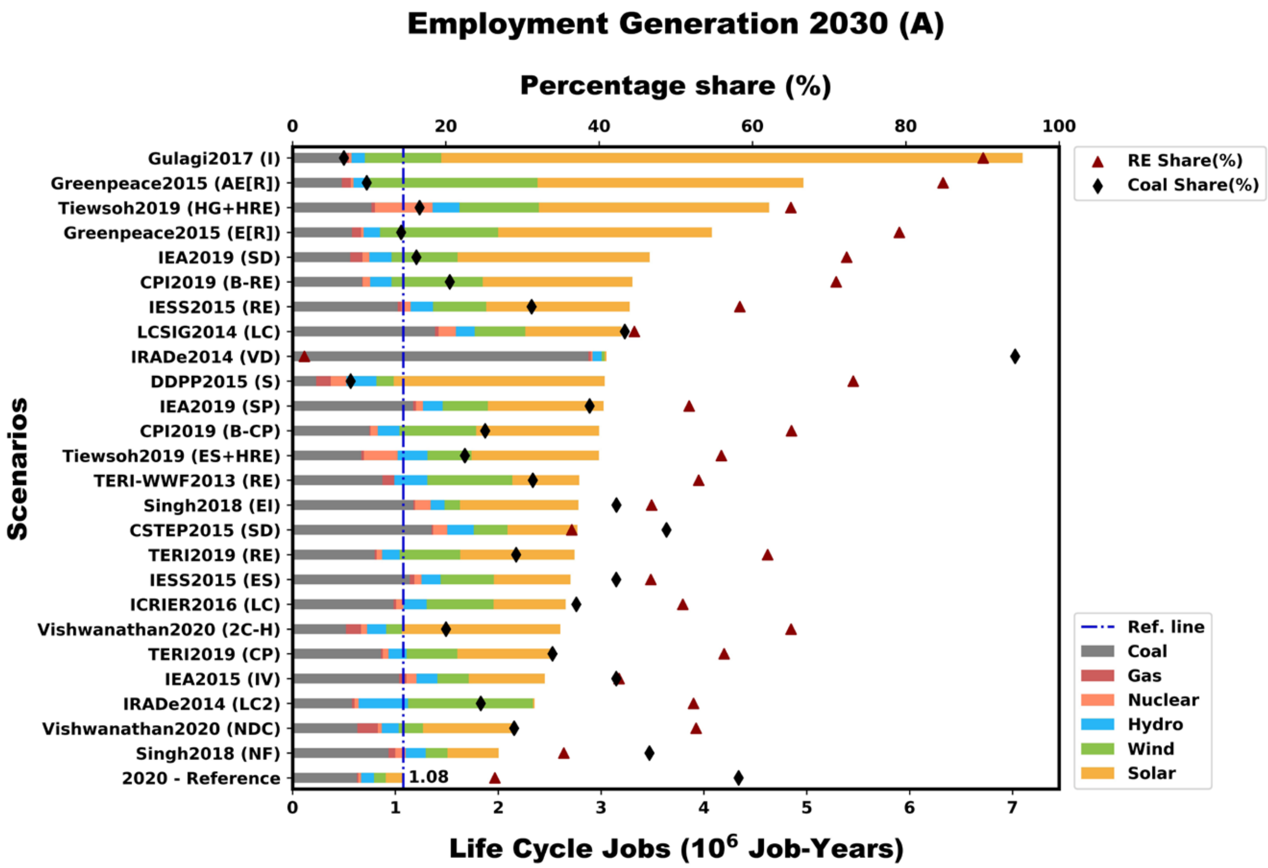


Figure 32: Employment Generation 2030 (alternate scenarios).

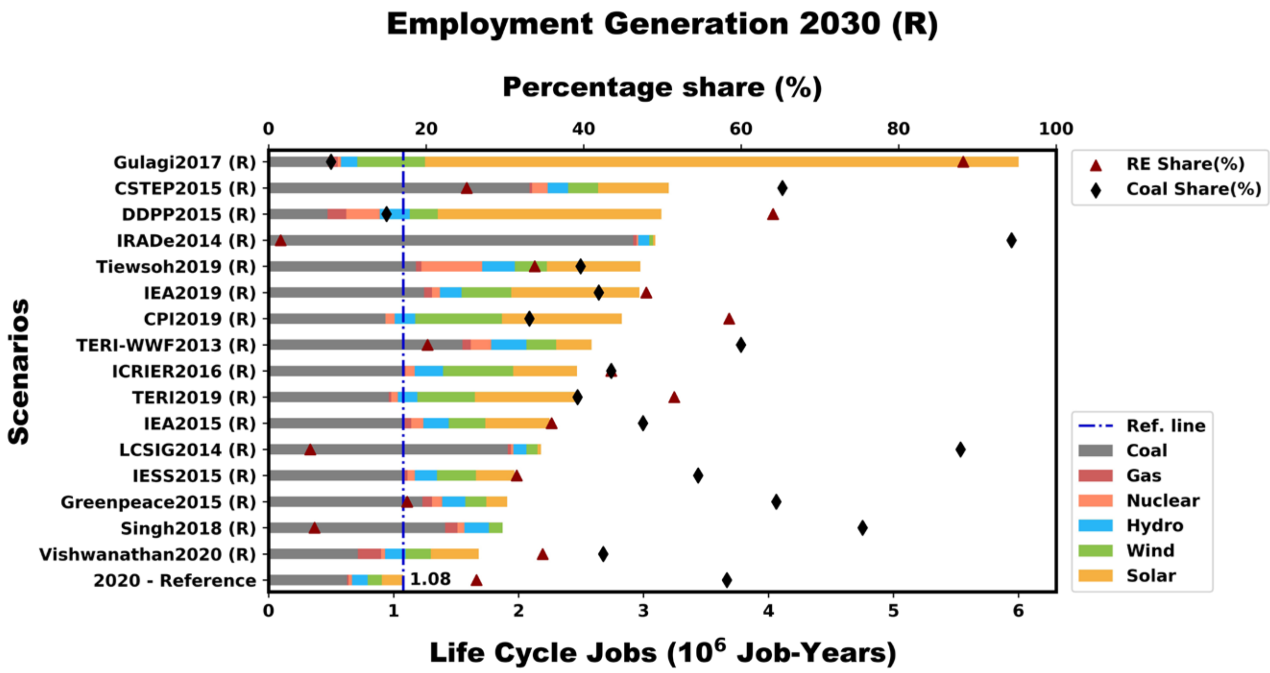
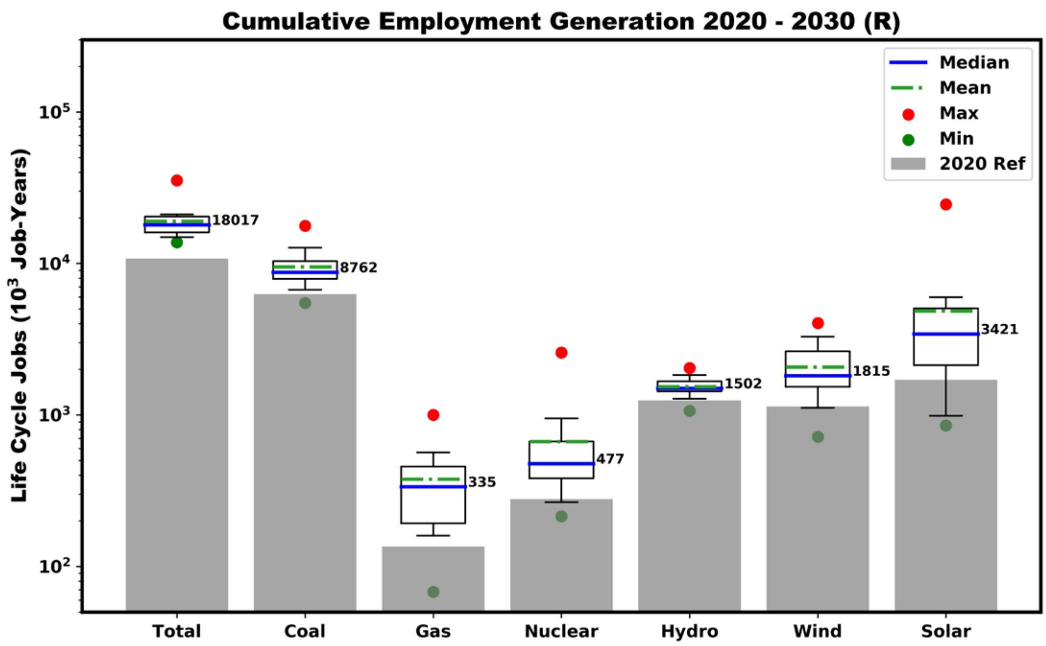


Figure 33: Employment Generation 2030 (reference scenarios).

Figure 34 shows the cumulative employment generation from different electricity sources during 2020 to 2030. For reference scenarios, the median values for the cumulative employment generation (2020-2030) are 18017, 8762, 335, 477, 1502, 1815, 3421 (10^3) Job-Years for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. For alternate scenarios, the median values for the cumulative employment generation (2020-2030) are 20276, 7129, 240, 488, 1596, 3157 and 6479 (10^3) Job-Years for total, coal, gas, nuclear, hydro, wind and solar electricity generation, respectively. Although the contributions from solar and wind are much lower in comparison to coal in total cumulative electricity generation figures (see **Figure 15**), their contributions in employment generation are significantly higher because they generate 3 to 5 times more jobs across their life cycle value chains in comparison to coal power generation (see **Figure 3**).

Comparing the cumulative median value for total employment generation in the reference scenario (18017 (10^3) Job-Years) with the best performing alternate roadmap scenario (Gulagi2017-I: 40881 (10^3) Job-Years), it can be noted that embracing the Gulagi2017 (I) roadmap could generate an additional 22863 (10^3) Job-Years during 2020 to 2030 (only).



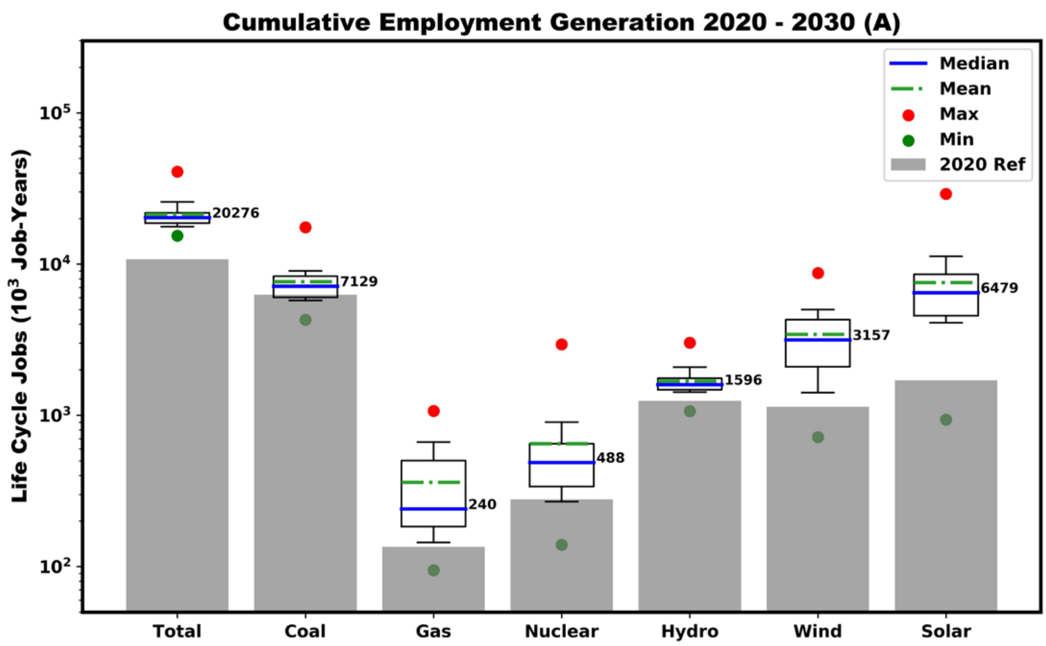


Figure 34: Cumulative employment generation from different electricity sources during 2020 to 2030.

Note: This plot has a logarithmic scale.

Photo by Casey Horner on Unsplash

6. BENCHMARKING INDIA'S ROADMAPS WITH OTHER COUNTRIES

In this section, we benchmark India's electricity roadmaps with four other key countries: emerging economies (China and Brazil) and developed economies (USA and Germany). We collected the required electricity supply data for these four countries from 11 modeling studies in total (4 for China, 2 for Brazil, 2 for USA and 3 for Germany). The list of the international modeling studies, the primary institutions that conducted these studies and the scenarios selected in our comparative assessment is briefly presented in **Table 4**. Overall, we analyzed the electricity supply data from 27 scenarios across these 11 selected modeling studies.

6.1. Electricity Generation 2030

The median electricity generation value for India is nearly one-third of China's generation in 2030.

The annual electricity generation projections for 2030 for the five countries across various modeling studies considered in our assessment are presented in **Figure 35**. In general, it is observed that the alternate scenarios project lower electricity generation in 2030 than reference scenarios for emerging economies (India, China and Brazil) because the alternate scenarios assume lower electricity demand growth in comparison to the reference scenarios due to effective implementation of electricity conservation and efficiency measures. On the other hand, the stabilization of total electricity generation figures for both reference and alternate scenarios for developed economies might be a sign of already stabilized electricity demand in these countries, and slight decreases in alternate scenarios might show the de-growth of these economies in addition to the implementation of higher efficiency and conservation measures in the coming years. Further, comparing the median values of the alternate scenarios, it can be noted that the electricity generation for India (2855 TWh) is nearly one-third of China's generation (9429 TWh) and is around 64% of the USA's (4474 TWh) electricity generation in 2030. We provide the breakdown analysis for the different electricity sources across these five countries in the subsequent sections.

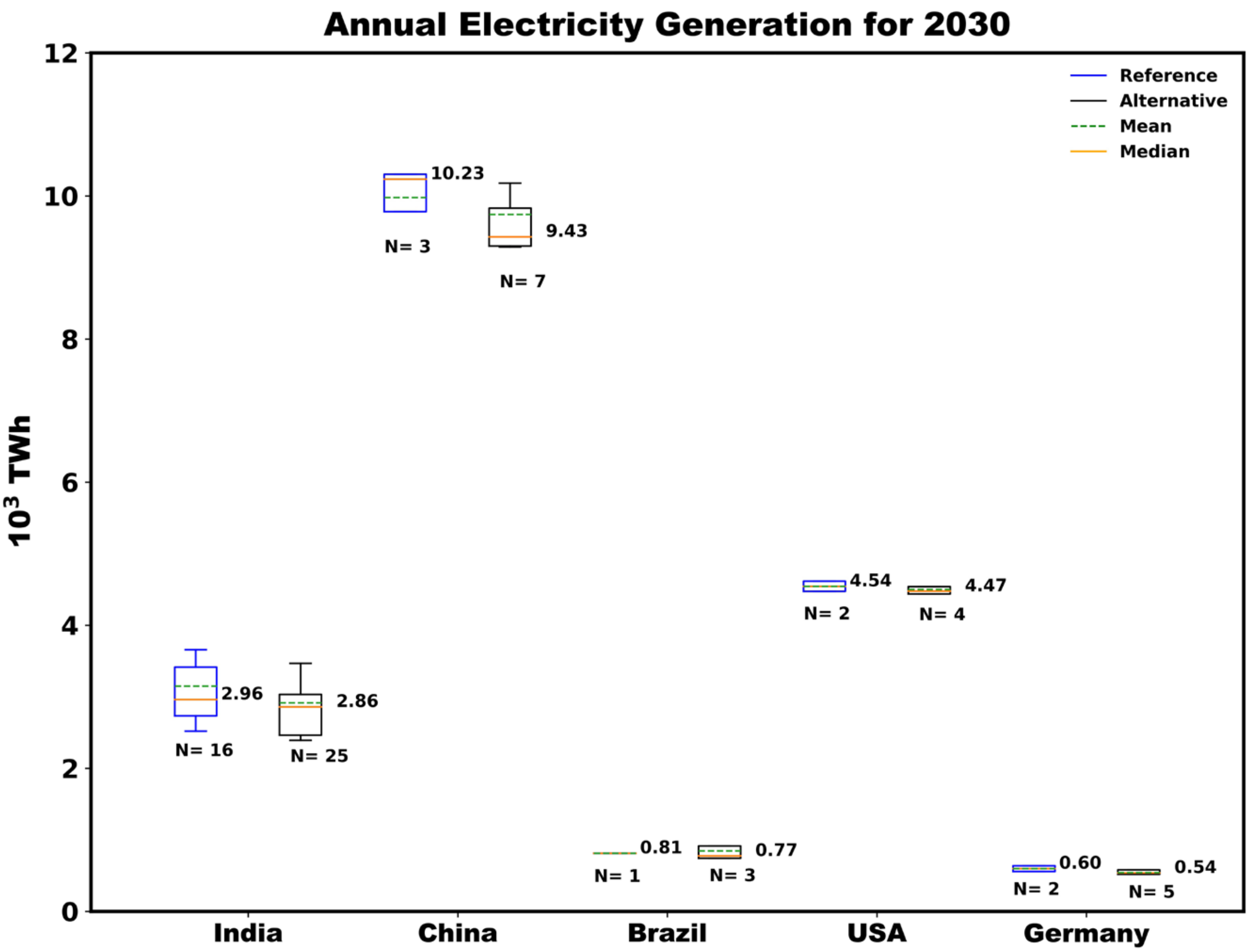


Figure 35: Annual electricity generation in 2030 - comparison across 5 countries.

Table 4: List of modeling studies from which electricity supply data for China, Brazil, the USA and Germany are collected.

Country	Study Name & Year	Primary Institution / Authors	Scenarios (selected for analysis)
China	Energy [r]evolution, A sustainable World Energy Outlook, 2015 [18]	Greenpeace International	Reference Scenario (R), Energy [R]evolution Scenario (A), Advanced Energy [R]evolution Scenario (A)
	World Energy Outlook, 2019 [22]	International Energy Agency	Current Policies Scenario (R), Stated Policies scenario (A), Sustainable Development Scenario (A)
	China 2050: High Renewable Energy Penetration Scenario and Roadmap Study, 2015 [34]	Energy Research Institute, China	High RE penetration scenario (A)
	Pathways to deep decarbonization in China, 2015 [35]	The National Center for Climate Change Strategy and International Cooperation (NCSC)	Central scenarios (R), High EV scenario (A), Low CCS scenario (A)
Brazil	Pathways to deep decarbonization in Brazil, 2015 [36]	The CentroClima - Center for Integrated Studies on Climate Change and the Environment	DDPP scenario (A)
	World Energy Outlook, 2019 [22]	International Energy Agency	Current Policies Scenario (R), Stated Policies scenario (A), Sustainable Development Scenario (A)
USA	2019 Standard Scenarios Report: A U.S. Electricity Sector Outlook, 2019 [37]	National Renewable Energy Laboratory (NREL)	Mid-case scenario (A), 2018 Annual Baseline Technology cost (R), High demand growth scenario (A)
	World Energy Outlook, 2019 [22]	International Energy Agency	Current Policies Scenario (R), Stated Policies scenario (A), Sustainable Development Scenario (A)
Germany	Pathways to deep decarbonization in Germany, 2015 [38]	Wuppertal Institute for Climate, Environment and Energy	Government Target (R), Renewable Electrification (A), 90% GHG Reduction (A)
	Pathways for Germany's Low-Carbon Energy Transformation Towards 2050, 2019 [39]	Technische Universität Berlin	Survival of The Fittest (R), European Island (A), Green Democracy (A)
	Long-term scenarios and strategies for the deployment of renewable energies in Germany, 2013 [40]	German Aerospace Center (DLR)	Scenario A (A)

6.2. Share of Coal and Renewables in 2030 Roadmaps

Figure 36 shows the share of coal and RE (solar and wind only) in the 2030 electricity generation-mixes predicted by various modeling studies across the five countries. Comparing the median values, it can be observed that the share of coal in total electricity generation-mix is projected to be reduced to 49%-63%, 47%-52%, 2%-3%, 22%-23% and 14%-30% (alternate/reference median values) for India, China, Brazil, the USA and Germany, respectively. However, when we look at the reduction in the percentage points of alternate scenarios in comparison to the reference scenarios, we note that the alternate scenarios for India's future expect ambitious reductions in the coal share in comparison to other countries as well as to India's present status-quo; for instance, compare the 14% reduction of median value (in alternate versus reference scenarios) for India with 5% for China and 1% for the USA in 2030. Moreover, the reduction of coal share to 49% by 2030 in comparison to today's coal share of 72% (i.e., 23% reduction in 10 years) could be considered as ambitious not only for India, but elsewhere as well.

On the other hand, the growth of RE share (solar and wind) in total electricity generation-mix by 2030 is expected to be around 10%-23%, 15%-22%, 13%-16%, 20%-21% and 50%-55% (reference/alternate median values) for India, China, Brazil, the USA and Germany, respectively. Given the recent growth in India's renewable energy sector, the country has already achieved 8% of RE share in 2019-2020. Hence, the lower projection of 10% (median for reference scenarios) for India by 2030 can be considered as already dated. Moreover, comparing the alternate scenarios across the five countries, India's RE share projection of 23% by 2030 is second only to Germany (55%) and India outperforms all the other three countries, particularly China.

The alternate scenarios for India's future expect ambitious reductions in the coal share in comparison to other countries as well as to India's present status-quo.

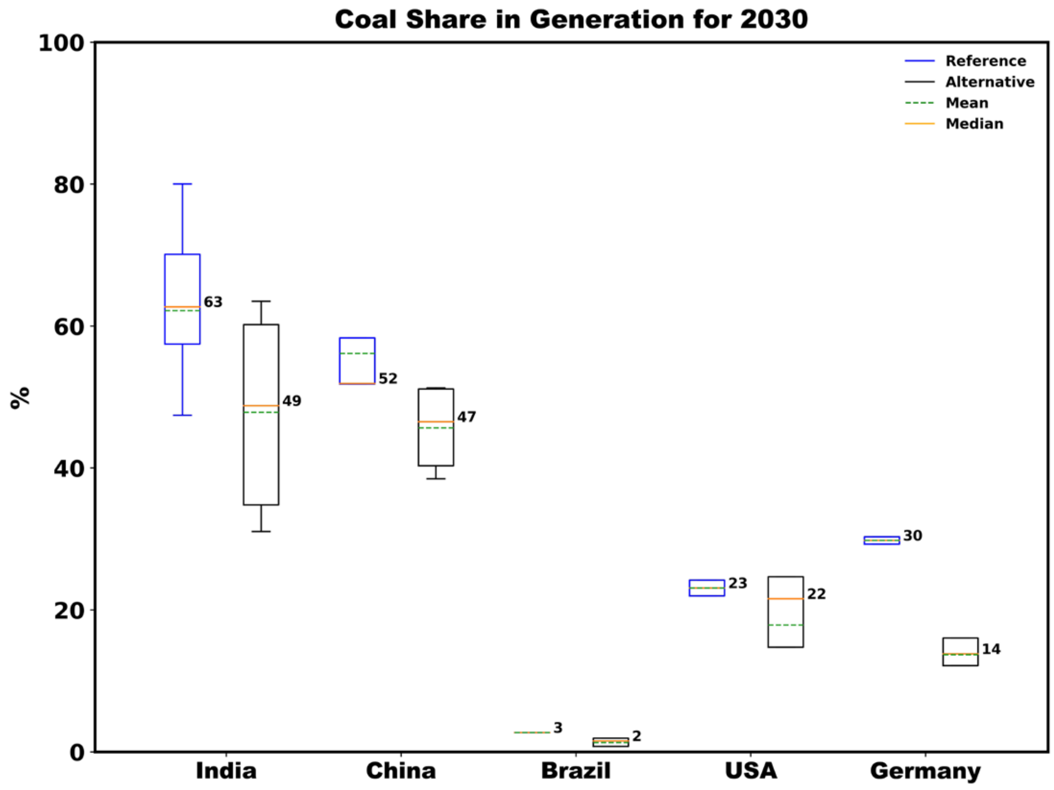
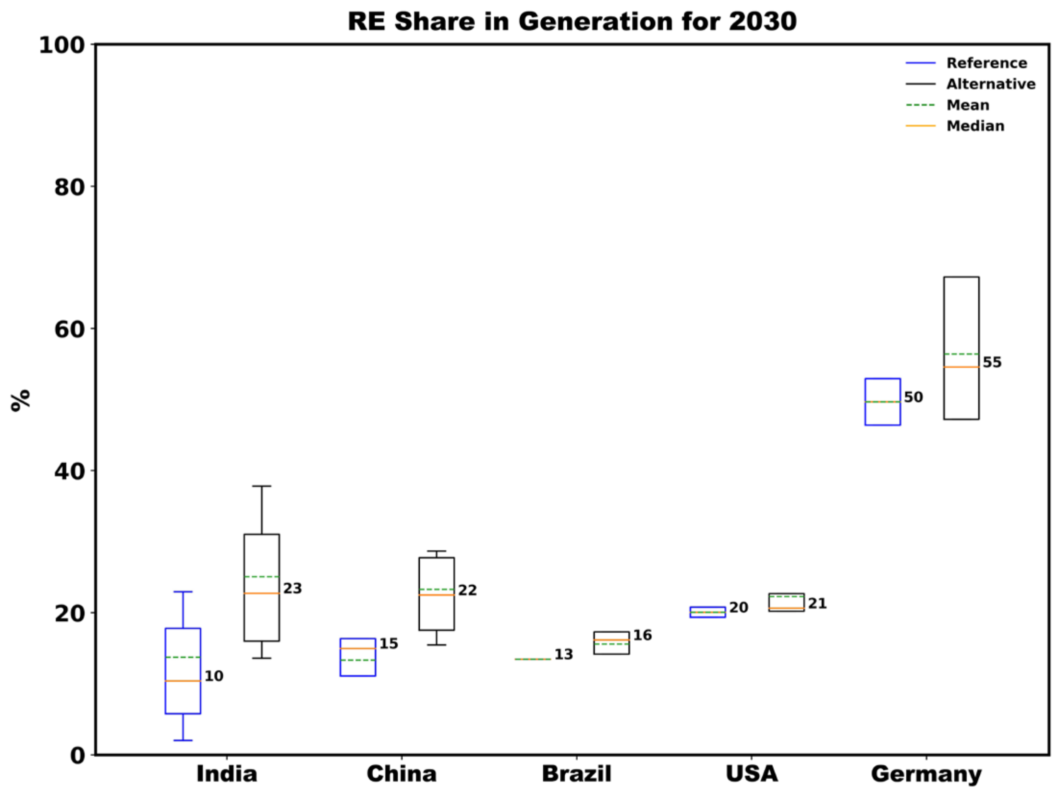


Figure 36: The share of coal and RE (solar and wind only) in the 2030 electricity generation-mixes across the five countries.



6.3. Projections for different Electricity Sources by 2030

The 2030 roadmaps predictions for coal, gas and nuclear across the five countries are presented in **Figure 37**. It is predicted that the annual coal power generation in 2030 (absolute median values) could be 1.27 to 1.79, 4.57 to 5.31 and 0.98 to 1.05 (10^3) TWh for India, China and the USA; and comparatively insignificant in the other two countries. In comparison to reference scenarios (business-as-usual roadmaps), coal power generation is expected to reduce in alternate scenarios for China and India particularly. India's coal capacity is nearly one–third of China's coal capacity, but nevertheless higher than the USA and the other countries. Further, the projections for electricity generation from gas and nuclear in India are insignificant in comparison to China and the USA, but are higher in comparison to Brazil and Germany.

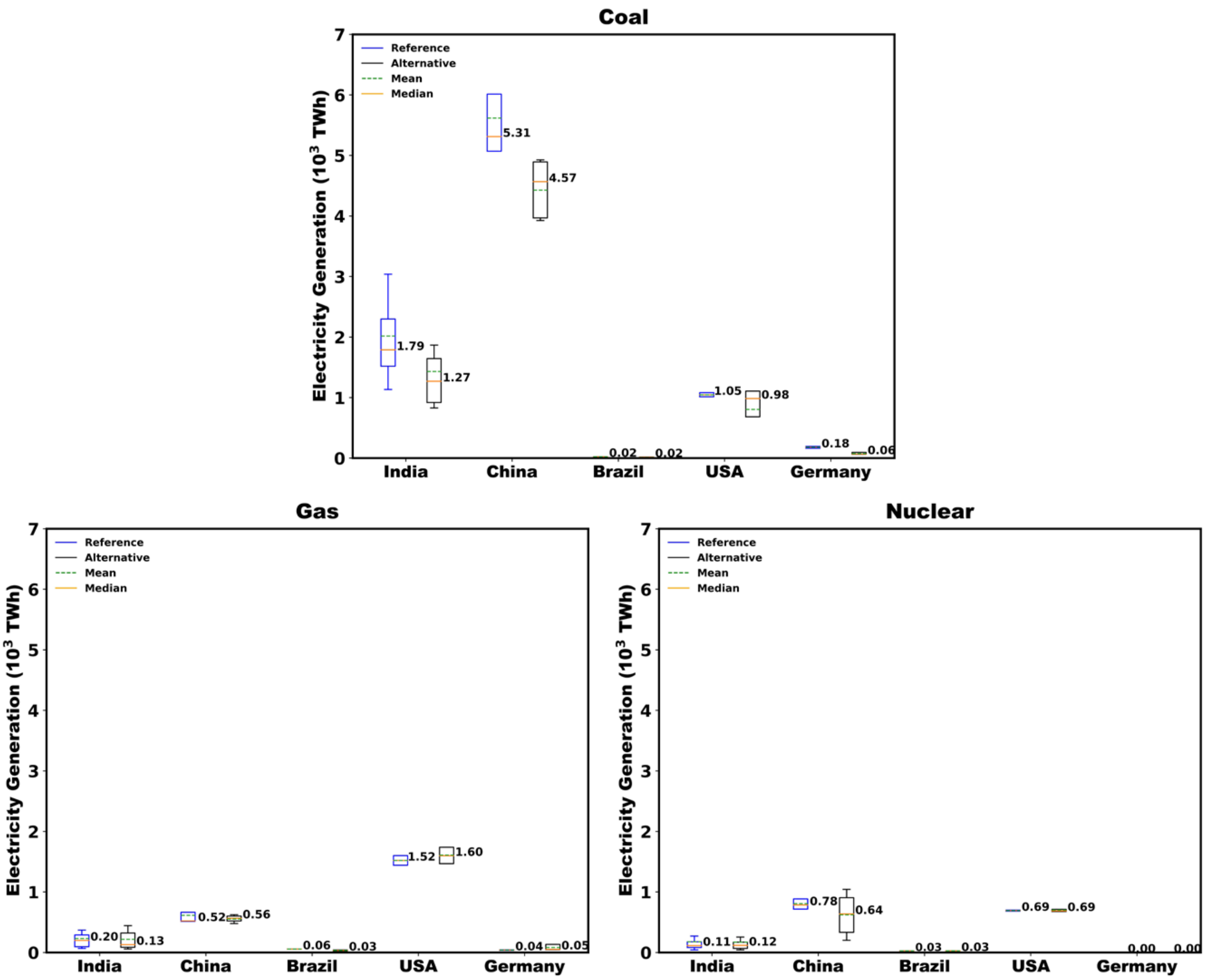


Figure 37: 2030 projections for coal, gas and nuclear across the five countries.

Note: The nuclear projections for Germany are "zero" both in the reference and the alternate scenarios due to its complete nuclear phase-out strategy by 2022.

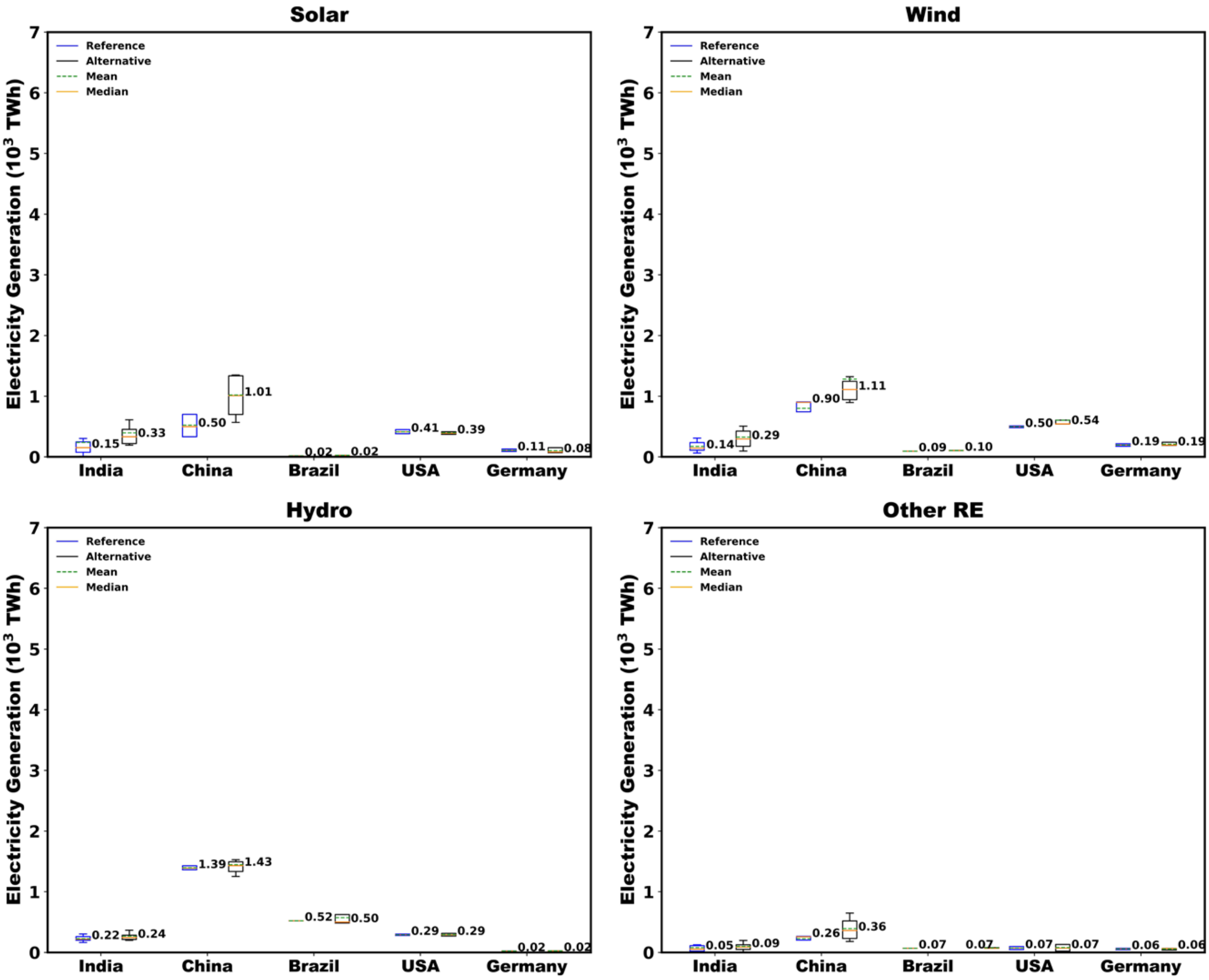


Figure 38: 2030 projections for solar, wind, hydro and other RE across the five countries.

The 2030 roadmaps predictions for solar, wind, hydro and other RE across the five countries are presented in **Figure 38**. Comparing the median values, the alternate scenarios predict nearly twice as much electricity generation as in the reference scenarios for both solar and wind in India by 2030. The same trend is true for China with respect to solar power generation. For absolute solar power generation, the predictions from alternate scenarios for India are second only to China and are comparable with the USA and significantly higher than Brazil and Germany; For wind, India comes after China and the USA (see top-right **Figure 38**). However, (comparing alternate scenarios) the annual solar (331 TWh) and wind (294 TWh) power generation in India by 2030 is nearly one-third of China (solar – 1009 TWh; wind – 1108 TWh). Further, China and Brazil outperform India when it comes to large hydro power projections for 2030, and the USA is comparable to India. The 2030 projections for other renewables (RE) have been minimal across all the countries, but China is better positioned than India.

Photo by Sharon Pittaway on Unsplash

7. INFERENCES AND CONCLUSION

In this work, we conducted a comparative review of major low carbon electricity transition roadmaps developed specifically for India from a supply side perspective. We harmonized the electricity generation-mix predictions for 2030/2050 and compared the electricity supply trends projected for India across the various electricity modeling studies. A series of indicators from environmental (climate footprint, water footprint, land transformation), economic (LCOE, external costs) and social (employment, air pollution) dimensions were chosen and integrated within our "Sustainability Framework" to assess the multi-dimensional aspects of electricity supply technologies and to evaluate India's low carbon electricity transition roadmaps.

The open source modeling tools have not yet found their place in India's electricity modeling community.

Overall, we reviewed 16 modeling studies with a total of 41 scenarios; five studies from think tanks and academia each, four studies from international organizations and two studies from governmental or related agencies. The electricity models used in India-specific studies ranged from simple excel based simulation type models (e.g., IESS2015 and scenario based approaches in TERI2019) to large scale simulation and optimization models (e.g., World Energy Model in IEA2019, LEAP in Tiewsoh2019) to integrated models based on computational general equilibrium (e.g., TIMES in CSTEP2015, MARKAL in TERI-WWF2013). However, we observed that the open source modeling tools have not yet found their place in India's electricity modeling community.

India specific modeling studies seriously lack high granular modeling with respect to prospective technologies over long-term duration (e.g., 2050)

In general, we found that the modeling granularity, data and assumptions used for projecting 2030 scenarios are more reliable than 2050 scenario projections, and also noted that the most of the India specific modeling studies have a short term focus on prospective electricity and storage technologies (and relevant energy policies). For instance, out of 16 modeling studies, only 5 studies accounted for solar CSP, 3 studies for wind offshore and 2 studies for coal based carbon capture and storage (CCS). In addition, the scope of other renewables (e.g., geothermal, ocean, hydro and waste to energy) is often discussed qualitatively rather than quantitatively in the studies that consider these options. The same argument holds true for the storage technologies in most of the studies, except that Gulagi2017 and CPI2019 made an initial attempt to present a prospective quantitative assessment of possible storage technologies (in particular, pumped hydro and battery storage) in future Indian electricity scenarios. This could be because of the lack of Indian specific detailed technological studies on different electricity generation sources and prospective technology types till 2050. In addition, we encountered serious data availability issues (India specific) while quantifying the technological impacts on the different sustainability indicators chosen in this study. We certainly recommend more policy oriented research in this direction.

7.1. Generic Comparison: 2030 and 2050 Roadmap Scenarios

In our generic comparison of electricity supply and demand projections for 2030 and 2050 scenarios, we estimated the median values to get an impression on the most probable pathway across the modeling scenarios. The median annual overall electricity demand estimations for India in 2030 and 2050 are 2256 TWh and 3657 TWh respectively in alternate scenarios. The annual electricity generation trends show that the median values for alternate scenarios are 2855 TWh in 2030 and 5464 TWh in 2050. The RE share (solar and wind only) in annual electricity generation is expected to rise from 8% in 2020 to 23% in 2030 to 45% in 2050 in alternate scenarios, and the RE share in total power capacity is projected to rise from 20% in 2020 to 39% in 2030 to 59% in 2050 in alternate scenarios. However, the reference scenarios project lower shares for RE than the alternate scenarios. Nevertheless, it is underscored that both reference and alternate scenarios predict increasing shares for RE and decreasing shares for coal in the electricity sector over the time period 2020 to 2050. It could further be observed that most of the roadmaps predict dramatic reductions for coal share in their annual electricity generation-mixes in the alternate scenarios: from over 72% in today's grid to 49% in 2030 to 21% in 2050.

For solar power, most alternate scenarios project an ambitious rise in solar capacity in comparison to reference scenarios (by a factor of 2 or more).

Further, comparing the median values for absolute power capacities, the alternate scenarios predict slight increase in coal power capacities during 2020 to 2030 (reaching 228 GW in 2030) and expect that the coal capacities will slightly drop afterwards and then stabilize around 2020 installed capacities (approx. 205 GW). For nuclear power, the future predictions are very conservative and most alternate scenarios expect that nuclear capacities might stabilize around 17 GW to 20 GW in the coming decades; that is, nearly thrice as much increase in nuclear power capacity as of today (7 GW in 2020). However, the predictions for natural gas based power plants are promising: 45 GW in 2030 to 115 GW in 2050 (compare with 25 GW in 2020); this might be because of their flexible role in balancing and maintaining the grid stability during peak loads and also during non-availability of renewable energy sources, among other reasons. For solar power, most alternate scenarios project an ambitious rise in solar capacity in comparison to reference scenarios; for instance, the median values for alternate scenarios for 2030 (190 GW) and 2050 (540 GW) are more than double their corresponding median values for the reference scenarios (90 GW and 210 GW respectively). It is underscored that these capacity additions are significant as they call for a dramatic increase in the solar power capacity by 2030 and 2050 in comparison to today's installed capacity; for example, the median values for alternate scenarios in 2030 and 2050 are higher by a factor of 5 and 15 in comparison to today's solar capacity installations (35 GW), respectively. The same trends hold true for wind power projections, except that their capacity projections are not as dramatic as for solar power. Nevertheless, the median values for alternate scenarios predict 130 GW and 290 GW of wind power capacities by 2030 and 2050, that is, an increase in the total wind power capacity by a factor of 3 and 8 in comparison to today's wind power capacity (38 GW), respectively. Further, the majority of roadmap scenarios expect large hydro to stabilize after reaching around 70 GW in the coming decades, from 46 GW in 2020. Lastly, the predictions for other renewable energies mainly include bioenergy (primarily) and micro/small hydro based electricity generation, and the roadmap scenarios expect higher contributions from these renewable energy sources in the future electricity-mix. However, the possible contributions from prospective renewable energy technologies are ignored or highly underrated in the present modeling studies.

7.2. Roadmap Scenarios 2030: Benefits & Trade-Offs

The possible contributions from major electricity sources (coal, gas, nuclear, hydro, wind and solar) in the 2030 electricity generation-mix projections were obtained from the selected 41 roadmap scenarios, and the cumulative contributions of each electricity source and the roadmap scenarios during 2020 to 2030 were quantified using simple straight-line escalation approach. Then, the impacts of the electricity sources and the roadmap scenarios on the 7 chosen sustainability indicators were quantified annually (2030) as well as cumulatively over a time period of 10 years (2020 to 2030). Table 5 lists the three best and three poorest performing roadmap scenarios with respect to the seven sustainability indicators. By analyzing the three best and three poorest performing roadmap scenarios in each of the sustainability indicators, we found that only 9 roadmaps out of the total 25 alternate roadmap scenarios make it to the best performance list across all the seven sustainability indicators, while only 6 scenarios make it to the poorest performance list. This underscores that a minority of alternate scenarios perform consistently best and poorest across all the indicators. For instance, Gulagi2017 (I) and Greenpeace2015 (AE[R]) perform consistently best in 5 indicators and DDPP2015 (S) in 3 out of 7 indicators, whereas IRADe2014 (VD) and CSTEP2015 (SD) perform consistently poorest in 6 indicators and LC-SIG2014 (LC) in 4 indicators.

Only 9 roadmaps out of the total 25 alternate roadmap scenarios make it to the best performance list across all the seven sustainability indicators, while only 6 roadmaps make it to the poorest performance list.

The in-depth comparative evaluation of the electricity generation-mixes for the three best and the three poorest performing roadmap scenarios across all the sustainability indicators allows the following observations. The best performing roadmaps across all the indicators have a very high share of renewables (solar and wind in particular) and a very low share of coal power in their total electricity generation-mixes. In contrast, the poorest performing roadmaps have not only the higher share of coal in their total electricity generation-mixes, but also have the higher coal power generation operation capacities (absolute power generation), in addition to a lower share of renewables in their generation-mixes. Further, comparing just the best performing roadmaps, it could be observed that the three best roadmaps have the lowest coal power generation (absolute value) in comparison to all the other road-

The performance of the roadmap scenarios is strongly dictated by both the absolute contribution from coal power generation and the higher share of renewables in their total electricity generation-mix.

maps. In fact, this is the main reason for the competitiveness of the DDPP2015 (S) roadmap that does not has a very high share of renewables like Gulagi2017 (I) and Greenpeace2015 (AE[R]), but has the lowest coal power generation (absolute value) in comparison to all the alternate scenarios. Thus, it could be stated that the absolute coal power generation plays a significant role in the performances of the roadmap scenarios across all the sustainability indicators. This point is further validated when we compare just the poor performing roadmaps: all the three poorest performing roadmaps have the highest coal power generation among the alternatives, and IRADe2014 (VD) has the highest absolute coal power generation – the scenario that is consistently ranked first for poorest performance across 5 out of 7 sustainability indicators. Hence, we underscore that the performance of the roadmap scenarios is strongly dictated by both the absolute contribution from coal power generation and the higher share of renewables in their total electricity generation-mix.

The reason for a strong dependence of the roadmap scenarios on mainly coal, solar and wind electricity sources is because coal power has significant impacts on other sustainability indicators (in addition to climate change) when compared to renewables. For instance, it is estimated that coal emits 36 to 68 times more GHG emissions, consumes 10 to 400 times more fresh water resources and emits 13 to 38 times more particulate matter emissions in comparison to wind and solar, respectively. Hence, the external costs for coal power generation that account for some of the above mentioned environmental impacts indicate that coal is a very expensive electricity source from a socio-environmental perspective and suggests that the external costs for coal power could be 26 to 36 times higher than wind and solar, respectively. Thus, it becomes evident that the impacts of electricity roadmaps increase 10s of times for every unit of coal power generated in their electricity generation-mix and likewise could decrease 10s of times for every unit of coal power being replaced by renewables.

The impacts of electricity roadmaps increase 10s of times for every unit of coal power generated in their electricity generation-mix and likewise could decrease 10s of times for every unit of coal power being replaced by renewables.

Furthermore, the LCOE and employment indicators again favor the renewables. The mean system LCOE favors the roadmaps with a higher share of renewables and a lower share of coal in the 2030 electricity-mix (e.g., Gulagi2017 (I) and Greenpeace2015 (E[R])). However, we have not accounted for systems costs resulting from large scale integration of electricity storage and auxiliary power sources to maintain a very high penetration of renewables in our assessment. Nevertheless, we believe that the cost savings resulting from a lower LCOE of renewables (in comparison to coal power) and the significantly avoided climate damage costs associated with coal (e.g., carbon costs) in future electricity markets could aid in setting-up a strong power grid and the necessary support infrastructure conducive for a very high penetration of renewables in India's electricity sector in the coming decades. For example, our LCOE estimates find that coal power costs 2 times higher than renewables by 2030 and the cumulative median value for total external costs during 2020 to 2030 indicate that adopting the best performing alternate roadmap scenario (DDPP2015-S) could save around INR 49756 billion in comparison to the median value for the reference scenarios. However, the external costs presented in this study are first order estimates

Table 5: The best and poorest performing roadmap scenarios in different sustainability indicators.

Sustainability Indicator	Best Performance	Poorest Performance
Climate Footprint	1. DDPP2015 (S) 2. Gulagi2017 (I) 3. Greenpeace2015 (AE[R])	1. IRADe2014 (VD) 2. LCSIG2014 (LC) 3. CSTEP2015 (SD)
Water Footprint	1. Gulagi2017 (I) 2. Greenpeace2015 (AE[R]) 3. Greenpeace2015 (E[R])	1. IRADe2014 (LC2) 2. IRADe2014 (VD) 3. CSTEP2015 (SD)
Land Transformation	1. Vishwanathan2020 (2C-H) 2. Vishwanathan2020 (NDC) 3. TERI2019 (RE)	1. IRADe2014 (VD) 2. CSTEP2015 (SD) 3. LCSIG2014 (LC)
Air Pollution	1. DDPP2015 (S) 2. IRADe2014 (LC2) 3. Greenpeace2015 (AE[R])	1. IRADe2014 (VD) 2. LCSIG2014 (LC) 3. CSTEP2015 (SD)
LCOE (system)	1. Gulagi2017 (I) 2. Greenpeace2015 (AE[R]) 3. Greenpeace2015 (E[R])	1. IRADe2014 (VD) 2. Singh2018 (NF) 3. CSTEP2015 (SD)
External Costs	1. DDPP2015 (S) 2. Gulagi2017 (I) 3. IRADe2014 (LC2)	1. IRADe2014 (VD) 2. LCSIG2014 (LC) 3. CSTEP2015 (SD)
Employment	1. Gulagi2017 (I) 2. Greenpeace2015 (AE[R]) 3. Tiewsoh2019 (HG+HRE)	1. Singh2018 (NF) 2. Vishwanathan2020 (NDC) 3. IRADe2014 (LC2)

Even-though we compare different modeling studies and identify the best performing and poorest performing roadmaps, our objective is not to rank the studies as such, but to analyze the basic characteristics of the electricity supply-mix projected by them.

and should be treated with caution. More in-depth assessment in future works is recommended. On the other hand, the employment indicator favors the roadmaps with higher absolute renewable power generation contribution in the total electricity-mix, particularly solar power as it would create 5 times more jobs than coal for the same amount of electricity generation. Hence, the roadmaps with highest absolute solar power capacity are favored by the employment indicator (e.g., Gulagi2017 (I) and Tiewsoh2019 (HG+HRE)).

The significantly avoided climate damage costs associated with coal (in future electricity markets) could aid in setting-up the necessary support infrastructure conducive for a very high penetration of renewables.

Finally, the interference from gas and hydro power also influences the performances of the roadmaps in some of the indicators. For instance, the entry of IRADe2014 (LC2) in the top three best performing roadmaps in air pollution and external costs indicators is due to the lower share of gas power in its electricity generation-mix; gas emits 10 times more particulate matter and costs 17 times more socio-environmentally in comparison to solar. Similarly, the entry of Greenpeace2015 (E[R]) among the top three roadmaps and the lack of competitiveness of DDPP2015 (S) in the water footprint indicator is due to the strong influence from hydro power; hydro consumes 7 times more freshwater than coal. Further, the strong impacts of hydro power on land transformation - and comparable impacts of solar and coal (see Figure 3) – favor totally different types of roadmap scenarios for the land indicator in comparison to other sustainability indicators. With respect to the land indicator, we highlight that we account for only the total land area affected by the electricity roadmaps, but do not account for the land quality degradation as different electricity sources affect land differently. For example, the land use type of coal mining dramatically differs from the land use type of solar power [41].

7.3. Electricity-Climate-Water Nexus

Reducing the dependence on coal power generation more ambitiously could yield considerable “emission space” for GHGs from industrial sectors.

There is a strong inter-linkage between the electricity generation and its impact on global climate change and local water security. Therefore, we investigate the cumulative median values for our alternate roadmap scenarios over a time period of 10 years (2020 to 2030) from an electricity-climate-water nexus perspective. The cumulative climate footprint for total power generation during 2020 to 2030 is predicted to be around (median) 13 Gt CO_2-eq. GHG emissions in alternate scenarios that could be equivalent to 4 years of overall GHG emissions from the whole of India [31]. Coal power accounts for nearly 92% of the total cumulative GHG emissions during 2020 to 2030 (comparing median values). Hence, we highlight that reducing the dependence on coal power generation more ambitiously – e.g., adopting the best performing roadmap scenarios instead of the pathway suggested by the median roadmap - could yield considerable “emission space” for GHGs from other sectors in India, for example heavy metal industries and other essential industries wherein there are often no alternatives for emission reductions (in the short run). Further, we underscore again that a shift towards renewables could help the country to reduce GHG emissions by 36 to 68 times for every unit of coal electricity being replaced.

The cumulative water footprint for total power generation during 2020 to 2030 is predicted to be around (median) 68 billion cubic meters, which is more than the annual domestic water demand from the whole of India [42]. Given that India is a water scarce country with 70% of its freshwater resources located in hard-to-access geographical areas and 50% of India's population currently struggling with acute water scarcity issues [43], this is a significant amount of water to lose for power generation over a period of just 10 years, especially when the country needs freshwater for other essential human services. Furthermore, it is already established that climate change will significantly exacerbate the water issues in India in the coming years [44]. Therefore, we argue that a radical shift is required in modeling future electricity roadmaps for India wherein the water footprint should be given its due place and must be considered as one of the key criteria, along with climate change and cost optimization. If direct integration of water criteria into the existing models is difficult in the short run, then we recommend that the projected low carbon roadmap scenarios should be filtered for freshwater consumption optimization in the second run through scenario based bottom-up quantification approaches (like this study). We further highlight that ignoring the water footprint indicator during electricity system modeling and policy design –which is often the case with the majority of existing modeling studies that are driven by climate mitigation and cost optimization objectives (top-down approach) - could also favor sub-optimal technologies that might not get practically scaled-up on-the-ground in future India owing to the strong influence from water scarcity issues. We underscore that a responsible action towards conserving India's freshwater resources (from power generation in this case) will certainly benefit the country directly; unlike climate mitigation efforts that often need concerted action across the globe and whose benefits are often indirect and circuitous.

A radical shift is required in modeling future electricity roadmaps for India wherein the water footprint should be given its due place.

In this study, we found a synergy between the best performing roadmaps in climate footprint and water footprint indicators (Gulagi2017 (I) and Greenpeace2015 (AE[R])), especially the roadmaps that depend on new renewables (solar PV and wind). It should be noted that solar PV and wind consume 10s and 100s of times less freshwater resources than coal. Although large hydro has a very significant impact on water resources, we underscore that the hydro power plants are built for multiple purposes and often power generation might not be the primary reason for their installations; therefore, this electricity source might to be treated on a case-by-case basis. Further, some of the prospective clean technologies, such as, solar CSP and coal based carbon capture and storage (CCS) that have not been taken into account in our study might not be favored from a water footprint perspective even though they might look promising from climate mitigation perspective [45]. More research in this direction is recommended. In a nutshell, we underscore that accounting for water footprint in electricity modeling and energy policy studies not only helps in fine-tuning and filtering the climate friendly technology-mix to meet on-the-ground India-specific requirements, but could also greatly support in directing the development of India's future electricity sector towards water conservation and efficient water utilization in the coming era of water scarcity and global warming.

Ignoring the water footprint indicator during electricity system modeling and policy design could favor sub-optimal technologies that might not get practically scaled-up on-the-ground in future India owing to the strong influence from water scarcity issues.

7.4. Benchmarking India's Roadmaps with other Countries

Comparing absolute solar electricity generation, the predictions from alternate scenarios for India are second only to China.

We benchmarked India's electricity supply trends projected in future roadmaps with other emerging (China and Brazil) and developed (USA and Germany) economies. We collected the required additional electricity supply data for these four countries from 11 modeling studies with 27 scenarios in total. We found that India's coal capacity is nearly one–third of China's coal capacity, but nevertheless higher than the USA and the other countries. The alternate scenarios for India's future expect ambitious reductions in the coal share in comparison to other countries as well as to India's present status-quo; for instance, the reduction of coal share to 49% by 2030 in comparison to today's coal share of 72% (i.e., 23% reduction in 10 years) could be considered as ambitious not only for India, but elsewhere as well. Further, the projections for electricity generation from gas and nuclear in India are insignificant in comparison to China and the USA, but are higher in comparison to Brazil and Germany.

On the other hand, comparing absolute solar electricity generation, the predictions from alternate scenarios for India are second only to China and are comparable with the USA and significantly higher than Brazil and Germany. For wind, India comes after China and the USA. However, the annual solar (331 TWh) and wind (294 TWh) power generation in India by 2030 (medians for alternate scenarios) are nearly one-third of China's 2030 projections (solar – 1009 TWh; wind – 1108 TWh). The growth of RE share (solar and wind) in total electricity generation-mix by 2030 is expected to be around 23% (India), 22% (China), 16% (Brazil), 21% (the USA) and 55% (Germany). Comparing the alternate scenarios across the five countries, India's RE share projection of 23% by 2030 is second only to Germany (55%) and India outperforms all the other three countries. Further, China and Brazil outperform India when it comes to large hydro electricity generation projections for 2030, and the USA is comparable to India. The 2030 projections for other renewables (RE) have been minimal across all the countries, but China is better positioned than India.

India is lagging behind the developed economies (e.g., Germany) in terms of the development of open source based electricity modeling tools and their applications in Indian context.

Lastly, we observed that India is lagging behind the other countries, especially when compared to developed economies (Germany and the USA), in terms of the development of open source based electricity modeling tools and their applications in Indian context. Moreover, we found that India specific modeling studies seriously lack high granular modeling with respect to prospective technologies over long-term duration (e.g., 2050), wherein Germany is better positioned than all the other countries.

7.5. Key Findings

- Our comparative assessment of India's future low carbon electricity transition roadmaps finds that the scenarios with a very high share of renewables and lower absolute coal power generation perform not only well in terms of climate footprint, but they could have dramatic co-benefits in terms of water footprint, air pollution, external costs and employment generation indicators. The opposite is true with respect to coal dominated roadmap scenarios. Further, we observed that the mean system costs for the roadmaps with very high renewables are optimal in comparison to coal dominated roadmaps. The cost savings resulting from the lower LCOE of renewables (in comparison to coal power) and the significantly avoided climate damage costs associated with coal (e.g., carbon costs) in future electricity markets could be utilized to build a strong support infrastructure for a very high penetration of renewable energies in India's future power grid.

- We recommend a radical shift in modeling future electricity roadmaps for India wherein the water footprint should be given its due place and must be considered as one of the key criteria, along with climate change and cost optimization. If direct integration of water criteria into the existing models is difficult in the short run, then we suggest that the projected low carbon roadmap scenarios should be re-evaluated for freshwater consumption optimization through scenario based bottom-up approaches (like this study). We further caution the policy makers that ignoring the water footprint indicator during electricity system modeling and policy design could also favor sub-optimal clean technologies that might not become practically scaled-up on-the-ground in future India owing to the strong influence from water scarcity issues. Moreover, we underscore that a responsible action towards conserving India's freshwater resources will certainly benefit the country directly; unlike climate mitigation efforts that often need concerted action across the globe and whose benefits are often indirect and circuitous.

- Although the electricity models used in India specific studies ranged from simple excel based simulation type models to large scale simulation and optimization models to integrated models based on computational general equilibrium, we observed that the open source modeling tools have not yet found their place in India's modeling community. We call for attention from energy modelers in the country to the application of open source tools and data sets in modeling India's future electricity system.

- In general, we found that the modeling granularity, data and assumptions used for projecting 2030 scenarios are more reliable than 2050 scenario projections, and also that most of the India-specific modeling studies have a short-term focus on prospective electricity and storage technologies. This could be because of the lack of Indian specific detailed future technological studies on different electricity sources and prospective technology types till 2050. In addition, we encountered serious data availability issues (India specific) while quantifying the technological impacts on different sustainability indicators chosen in this study. We certainly recommend more policy oriented research in this direction.

- Benchmarking India's electricity transition roadmaps with other emerging and developed economies highlights that the alternate scenarios for India's future expect ambitious reductions in the coal share and significant escalations in the RE share in comparison to other countries as well as to India's present status-quo. Further, the median projection for India's RE share by 2030 (23%) is second only to Germany (55%) and India outperforms all the other three countries that were studied. Lastly, we observed that India is lagging behind the other countries, especially when compared to developed economies (Germany and the USA), in terms of the development of open source based electricity modeling tools and their applications in Indian context.

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