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WORKING PAPER

ASSESSING THE SUSTAINABLE DEVELOPMENT IMPACTS OF RENEWABLE POWER TECHNOLOGIES IN INDIA: AN ECONOMIC RETURNS FRAMEWORK

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EXECUTIVE SUMMARY

Highlights

- Renewable energy (RE) is poised to significantly contribute to the energy mix in India. It has the potential to deliver a range of sustainable development (SD) benefits related to health, water, employment, and greenhouse gas (GHG) mitigation.
- This working paper proposes a framework to identify and assess the relevant socioeconomic and environmental impacts of RE power technologies in India and to estimate their economic rate of return (ERR). The paper proposes ERR as an indicator due to its ability to summarize SD impacts of RE in an understandable and comparable metric to guide decision-making.
- When used in the decision-making process, SD impact assessments and ERR estimates can better inform policy choices and improve implementation of RE technologies, minimizing associated societal costs and optimizing potential benefits. A better understanding of SD impacts of RE deployment can also help better align RE targets and policies with sustainable development goals (SDGs).
- Based on the available impact estimation methodologies and data, this paper applies the framework to assess the ex ante health, water, land, and climate impacts for prominent grid-connected RE technologies in India—including ground-mounted and rooftop solar photovoltaic (PV), wind, biomass, and small hydro—and estimates the ERR using benchmark data and technology norms in India.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working papers may eventually be published in another form and their content may be revised.

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- These illustrative estimates show that ground-mounted solar power provides the highest economic returns, and wind power provides the lowest returns. Both small hydro and biomass power generation demonstrate a nonstandard cash flow owing to high and increasing operation and maintenance costs and, hence, do not provide conclusive ERR estimates in our study. The economic net present value of the cash flows for small hydro and biomass also indicates negative net returns to society. The consideration of context-specific benefits, such as increasing water availability for agriculture due to irrigation or health benefits from the abatement of open crop burning, may change the results.
- Applying the framework to estimate the ERR for RE technologies in India demonstrates that the economic returns of RE deployment depend on the prevailing technology specifications, local context, scale of the deployment, economic value assigned to the impacts, and the availability of reliable data.
- Applying this framework in regional contexts can provide a nuanced understanding of the relative returns of RE technologies and thus support improved RE planning and deployment based on local priorities, technology availability and costs, and the local socioeconomic and environmental circumstances.

Introduction

Access to reliable, affordable electricity can improve indoor air quality, health, and education outcomes as well as support poverty alleviation, irrespective of the power-generation technology used. However, power generation itself, using fossil fuel or RE technologies, may entail socioeconomic and environmental externalities that are often not considered in decision-making. Apart from the health, safety, and environmental impacts of mining and resource extraction, fossil fuel–based power generation is highly water intensive and is associated with negative health impacts due to pollutant emissions; it also contributes to climate change due to GHG emissions. RE-based power generation has the potential to alleviate some of these social and environmental challenges and create new jobs. India aims to install 175 gigawatts of RE by 2022. As India implements ambitious RE targets with almost 20 percent average annual growth in installed capacity over the past five years, some RE projects have been commissioned at prices competitive with those for cheap fossil fuels (MNRE 2018a, 2019a). With this increasing pace of RE deployment, there is also a need to be cognizant of the potential costs of RE technologies, some of which are intermittent or land intensive or may add to particulate matter emissions.

About This Working Paper

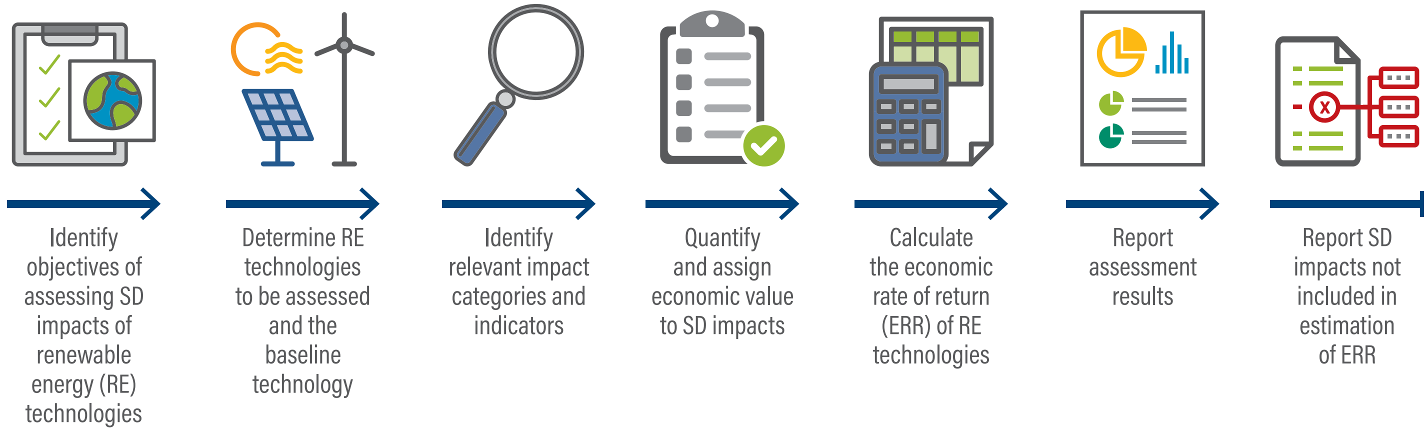
This working paper is aimed at policymakers and researchers in the energy, power, environmental, and developmental sectors to support informed and evidence-based policy planning and implementation. We draw on the Initiative for Climate Action Transparency (ICAT) Sustainable Development Guidance Methodology to develop a methodological framework for an ex ante assessment of socioeconomic and environmental impacts of RE technologies in India. The framework provides a stepwise approach (see Figure ES-1) to assess these impacts in economic terms and to arrive at the ERR for RE technologies. As a demonstration, we apply the framework to estimate the ERR for grid-connected RE power technologies relative to a coal baseline in India. These estimates highlight the drivers of costs and benefits for RE technologies in India. The paper concludes with guidance on applying the framework in different regional or local contexts and discusses how results from such analyses can be utilized to inform policies in the country.

Research Problem

While various socioeconomic or environmental impacts have been estimated at the regional or aggregate level (see Appendix A), there are few studies contextualizing these to systematically guide decision-making. Power-generation projects are relatively long-term investments with potentially longer-term impacts on human well-being and on the environment, economy, and climate. There is a need for holistic, proactive, and evidence-based energy planning that minimizes costs and optimizes benefits associated with RE technologies.

Our approach involves estimating the ERR, an index of the socioeconomic profitability of a project, which is the discount rate that makes project benefits equal to present costs, meaning the economic net present value (ENPV) is equal to zero (European Commission, n.d.). It may be different from the financial rate of return due to price distortions. The ERR provides a single comparable metric summarizing the socioeconomic returns of different RE technologies. Unlike financial analyses that have typically informed energy-related decision-making and investment planning, economic analyses consider the broader SD impacts, which are especially critical in energy policymaking and planning. Economic analyses help assign a value to nonfinancial or nonmarket impacts, such as health outcomes, ecological damage, or climate change impacts, and they integrate these in decision-making. Comparing ERR estimates with the opportunity costs of investment and financial returns can help justify public investments and estimate the level of incentives for RE technologies (see Table ES-1). It should be noted that whereas ERR comprehensively captures the economic returns of a technology, its accuracy largely depends on the accuracy of its components—that is, on how well the nonmarket impacts such as health, environment, or climate change impacts can be measured and assigned an economic value. Such analyses for policies or projects can also help plan implementation in ways that reduce socioeconomic or environmental costs, thus reaping the potential societal cobenefits of RE. Finally, applying such a framework at the local or national level can help map and report progress on SDGs.

Figure ES-1 | **Framework to Assess the SD Impacts of RE—Overview of Steps**



Source: WRI authors.

Table ES-1 | **Evaluation of Economic Justification for Public Investment and Policy Support**

ECONOMIC VIABILITY	PUBLIC INVESTMENT JUSTIFIED	FINANCIAL VIABILITY	POLICY SUPPORT NEEDED
ERR>SDR	Yes	IRR < benchmark rate of return	Yes
ERR>SDR	Yes	IRR > benchmark rate of return	No
ERR<SDR	No	NA	NA

Note: ERR = economic rate of return; IRR = internal rate of return; SDR = social discount rate.

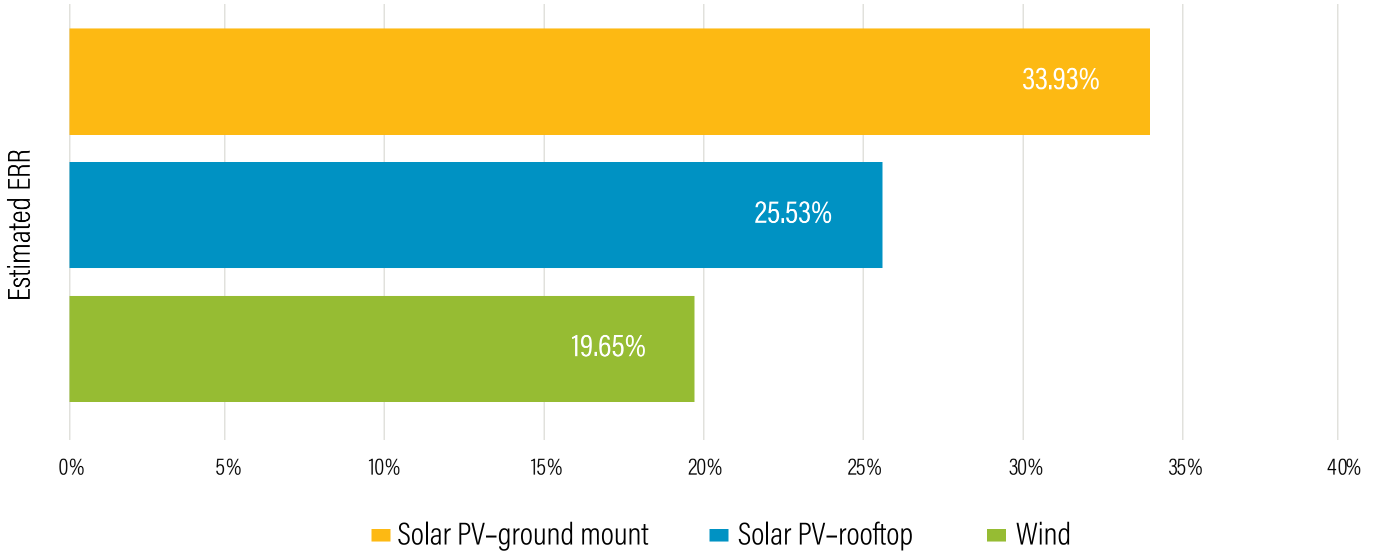
Source: Adapted from MNRE 2018.

Key Findings

We apply our framework using average benchmark data available at the national level in India and consider the marginal costs and benefits from RE deployment. These illustrative estimates show that whereas ground-mounted solar power provides the highest economic return to society across different input scenarios, wind power demonstrates the lowest economic returns (see Figure ES-2). Our analysis does not provide conclusive estimates for small hydro and biomass power generation due to their high up-front capital costs and high operational costs, which increase over the lifetime of these installations. ERR estimations are driven by the efficiency and costs of technology, the specificity and relevance of data and impact estimation methods used, and the physical context in which RE is deployed. However, ERR estimates that use a marginal approach may not capture system-level impacts and/or aggregate impacts of policies or projects unless such impacts are quantified or are included in the costs or benefits. Where significant, additional analysis to estimate and include such impacts on the ecology, economy, or overall electricity system is recommended.

These illustrative estimates from our analysis highlight the drivers of economic returns for power generation based on RE technologies. The estimates provided in this paper can be improved with context-specific technology data, location-specific socioeconomic and environmental data, and improved methodologies for assessing and valuing impacts. Additionally, because the estimates represent ex ante SD impacts, the actual SD costs and benefits realized depend on the ways in which deployment and operations are carried out, the availability of finance and resources, and changes in technology parameters. The framework presented in this paper can be used to assess impacts across the value chain of power generation.

Figure ES-2 | **Economic Rate of Return for RE Power Technologies in India**



Note: ERR = economic rate of return; PV = photovoltaic.

Source: WRI authors.

Conclusion

Although the analysis presented here is a first step in that direction, including the upstream and downstream costs and benefits of power generation within the boundary of assessment, where possible, can provide more holistic insights on the broader societal outcomes of RE power technologies. The framework proposed in this paper can also be applied in other emerging economies using locally relevant data and methods or in regional contexts within India to provide a nuanced understanding of which RE power technologies offer the highest societal returns. Accordingly, the results and the policy insights will vary depending on the potential of generation, the local physical and environmental context, policy priorities, and the cost of deployment in the region. To understand these regional impacts and local applications, our further research aims to apply the framework at the state level in India to estimate the ERR and provide policy recommendations for improved RE planning and deployment.

ABBREVIATIONS

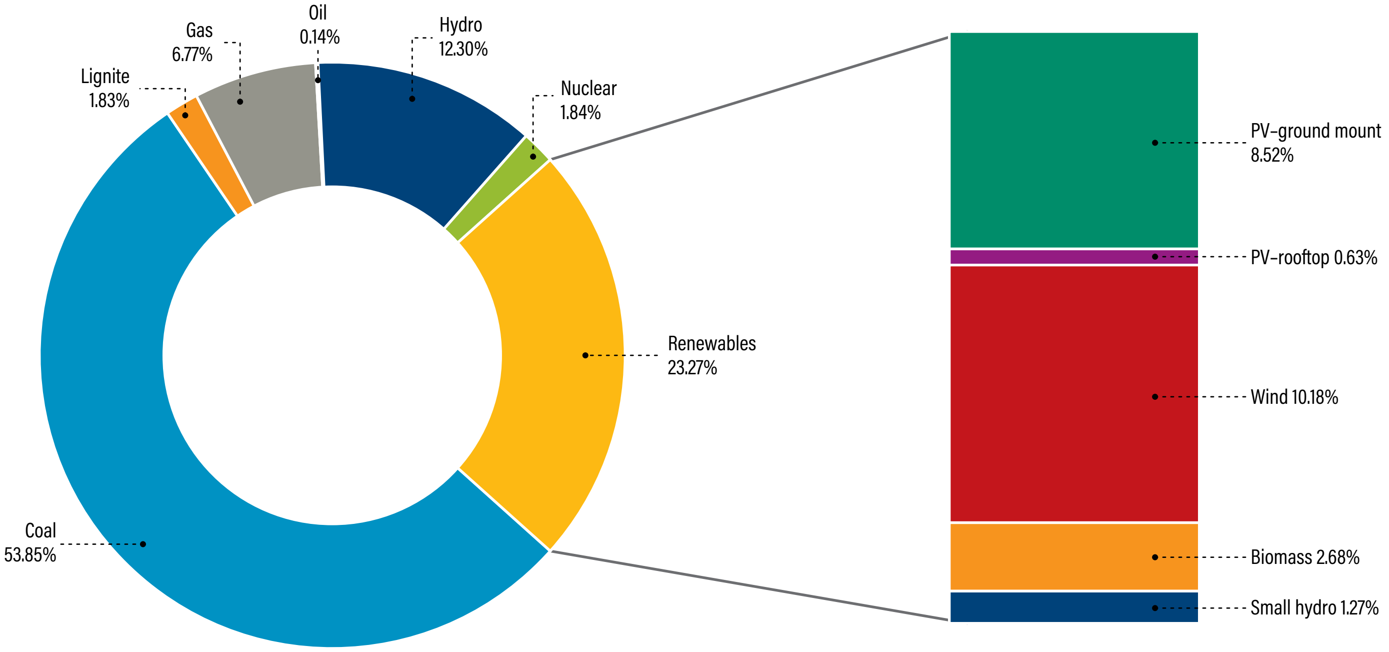
BAU	business as usual
CAGR	compounded annual growth rate
CARMA	Carbon Monitoring for Action
CEEW	Council on Energy, Environment and Water
COPD	chronic obstructive pulmonary disease
DALY	disability-adjusted life year
DICE	dynamic integrated climate-economy
ENPV	economic net present value
EPC	engineering, procurement, and commissioning
ERR	economic rate of return
GDP	gross domestic product
GHG	greenhouse gas
GNI	gross national income
GW	gigawatt
ICAT	Initiative for Climate Action Transparency
INDC	intended nationally determined contribution
ICP	International Comparison Program
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRIS	Impact Reporting and Investing Standards
IRR	internal rate of return
MNRE	Ministry of New and Renewable Energy
MRV	mortality risk value
NDC	nationally determined contribution
NPV	net present value
NRDC	Natural Resources Defense Council
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PLF	plant load factor
PV	photovoltaic
RE	renewable energy
SCC	social cost of carbon
SD	sustainable development
SDG	sustainable development goal
SDR	social discount rate
TEV	total economic value
VSL	value of statistical life
WHO	World Health Organization
WRI	World Resources Institute

1. INTRODUCTION

Access to affordable, reliable, and sustainable energy is a global priority and has critical implications on other developmental priorities, including economic growth and poverty alleviation, infrastructure development, employment, climate change, better health, and safeguarding natural ecosystem services (UNDP, n.d.). Energy is a particularly important area of policymaking in India. It is the cornerstone for the country's economic growth, infrastructure development, and improvement in the standard of living of its people. Power generation represented 49 percent of India's primary energy demand in 2017, and it is expected to rise to 56 percent by 2040 (BP 2019). India's power demand is set to increase multifold with greater economic activity; electrification through schemes such as the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (or Saubhagya Scheme); and increased domestic consumption, mobility, and cooling needs (NITI Aayog and IEEJ 2017). Even though currently self-sufficient (CEA 2018b), India is expected to significantly add to its installed power capacity to meet these needs (CEA 2016; NITI Aayog and IEEJ 2017; TERI 2017).

Although conventional low-efficiency coal-based power dominates the Indian electricity grid (see Figure 1), additional power capacity is expected to come from a mix of relatively higher-efficiency coal-based power, nuclear energy, and, to a great extent, renewable energy (RE) technologies (CEA 2019b). Currently at 85.7 gigawatts (GW) of installed capacity (MNRE 2020), renewables contribute 17 percent to the total generation in India (IEA, n.d.b), and the deployment of RE technologies in India has a compounded annual growth rate (CAGR) of 15 percent since 2010–11 (MNRE 2018a, 2019a). Additionally, India has set a target of 175 GW of RE installation by 2022, which includes 100 GW of solar, 60 GW of wind, 10 GW of biomass, and 5 GW of small hydropower (MoF 2015). Likewise, in its nationally determined contribution (NDC), India has committed to increasing the share of nonfossil installed power to 40 percent by 2030 (MoEFCC 2015a). More recently, India has updated its overall RE target to 450 GW (PMO 2019).

Figure 1 | **India's Installed Capacity by Technology**



Source: MoP 2020.

Although some of the impacts of modern electricity, such as increased economic opportunities, improved indoor air quality, and better education outcomes, are technology agnostic, different power-generation technologies offer a mixed set of costs and benefits. RE is a relatively clean source of power generation, with expected cobenefits that include improving health outcomes, employment generation, skill development, energy security, and water availability; mitigating climate change; and building climate resilience. Yet RE may also entail certain trade-offs, such as increased diversion of agricultural and forest land, particulate matter emissions from the combustion of biomass, and ecosystem impacts from diverting rivers for hydropower, in addition to the technological costs of integrating variable and intermittent RE power.

It is critical to consider the sustainable development (SD) impacts of energy policy planning and implementation in the Indian context. Health costs related to particulate matter emissions in India were estimated at almost 7.7 percent of India's gross domestic product (GDP) in 2013, killing 1.4 million Indians each year (World Bank and IHME 2016). With its ongoing demographic shift, estimates suggest that India needs 4–8 million new jobs each year (Dewan 2018; World Bank 2018b), and at least 70 percent of India's building stock requirement by 2030 has yet to be built (GBPN 2019; MGI 2010). By 2030, the country's water demand is projected to be twice the available supply, implying severe water scarcity for hundreds of millions of people and an eventual 6 percent loss in the country's GDP (WBG 2016). India is highly vulnerable to climate change impacts and is estimated to have the highest economic costs, in absolute terms, of climate change impacts globally (Ricke et al. 2018). Therefore, as India grows at an expected average rate of 7 percent annually (IMF 2019), addressing these socioeconomic and environmental issues is important for ensuring a sustainable and inclusive development path. Given the lock-in period of deployed energy systems and technologies, energy policy choices have long-term consequences on some of these SD priorities. Even though the energy sector alone cannot address these SD issues, it has the potential to contribute to desired outcomes across priorities such as health, jobs, and water availability, among others. Hence, a systematic evaluation of the socioeconomic and environmental costs and benefits can facilitate better-informed choices, planning, and implementation.

In this paper, we develop a methodological framework for identifying and assessing the relevant socioeconomic and environmental impacts of RE technologies and estimating the economic rate of return (ERR) as a comparable summary metric to support decision-making processes in India's energy sector. To illustrate the use of the framework, we estimate the country-level ERR for RE technologies in India using benchmark data. The paper also provides guidance on the use of the framework to inform policymaking and deployment of RE technologies in the country.

The following section outlines the need for this study and lays out the approach used to develop the framework and estimate the ERR for RE technologies. Section 3 describes the stepwise framework to assess the SD impacts of RE technologies. In each step, it explains how the framework has been applied to estimate the ERR for these technologies in India. It also defines the scope and limitations of the estimations, illustrating the use of the framework. Section 4 provides guidance on applying the framework and its possible policy applications.

2. ABOUT THIS RESEARCH

The Need for This Study

Investment decisions are generally guided by financial analyses. A financial model typically considers cash outflows, such as investment, operating costs, taxes, and interest on loans, and inflows, including revenues or tax benefits, rebates, and any income from rent. These, along with the time value of money, indicate the financial returns on the investment; when positive and high enough, they make for a lucrative investment. However, this model assumes a world in which power generation only interacts with the larger society and environment in terms of cash flows. In reality, power generation is deeply interconnected with various aspects of human life and the environment. In addition to the utility of generating and providing power for productive purposes, a power plant can significantly impact several socioeconomic and environmental aspects of society due to its lifetime of 20–25 years. This is in addition to the impacts across the upstream and downstream value chain, including the mining of resources, the manufacturing of equipment, and the disposal of waste products and equipment at the end of operational life. However, market prices and decision-making based on financial analysis fail to capture such impacts. Given India's vision for sustainable economic growth and its developmental priorities, considerating such impacts can strengthen decision-making, policy planning, and progress toward meeting sustainable development goals (SDGs).

Conventional power dominates Indian grid capacity (MoP 2020). Whereas gas, lignite, and diesel make up only 8 percent of the total installed capacity, coal accounts for 54 percent, making it the most prominent power-generation technology in India (MoP 2020). With a domestic shortage of crude oil and natural gas and low efficiencies with lignite, coal—which is cheap and readily available—is also expected to be the primary fossil fuel–based technology in the Indian electricity supply in the near future. Even with decreasing prices for RE, coal features among the most competitive fuel sources of power generation in India. However, these prices do not reflect the costs of negative externalities from coal power generation, including the health costs of air pollution from particulate matter released from the combustion of coal (Barreira et al. 2017; CAT and Urban Emissions 2017; Guttikunda and Jawahar 2014; Mahapatra et al. 2012), lowered water availability due to water-intensive operations (Chaturvedi et al. 2017; Luo et al. 2018), the ecosystem costs of mining (TERI 2013), and the climate change impacts from greenhouse gas (GHG) emissions (Barreira et al. 2017). The competitive prices are a result of the availability of cheap coal, the economies of scale offered by large coal-based power plants, and the power distribution infrastructure built around the technology. Additionally, policy support in the form of income tax exemptions and access to land at preferential rates for coal power plants and subsidies to the coal-mining sector provided through tax breaks and concessional duties (IISD 2017) have also contributed to coal being the cheapest power-generation technology in India.

By definition, renewable power harnesses nondepleting resources, including solar, wind, geothermal, biomass,[1] hydro,[2] tidal, and so on, and emits little or no GHGs.[3] These technologies have potential cobenefits, such as improving health outcomes due to reduced particulate matter emissions, local employment generation and skill development, and energy security from reduced dependence on fuel imports; lowering water demand for generation; and building climate resilience (Chaturvedi et al. 2017; ICSU 2017; IRENA 2016, 2017a, 2017b; McCollum et al. 2018; OECD/IEA and IRENA 2017; SCGJ 2016). Policy incentives and technology improvements have substantially lowered costs for RE. Yet compared to coal power generation, RE deployment in India continues to face financial hurdles due to high land costs, lower tariff caps in the case of solar, increasing technology costs in the case of wind power, expensive organic waste logistics and operation and maintenance (O&M) costs for biomass, and the overall cost of capital and funding (CRISIL 2019; Sen et al. 2016). Additionally, solar and wind power is variable and intermittent because it depends on sunshine and wind speed, respectively. Biomass-based power generation depends on the local availability of biomass, which is also seasonal. RE may also be land intensive, as in the case of ground-mounted solar, and it may divert productive agricultural or forest land. RE technologies such as biomass, which involves burning plant-derived residue, may still contribute to particulate matter emissions, thus impacting respiratory health and quality of life. Even small hydropower projects may lead to significant ecosystem impacts by diverting forest land and disrupting the flow of rivers.

Despite the ample evidence on these potential SD impacts (key studies and findings are summarized in Appendix A), prevalent decision-making approaches rely on financial indicators, such as the internal rate of return (IRR), which consider investment costs and financial returns based on the cost of marketable goods and services and the influence of financial taxes and subsidies. The SD implications represent nonmarket externalities, which do not translate into financial costs and benefits. Thus, financial analyses do not allow for a systematic consideration of the broader SD goals and priorities. And although factors such as land availability, integration costs, and health costs may influence project decisions and policymaking, a standardized framework or methodology for central and state energy planning departments, power utilities, and investors is needed to identify and assess the relevant impacts and systematically include them in decision-making. The decision-making process therefore lacks a holistic understanding of the SD impacts of policy options. Additionally, with ambitious RE targets and a large-scale deployment of RE in India, cognizance and consideration of broader SD impacts in planning and implementation would help deliver greater cobenefits across local ecology and economy and minimize the societal costs of RE.

Through this paper, we propose a framework for such an assessment based on the Initiative for Climate Action Transparency (ICAT) Sustainable Development Guidance Methodology and suggest a comparable metric, ERR, to aggregate and understand these impacts across different technologies. An assessment of these SD impacts and overall societal returns across technology options can help policymakers understand the relative economic efficiency of each technology and identify options that also address broader social, environmental, and development priorities and improve policy design and implementation. Such an analysis can support policy decisions about which technologies offer net-positive benefits to society, which technologies need policy support, and how deployment can be planned to reduce societal costs. An analysis like this can support policy planning to meet SDGs and better track their progress in the national or regional contexts.

The Approach

The ICAT methodology provides tools and guidance for countries to transparently measure and assess the impacts of climate policies and actions. It uses a stepwise approach to assess SD impacts of policies (ICAT 2018). This paper builds upon the ICAT guidance to develop the framework for identifying and estimating the SD impacts of RE technologies.

Multiple methods, including cost-effectiveness analyses, cost-benefit analyses, ERR, and multicriteria analyses may be used to understand the SD impacts of RE technologies. Given the relative utility of these methods (summarized in Table 1), we choose ERR as the metric to understand and interpret the broader SD impacts.

Although all metrics have their respective advantages and disadvantages, all economic analyses entail considerable subjective elements, including valuation and discount rates. However, given the purpose of such an assessment, we chose ERR for our framework because it has the following advantages:

- It provides a single summary metric bringing together all societal costs and benefits to provide the economic justification for the proposed investment.
- It is similar to IRR; hence, it is easily understood by a wider audience, including decision-makers and key stakeholders like energy planners, utilities, and investors.
- Since it is similar to IRR in computation and representation of project cash flows, it is easily comparable to financial analyses that investors often use to justify investment and development plans in the energy field from a financial perspective.

Table 1 | **Comparison of Alternate Methods to Understand SD Impacts**

METHOD	DESCRIPTION	POLICY APPLICATION	ADVANTAGES	DISADVANTAGES
Cost-effectiveness analysis	Ratio of costs to effectiveness for a given impact category	Compare policy options to determine which is most effective in achieving a given objective for the least cost	Simple approach; does not require valuation of benefits be quantified in economic terms; fewer subjective elements	Results in multiple indicators when assessing more than one impact category; requires discount rates
Cost-benefit analysis	Determines the net benefits to society (the difference between total social benefits and total social costs) of policy options	Compare policy options to determine which has the greatest net benefit to society or to analyze a single policy or action to determine whether its total benefits to society exceed its costs	Assesses aggregated benefits of policy options with one single indicator	Requires valuation of costs and benefits and requires discount rates; can underestimate nonmarket benefits
Economic rate of return (ERR)	Summarizes the costs and benefits over the lifetime of an investment	Compare policy options to determine most economically efficient investment; assess economic viability of options	Considers timing of costs and benefits; provides a comparable summary statistic; comparable to financial indicators	Requires valuing nonmarket costs and benefits and requires discount rates
Multicriteria analysis	Compares the favorability of policy options based on multiple criteria	Determine the most preferred policy option	Assesses aggregated benefits of policy options with one single indicator; does not require that nonmarket benefits be valued in economic terms; does not require discount rate	Has significant subjective elements and interpretation of results; harder to compare across options

Source: Adapted from ICAT 2018.

In general, ERR is an index of the socioeconomic profitability of a project (European Commission, n.d.). Like IRR, ERR is the discount rate at which SD benefits exactly equal the SD costs of the proposed project. The higher the value of the benefits relative to the costs, the higher the ERR. Similarly, benefits that accrue sooner relative to the time when costs are incurred will also generate higher ERRs than projects with the same amount of benefits that accrue further in the future (MCC, n.d.). However, unlike IRR, ERR includes important societal benefits (e.g., environmental and health impacts) that enable decision-making based on an economic perspective where societal benefits and cost are considered.

A brief overview of the framework is illustrated by Figure 2. The first step of the framework involves identifying the objectives of assessing the SD impacts of RE technologies (Step 1). This allows users to select the relevant RE technologies to be assessed and the baseline scenario (Step 2). The next step includes selection of the relevant impact categories and indicators for the analysis (Step 3). Based on these, users can undertake the next steps to quantify the impacts (Step 4) and assign an economic value that reflects the value of socioeconomicand environmental costs and benefits of the RE technologies (Step 5). The final steps include transparently reporting assessment results (Step 6) as well as reporting impacts not included in the ERR estimation due to a lack of data or methodology to assess the impacts or assign an economic value (Step 7).

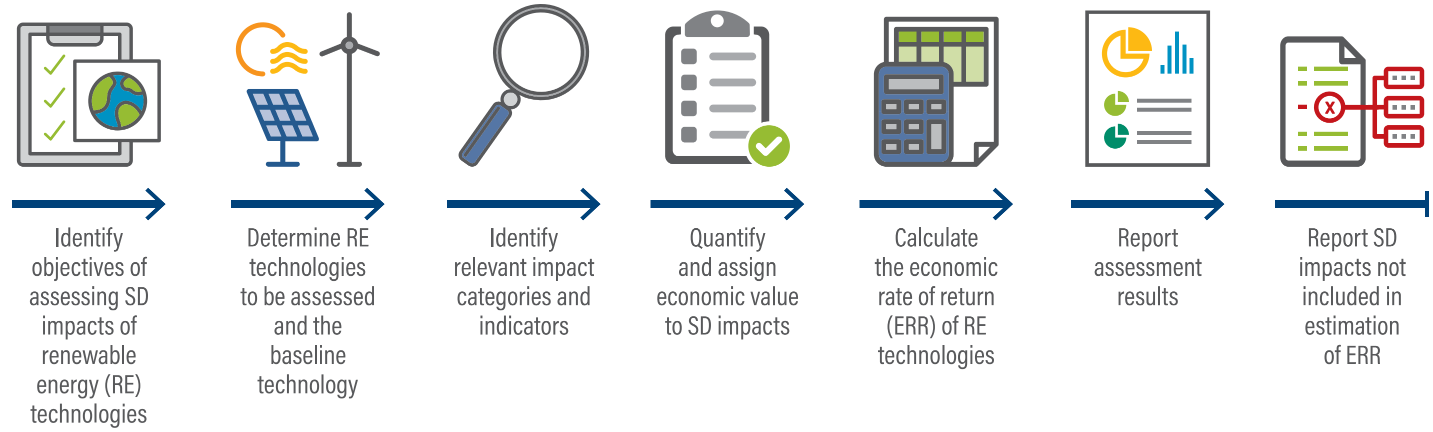
3. FRAMEWORK TO ASSESS SD IMPACTS OF RE TECHNOLOGIES

This section lays out the methodological framework to identify and assess key SD impacts of RE. This framework draws from the ICAT Sustainable Development Guidance Methodology to provide a stepwise approach for estimating and reporting the socioeconomic and environmental costs and benefits of RE in India. The impacts and indicators proposed are associated with major SD categories that cover the key socioeconomic and environmental priorities globally as defined through the SDGs. However, the framework provides users with the flexibility to choose relevant SD impacts based on policy priorities. Although in this document we focus on RE, the steps and guidance can be used to assess other sources of energy production (e.g., from fossil fuels). This section describes each step and demonstrates its application to arrive at the ERR for RE technologies at the national level in India.

Step 1: Define the Objectives of Assessing SD Impacts

The aim of this step is to define the objectives of assessing the SD impacts of RE technologies and what metrics may help to reflect the associated SD impacts. The first step helps users identify the aim of the assessment in line with the priorities and interests of stakeholders. This may entail identifying the purpose of the assessment, defining

Figure 2 | **Overview of Steps**



Source: WRI authors.

the metrics of interest, and outlining how the results are intended to be used. Although the framework proposes an ERR estimate as a metric summarizing the various costs and benefits across the lifetime of RE technologies, users may also use it to estimate and report the costs and benefits across SD categories.

As described earlier, energy is one of the key development priorities because it enables manufacturing, agriculture, mobility, lighting, heating, and cooling, which are key services that sustain the continuous growth and development of countries (ICSU 2017). Each energy technology, RE included, has its own set of potential cobenefits and trade-offs across socioeconomic and environmental dimensions. Having a comprehensive understanding of the SD impacts of RE technologies would help inform policymakers and decision-makers in their efforts to address multiple priorities, compare SD impacts across different RE technologies or, with the existing technology scenario, assess the impacts of a specific RE deployment initiative and improve their design and implementation to maximize the positive impacts and minimize and mitigate the negative impacts. Although the actual manner of implementation has important consequences on realizing the SD impacts estimated ex ante, understanding the potential impacts at the planning stage can better inform planning and decision-making to ensure that positive impacts are realized and negative impacts are mitgated.

Using this methodological framework, we identify and assess the relevant SD impacts of RE technologies in India and estimate the average ERR for key RE technologies prevalent in the country. This assessment illustrates how the framework is applied using benchmark national-level data and demonstrates how the results from such assessments may be used in decision-making.

Step 2: Determine the Technologies to Be Assessed and the Baseline Technology

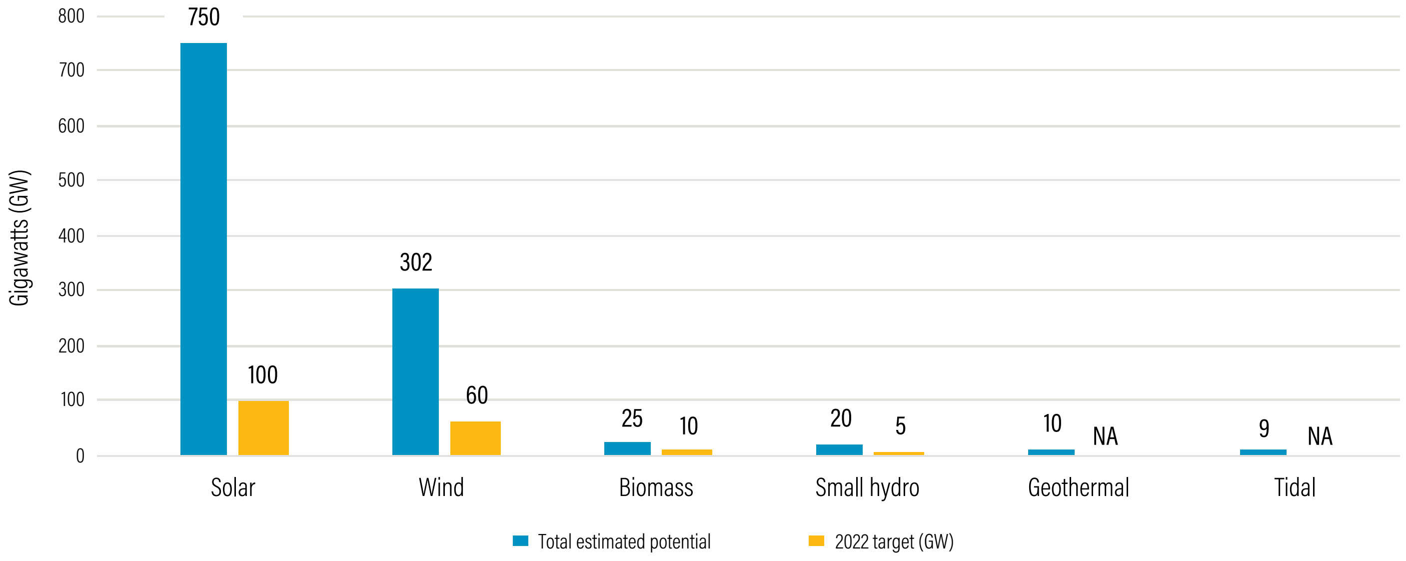
The objective of this step is to determine the specific technology options to be assessed and the baseline scenario relevant to the region or jurisdiction under consideration. This decision is guided by the relevance to key stakeholders, the potential of the RE technologies, the prevalent energy mix, the electricity supply-and-demand patterns, the policy goals (e.g., RE and energy access targets), and other trends in the energy landscape of the country/region or jurisdiction considered. This information helps select RE technologies that are of interest and must be included in the assessment. It also helps determine the reference or baseline scenario against which the RE technologies are compared to in order to estimate the impacts.

RE Technologies to Be Assessed

For this study we apply the framework to **grid-connected solar photovoltaic (PV) (ground mount and rooftop), onshore wind, biomass,**[4] **and small hydro projects.**[5] This is due to the following factors:

- **High potential.** Solar, wind, biomass, and small hydro energy potential in India are estimated to be 750 GW, 302 GW (NIWE, n.d.), 25 GW, and 20 GW (MNRE 2017), respectively. In contrast, India's geothermal energy potential is 10 GW (MNRE, n.d.c) and tidal energy potential is about 9 GW (MNRE 2019b); thus, we do not include geothermal and tidal power (see Figure 3).
- **Prominence of these technologies in policy targets.** The current target of 175 GW by 2022 includes 100 GW of solar, 60 GW of wind power, 10 GW biomass, and 5 GW of small hydro, with no targets for geothermal or tidal energy. Although recent efforts with offshore wind have focused on the research and development of demonstration projects, India has yet to exploit this renewable resource commercially or set targets (MNRE, n.d.b).
- **Prevalence and feasibility of commercial-scale projects.** Although solar, wind, biomass, and small hydro have seen large uptakes, there are no operational offshore wind,[6] geothermal, or tidal energy power plants in India. This is due to the extremely high capital costs, even as research on these technologies is being prioritized for future application (MNRE, n.d.b). Similarly for waste-to-energy technologies, despite high potential, prevalence is extremely low due to issues related to the segregation of waste and the high costs thus far.
- **Availability of technology-specific data.** Given the lack of commercial applications to date, scarcely any data are available on the implementation of geothermal or tidal projects, which thus limits their inclusion in the analysis.

Figure 3 | **Potential and 2022 Targets for RE Technologies in India**



Source: MNRE 2017.

Baseline Scenario

Assessing the impacts of a technology or intervention requires a frame of reference against which the performance of the technology or intervention may be compared or measured. This frame of reference is called the baseline scenario and is defined as the conditions mostly likely to occur in the absence of an intervention—in this case, the RE technology under consideration. In the context of this study, we assess two questions to determine the baseline scenario:

- In the absence of RE investment, would India build power plants using other technologies?
- If so, what technology specification is most likely to be used?

India's electricity demand is expected to rise over time. Various economic models predict its electricity demand to increase at a CAGR in the range of 6–8 percent annually (CEA 2016; NITI Aayog and IEEJ 2017; TERI 2017). This increase may be attributed to rapid urbanization, additional infrastructure, increased consumption with rising incomes, universal electrification, and the ongoing electrification of industrial processes and electric mobility initiatives. As a result, studies estimate that the overall electricity demand is expected to at least double by 2030 (Ali 2018; CEA 2016; NITI Aayog and IEEJ 2017; Spencer and Awasthy 2019; TERI 2017) relative to 2015–16.

For our baseline scenario, we find that the most likely technology to meet the demand in the absence of RE technology would be supercritical coal power generation.[7] Due to its readily available domestic supply (Spencer et al. 2018), coal is the most commercially competitive among other technologies (e.g., gas and diesel), including nuclear power, which contributes less than 3 percent to India's power mix (MoP 2020) and is lagging its planned uptake of 27.5 GW by 2032 due to technology, safety, and operational reasons (World Nuclear Association 2019). In fact, coal is the dominant technology used in India, accounting for 76 percent of total generated power (MoP 2020). Because this study aims to assess the SD impact of RE technologies, it conservatively uses the most efficient coal-based power-generation technology available today, assuming policy compliance by 2030, as the baseline scenario.[8]

Although coal-based power generation represents the baseline scenario at the national level, in specific regions the baseline may be a different technology or a mix of technologies, depending on the local potential and feasibility; for example, hydropower in the states of Assam, Himachal Pradesh, and Sikkim, and gas-based power generation in Assam. Thus, this framework should assess the most likely baseline scenario in a given region.

Step 3: Identify the Relevant SD Impact Categories and Indicators

The aim of this step is to identify the relevant SD categories and indicators that would be included in the assessment. These include impact categories (See Box 1) that are that are assigned an economic value to be included in the ERR. Impact categories that cannot be assigned an economic value should also be assessed and reported separately, when feasible and relevant, to provide context for decision-making.

This step involves two substeps:

- Identify impact categories to be included in the assessment.
- Identify indicators for each impact category and determine if they are suitable for ERR analysis.

Identify the impact categories

RE technologies are likely to have a wide variety of SD impact categories across the three dimensions of environmental, social, and economic impacts. Any specific technology is likely to have positive impacts on some categories and negative impacts on others.

To provide a balanced understanding of RE technologies, identification and inclusion of impact categories should use three criteria (Rich et al. 2018):

- **Relevance.** The impact category should be seen as relevant based on the objectives of the assessment, national or local policy objectives, SDGs and priorities, local circumstances, and stakeholder priorities.
- **Significance.** The impact category should be significantly affected by the technology.
- **Comprehensiveness.** Both negative and positive impacts should be included; impact categories from each of the three dimensions of SD (economic, social, and environmental) should be considered.

The SDGs provide a useful framework to filter impact categories through these three criteria. The SDGs are a set of agreed upon development priorities, making them relevant to decision-makers and stakeholders. However, based on the objectives of the assessment, relevant goals or priorities may be used to select impact categories. By design, the SDGs represent a list of integrated goals that interact with each other (ICSU 2017), therefore providing a comprehensive starting point to select impact categories. At the same time, many impact categories do not have significant differences across various power-generation technologies. For example, electricity access can have positive impacts on poverty reduction and quality education no matter which technology is used, even though the level may vary across technologies or type of installation (Odarno et al. 2017). Since we are interested in the SD impacts of RE technologies, we exclude from this analysis impacts related to access and those where the generation technology does not have a direct bearing on the outcome.

Box 1 | **Impact Category**

Impact category refers to the type of sustainable development impact (for example, health, water, or climate) affected by the technology. *Indicator* refers to a metric that can be estimated to indicate the change or impact attributable to a technology on a given impact category (for example, avoided water consumption and greenhouse gas emissions in wind or solar power generation).

Our analysis examined the interlinkages and causal links between the energy SDG (SDG 7) and other SDGs (ICSU 2017; McCollum et al. 2018) affected by RE deployment, their relevance to national developmental priorities and issues of concern (stated in prior sections), and the significance of RE technologies to the individual impacts. Table 2 outlines the impacts we selected to be included in the assessment.

Although RE may have impacts across a larger set of SD priorities, including industry, innovation, and infrastructure (SDG 9); sustainable cities and communities (SDG 11); and responsible consumption and production (SDG12), based on the relevance and significance criteria, the ERR estimation for RE technologies in India is limited to the impact categories summarized in Table 2.

Identification and suitability of indicators

The next substep is to identify the representative indicators and determine whether they are suitable for economic valuation.

Table 2 | **Impact Categories Selected for RE Technologies in India**

IMPACT CATEGORY CONSIDERED[a]	CAUSAL LINK OF POTENTIAL IMPACTS	RELEVANT POLICY PRIORITY/SDG GOAL
Health impacts	Renewables such as solar and wind can support reduction or avoidance of local air pollution compared to fossil fuels because they do not involve the combustion of fuels and the associated pollutant emissions. Biomass, and in some cases hydro, may have associated emissions due to combustion of organic matter or the use of backup diesel generators, respectively.	Reduce disease burden and public health costs attributable to air pollution—good health and well-being (SDG 3)
Water impacts	Scaling up renewables will, in most instances, reinforce targets related to water access, scarcity, and management; for example, by lowering water demands compared to fossil-dominant energy systems. Deployment of renewable energy (RE) requiring water for its operations, in acutely water-stressed or drought-prone regions, may exacerbate water scarcity.	Enhance water availability for domestic, agricultural, and sanitation—clean water and sanitation (SDG 6)
Land impacts	Large-scale energy projects (e.g., utility-scale solar or onshore wind) may affect food production and agricultural incomes by competing for scarce land. Large-scale use of RE by diverting forest land could lead to increased deforestation, degradation of ecosystems, and biodiversity loss.	Ensure food security, progress on nationally determined contribution (NDC) goal of creating a carbon sink, protection of biodiversity and ecosystem services—end hunger (SDG 2); life on land (SDG 15)
Climate change mitigation (climate impacts)	Meeting the RE targets is a necessary, but not entirely sufficient, condition for long-term temperature stabilization below 2°C. Deployment of RE can reduce carbon dioxide emissions, and this, in turn, will slow the rates of ocean acidification. Deployment of RE will aid climate change mitigation efforts, which can help to reduce the exposure of the world's poor to extreme climate-related events and negative health impacts from climate change.	The NDC target of 40 percent installed power from nonfossil energy sources and 33–35 percent reduction in emissions intensity of GDP by 2030 (relative to 2005)— climate action (SDG 13); life below water (SDG 14); no poverty (SDG 1)
Employment impacts	Deploying renewables, combined with supporting economic policies, can help reinforce local, regional, and national industrial and employment objectives. Gross direct employment effects from the deployment itself seem likely to be positive; however, uncertainty remains regarding the net employment effects due to several uncertainties surrounding macroeconomic feedback loops playing out at the global level. Moreover, the distributional effects experienced by individual actors at the local level may vary significantly. If designed as such, job opportunities in RE power deployment and operations can also help increase women's agency and employment. However, it cannot be assumed to be a certain impact by default and would depend on the design of the deployment as well as the actual implementation.	Provide decent employment, livelihoods, and workforce skilling—decent work and economic growth (SDG 8); gender equality (SDG 5)
Energy security	Deployment of RE can promote energy security through lower external dependence on primary fuels. At the same time, RE may be dependent on imports for components, parts, or minerals. RE deployment may help diversify the energy mix of the grid, thus enhancing energy security.	Energy independence, security, or sovereignty; manage balance of trade (imports and exports), balance of payments, and foreign exchange reserves

Note: [a] Here, *impact categories* refers to the broader or more general impact categories, and the assessment presented here only addresses a subset of all the possible impacts, selected based on comprehensiveness, relevance, and significance criteria, and not all the possible impacts under health, land, water, and so forth. This is different from the Initiative for Climate Action Transparency (ICAT) Sustainable Development Guidance Methodology, which refers to impact categories as more specific impacts under environmental, social, and economic dimensions.

Source: WRI authors.

Indicators should enable users to adequately assess how the RE technology affects the corresponding impact categories. The choice of specific indicators should be based on the objectives of the assessment and the availability of data (Rich et al. 2018). In the context of ERR assessment, indicators that are possible to quantify and assign an economic value will be the most useful. It is possible to assign an economic value to indicators if they meet the following criteria:

- Availability of a relevant and robust methodology to quantify impact
- Availability of relevant and robust methodology to allocate an economic value to the indicator
- Availability of data needed for quantification and valuation

This paper identifies relevant indicators based on the impact categories identified above and on their suitability for ERR as demonstrated in Table 3.

Table 3 | **Relevant Impact Categories and Indicators**

SD IMPACT CATEGORY	INDICATOR	QUANTIFIABLE	ABILITY TO ASSIGN AN ECONOMIC VALUE	INCLUDED IN ERR ESTIMATION
Health impacts	Mortality	Yes	Yes; estimation of the mortality risk value per life saved	Yes
Water impacts	Water consumption	Yes	Yes; estimation of the economic value of water based on alternative uses of water	Yes
Land impacts	Area of displaced land	Yes	Yes; estimation of the economic value of land diversion	Yes
Climate change impacts	Greenhouse gas emissions	Yes	Yes; estimation of the social cost of carbon	Yes
Employment impacts	Number of jobs created	Yes, but may not be able to assess net employment created at the application/unit level	Maybe; economic value of a job created at the microeconomic or marginal level	No
	Quality of jobs created[a]	No; lack of standardized methodology to quantitatively measure the job quality	No; lack of standardized methodology to apply an economic value to the quality of jobs	No
	Labor force participation of women	No; lack of data and methodology to assess the net impact of RE deployment on women's labor force participation	Maybe	No
Energy security	Is a combination of multiple indicators covering aspects of availability, affordability, accessibility, and acceptability.[b] No one ideal indicator, as the notion of energy security is highly context dependent	No; choice of indicators and direction of impact are highly dependent on political, sovereign, and economic priorities; lack of standardized methodology to quantitatively assess the net impact of RE deployment on India's energy security	No; lack of standardized methodology to apply an economic value to energy security	No

Notes: ERR = economic rate of return; RE = renewable energy.

[a] The International Labour Organization (ILO 2013) defines a good job as one that provides decent income, health benefits, stability and security of employment, a safe working environment, fair working hours, professional and personal life balance, and opportunities for promotion and progression of skill development. Jairaj et al. (2017) further refine the definition by adapting Impact Reporting and Investing Standards (IRIS) metrics, including reliability of income, health care benefits, employee safety policy, and training opportunities. However, job quality is a subjective term and depends on the societal, individual, and investor priorities in the specific context. Further, there is a lack of standardized study or method for quantifying job quality or its economic value; hence, it is not considered in the illustrative analysis of this paper.

[b] Badea 2010; Kruyt et al. 2009.

Source: WRI authors.

Accordingly, the impact categories included for the ERR estimation and qualitative assessment are illustrated by Figure 4.

Step 4: Quantify and Assign an Economic Value to SD Impacts

This step describes how to quantify (if quantifiable) and assign an economic value (if possible) to the impact indicators identified in Step 3. This paper adapts the substeps outlined in the ICAT methodology (Rich et al. 2018) for the purpose of assessing selected indicators. For each indicator, the substeps include

- defining the assessment boundary and period;
- choosing the assessment method;
- estimating the net impact for each indicator; and
- estimating the net economic value for the indicators.

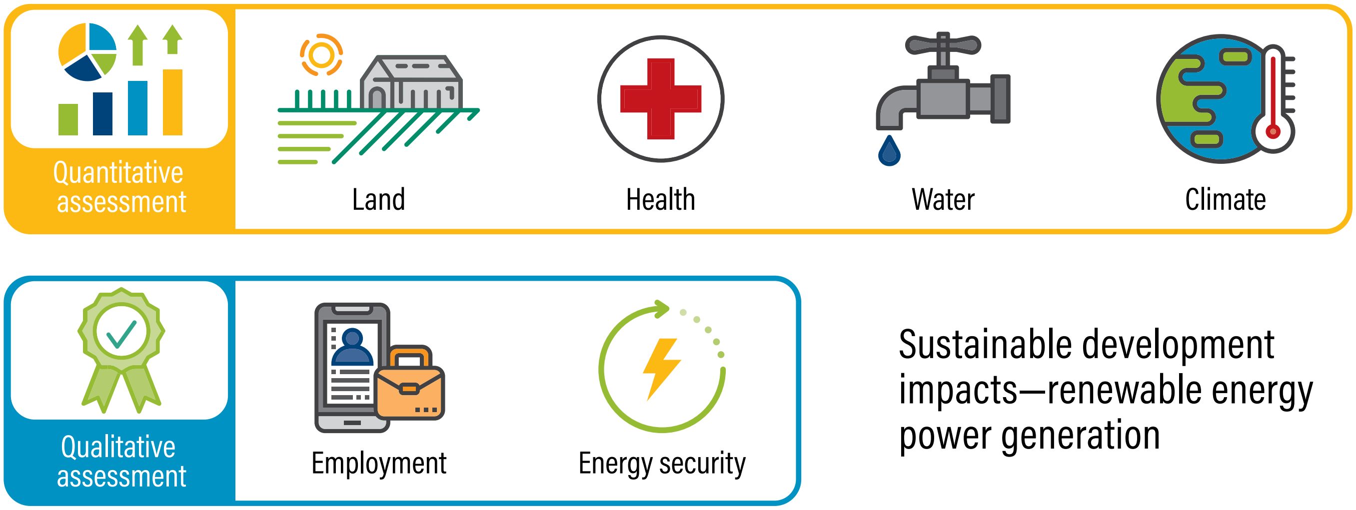
This section summarizes how the identified indicators are assessed and the impacts are estimated for RE technology deployment in India following these substeps. A more detailed description of the methodology for each impact and data usage can be found in Appendix C.

Define the Assessment Period and Boundary

Assessment period refers to the period over which impacts resulting from the power technology are assessed. Since most of the impacts take place during the lifetime of a power plant, this paper uses 25 years[9] (CERC 2018; KERC 2018; MERC 2018) as the useful life of RE technology power plants as the assessment period for all indicators of the corresponding technologies.

The assessment boundary determines whether a specific impact of RE technology is included in the assessment. The assessment boundary considered only includes impacts from the generation phase and does not include upstream or downstream impacts from the deployment of RE technologies. Although life cycle assessments may allow for an analysis across the value chain of RE technologies, the analysis presented here limits itself to the generation phase only. This is because life cycle impacts are highly specific to the technology used as well as its operational parameters across the value chain. However, where possible, life cycle assessments are recommended to provide a comprehensive understanding of SD impacts. Additionally, not all impacts during the generation phase may be included in the assessment boundary, depending on the significance or feasibility. A summary of the assessment boundary for each indicator is presented in Table 4.

Figure 4 | **Selected Impact Categories**



Source: WRI authors.

Table 4 | Assessment Boundary and Limitations

INDICATOR	ASSESSMENT BOUNDARY	JUSTIFICATION
Mortality	▪ The estimated health impacts in this study cover four adult diseases causing increases in mortality risks: lung cancer, chronic obstructive pulmonary disease, ischemic heart disease (from reduced blood supply), and stroke.	▪ These diseases are associated with exposure to sulfur oxide (SO_x), nitrogen oxides (NO_x), and particulate matter ($PM_{2.5}$), and their prevalence rises with increases in pollution exposure.
	▪ We only estimate the avoided mortality impacts and do not include morbidity impacts.	▪ Exposure to the pollutants also causes a range of morbidity impacts, such as impaired vision and nonfatal heart and respiratory illnesses (increase in morbidity), adverse effects on local agricultural production, damage to local building, and increases in local water pollution. However, studies for China, Europe, and the United States find that mortality impacts typically account for 85 percent or more of the total damage from local air pollution (European Commission 1999; NRC 2010; U.S. EPA 2011; World Bank and SEPA 2007; Watkiss et al. 2005).
	▪ Health impacts are evaluated only for exposure during power generation. Upstream health impacts, such as those from activities like fossil fuel extraction by mining, during transportation of these fuels, and so forth, are not included.	▪ This is due to the availability of data.
	▪ Only the population over 25 years of age exposed to pollutant emissions is considered for the calculations, thus excluding impacts on individuals younger than 25 years as well as impacts on infant mortality.	▪ This is because valuation of the mortality risk for infants is contentious and incomplete since children have not been the subject of revealed and stated preference studies. Again, the estimated effects represent the lower bounds of the overall impact.
Water consumption	Water use is during the generation phase only. Water use during the site preparation and installation phase is not included. Water consumption (and, hence, water impacts) of hydropower are not considered here.	Water use during the installation phase is highly dependent on the site's characteristics and cannot be generalized. Water impacts for hydropower are not included due to the lack of benchmark data on water consumption and potential water made available for irrigation by hydropower, both of which are highly context and location specific.
Greenhouse gas (GHG) emissions	GHG emissions are avoided during the generation phase. GHG emissions in upstream and downstream activities, such as manufacturing of equipment or end-of-life disposal, are not included.	There is a lack of technology-specific benchmark data.
Area of displaced land	This considers the impact from agricultural or forest land diversion for deployment of RE technologies at the site. It does not include the land required for access roads.	Land use for RE deployment in upstream and downstream activities (e.g., manufacturing facilities or access roads for the site) are not included because these data are highly project or site specific and there is a lack of standardized data.[a]

Note: [a] Where available for specific projects or applications, this should be included.

Source: WRI authors.

Choose the Assessment Method

Generally speaking, there are three types of assessment method for each indicator (Rich et al. 2018):

- **Scenario method:** A comparison of a baseline scenario with a technology scenario for the same region, where separate baseline and technology scenarios are defined and estimated.
- **Deemed estimates method:** A simplified approach to the scenario method, where the change resulting from a technology is estimated without separately defining and estimating baseline and technology scenarios.
- **Comparison group method:** A comparison of one region affected by the technology with an equivalent region not affected by the technology.

Since this framework is applied to assess ex ante ERR, we do not use the comparison group method, which may be used for an ex post assessment. Based on the available impact assessment methods, this paper uses the deemed estimates method to assess the relevant impacts for all RE technologies as a net impact (the impact of RE relative to the baseline scenario), as demonstrated by Table 5. The scenario method uses a similar approach and will give the same results.

Estimate the Net Impact for Each Indicator

RE technology scenarios are determined by Step 2 when identifying technology options to be assessed. Table 6 summarizes the method used by this study to estimate the net impacts for the indicators under consideration. Please refer to Appendix C for a detailed description of the methods, equations, data, and key assumptions.

Estimate the Net Economic Value for the Indicators

This substep involves assigning economic values to the costs and benefits for each indicator. There are multiple methods of economic valuation, including estimating opportunity costs, stakeholders' willingness to pay to create or remove certain conditions, and the market costs to create or remove certain conditions. The exact method used should be determined by data availability, stakeholders' acceptance, technical and resource constraints, and the objective of the assessment. The results also need to be disaggregated to show how the economic values change over the assessment period.

Table 7 illustrates how the economic values are assigned for the net impacts estimated under each indicator in the context of this study.

For assessment that intends to calculate ERR, which requires aggregation of valued impacts across different indicators, it is important to ensure that the valuation methods used for different indicators will not result in the double counting of specific impacts. For example, in Table 7, the mortality risk value indicator is used only to value the health risks from particulate matter emissions, and climate-related health impacts[10] are covered under the social cost of carbon (SCC).

Step 5: Calculate the Economic Rate of Return

In this step, all economic values are converted into a net cash flow, which will be used to estimate the ERR, the rate that produces a zero net present value (NPV) for the cash flow.

$$\sum_{y} \frac{Net\ \text{Cash Flow}_{y,t}}{(1+r_t)^y} = 0$$

$Net\ Cash\ Flow_{y,t}$ is the net economic values of economic benefits minus the costs in year y for RE technology t relative to the baseline, and r is the economic rate of return where the value of the equation equals zero.

The Scope and Limitations of the Estimates

The ERR estimates for RE technologies in India presented in this paper demonstrate the application of the framework, and the results represent average economic returns for different RE technologies in India.

Technology selection

Although the larger range of RE technologies includes solar (thermal/PV), wind (onshore/offshore), biomass, small hydro, tidal, and geothermal energy, this study is limited to **grid-connected solar PV, wind, biomass, and small hydro projects**. This is due to their high potential in India, their prominence in policy targets, the prevalence and feasibility of commercial-scale applications, and the availability of relevant data (as elaborated

Table 5 | **Assessment Method for Indicators**

INDICATOR	ASSESSMENT METHOD
Mortality	Health impacts determined in terms of the net change in mortality—that is, the change in the incidence of premature deaths due to pollution-related illnesses in the population exposed to particulate matter ($PM_{2.5}$), sulfur oxide (SO_x), and nitrogen oxide (NO_x) emissions from power generation from RE deployment relative to the baseline technology
Water consumption	Difference in water use during power generation for RE technology relative to baseline technology
Greenhouse gas (GHG) emissions	Difference in GHG emissions during power generation for RE technology relative to baseline technology
Area of displaced land	Net diversion of land for RE technology deployment relative to the baseline technology

Source: WRI authors.

Table 6 | **Estimation Method of Net Impacts for Indicators**

INDICATOR	METHOD USED TO ESTIMATE BASELINE AND RENEWABLE ENERGY (RE) TECHNOLOGY VALUES	NET IMPACT
Mortality	First, estimate pollutant emissions for the baseline; second, estimate increased exposure to pollutants based on pollutant emissions, population, and fractions of pollutant inhaled; third, estimate the increased mortality based on increased exposure	Biomass: difference in mortality per megawatt (MW) between baseline and biomass technology scenarios Other RE technologies: No increased mortality risk because no pollutant is emitted; net benefit equals avoided mortality per MW relative to baseline technology scenario
Water consumption	Estimate water consumption per MW for baseline and RE technology scenarios based on previous Indian-specific studies	All RE technologies: Difference in water consumption per MW between baseline and RE technology scenarios
Greenhouse gas (GHG) emissions	Estimate GHG emissions per MW based on GHG emissions factor for baseline technology and zero for RE technology scenarios	All RE technologies: No GHG emissions as RE technologies do not emit GHG; net benefit equal to the avoided emissions relative to baseline technology scenario
Area of displaced land	Estimate land requirement per MW for RE and baseline technology deployment and level of diversion from agricultural and forest land	Rooftop solar photovoltaic: No additional land displaced as installation is on existing rooftops Other RE technologies: Difference in land requirement per MW for RE technologies and baseline technology

Source: WRI authors.

in Section 3.2.1). Where relevant, and if data are available, the framework may be applied to assess the impacts and ERR for other technologies.

Assessment boundary

The assessment of these impacts and the ERR estimates are **based on the generation phase** only. Although important, the upstream operations, such as the mining of materials or the manufacturing of equipment, and downstream operations, such as the disposal of waste, are not included. However, the framework may still be applied to a larger assessment boundary (see Section 4.1), where data are available.

Impact categories

Although RE technologies may impact employment and energy security, this study does not include the same in the ERR calculations due to the lack of standardized

Table 7 | **Economic Value for Net Impacts**

INDICATOR	ECONOMIC VALUE PARAMETER	PARAMETER DEFINITION AND INCLUSIONS
Mortality	Mortality risk value ($) per life saved	Value of statistical life (VSL) or the assigned value for reductions in mortality risks;[a] we use the most conservative estimate of VSL from available estimates for India to avoid overstating the positive impacts of pollution abatement; the VSL is estimated using the human capital approach where VSL represents an individual's market productivity, a value assumed to be reflected by the individual's earnings;[b] we also use alternate VSL values in the middle- and upper-bound ranges
Water consumption	Total economic value (TEV) of water ($) per cubic meter ($m^3$)	Impact on agriculture due to reduced water availability; impact on domestic water availability; health impact from diseases caused by poor sanitation or malnutrition attributed to water scarcity; environmental impact from ecosystem damage due to water scarcity
Greenhouse gas (GHG) emissions	Social cost of carbon ($) per ton of carbon dioxide equivalent emissions	Discounted economic value of the climate impacts associated with the emissions of one ton of carbon dioxide equivalent in the atmosphere; the climate impacts include costs and benefits from carbon emissions, accounting for economic and agricultural productivity changes as well as impacts from the carbon cycle and climate change and the economic damages associated with climate change
Area of displaced land	Agricultural land: Opportunity cost of agricultural income lost due to land diversion ($) per hectare Forest land: Net present value (NPV) of diverting forest land ($) per hectare Barren land: Economic value of diverting barren land is assumed to be zero	Agricultural land: Loss in agricultural income based on average agricultural income per hectare calculated as a weighted average of crop yields per hectare and crop price Forest land: NPV of loss of ecosystem services, carbon sequestration, biodiversity losses, timber and nontimber utility of forest land Barren land: Barren land may lead to positive or negative economic impacts due to alternate economic activities that may take place in the absence of RE deployment; however, due to the lack of data on the alternate activities or a standardized methodology to assign an economic value to the land, we exclude the impacts; where such methodologies and data exist, the economic impacts from utilization of barren land for RE may be included for estimating land impacts

Notes: [a] Although a contentious concept, economists and policymakers use the VSL as a policy tool to measure the risk-money trade-off for the tiny amount of fatal risk or amount of money that a person or society is realistically willing to pay to save one statistical life (Andersson and Treich 2008; Majumder and Madheswaran 2018). Different approaches to estimate the VSL exist, including revealed or stated preferences through labor market, consumer preferences, or human capital methods.

[b] See Mahapatra et al. (2012).

Source: WRI authors.

methodology to quantify and value these impacts, but it discusses the potential impacts qualitatively. The framework may be used to assess a larger set of SD impacts (see Appendix B) based on policy priorities and the availability of methods and data to quantify and assign an economic value to these impacts. The **impact categories chosen** for ERR estimates for India are based on the selection criteria, including the relevance, significance, comprehensiveness, and availability of standardized methods and data, detailed in Step 3 (see Section 3.3).

Scale of impacts

An underlying assumption in the chosen methods and estimations is that the **impacts occur at the margin**. That means that although the framework may assess SD impacts of RE technologies in any context or for any scale of policies or projects, the illustrative estimates for India assume that the RE deployment under consideration does not materially impact the system (economy, ecology, or grid) or that such impacts are minimal. However, for large projects or a large number of smaller projects or policies, where such system-level impacts may be significant, it is recommended to estimate such cumulative impacts. For example, the ecosystem impacts from a large number of small hydro projects may be more than a sum of the impacts estimated for the individual projects. This is because the impact on habitats, flora and fauna, or sedimentation patterns does not change linearly with the scale or number of projects. Similarly, for projects in regions with very high RE penetration, any additional RE capacity may lead to significant integration costs, which need to be duly considered.

For our estimates, we consider one megawatt (MW) as a unit size for RE technology deployment. This allows for estimate comparisions across technologies. For our calculations, we use average per-MW values, such as capital costs, O&M costs, land requirements, and so forth. Therefore, the results represent **average SD impacts and ERR estimates for different RE technologies in India**. These estimates illustrate the application of the framework and explain the drivers of costs and benefits related to the economic returns from RE deployment. They should not be used to derive ERR for any project or policy without the associated project- or policy-specific data. This is because the costs and benefits of deployment depend on the size, location, and actual deployment parameters, such as the agricultural or forest land diverted, the pollutant abatement technology used, and, hence, the resultant particulate matter emissions factors and so forth. Additionally, some of the costs and technology specifications may vary due to local circumstances or due to the size of the projects and the economies of scale they may offer. For example, the land requirement may not increase linearly for a coal-based power plant or for a hydro project, or the project costs for a large ground-mounted or rooftop PV power plant may, in fact, be lower than the average or benchmark value considered by local tariff orders. Similarly, RE technologies may provide varying load factors depending on the regional potential. The framework, however, may be used to assess impacts and estimate the ERR for any size, location, or technology, with the associated data.

The ERR estimates are based on the application of the framework at the country level for India and the individual impacts assessed **based on the average benchmark data available.** These estimates are for illustrative purposes and may be improved upon over time based on more granular, location-specific, primary data. This framework may also be applied for a broader assessment boundary, including upstream and downstream impacts, where possible.

Grid-integration costs

Costs associated with **integrating renewable power** in the grid are significant when considering large-scale RE deployment. This is because RE depends on temporal weather conditions; thus, system operators need to accommodate significant increases and decreases in RE generation with dynamic demand to maintain system balance. For example, in the absence of cost-effective energy storage technologies, increasing the share of variable RE requires greater flexibility to respond to steep increases and reductions to balance the dynamic demand and supply of power at different times of day. Thus, in spite of the predictability in overall generation levels, accommodating real-time variability in RE generation would need better planning, technology, and efficiency in distribution. These factors require an agile and smarter grid, an increase in reserve allocation to compensate for generation forecast errors, and innovations in energy storage (OECD/IEA and IRENA 2017). Although these grid-integration costs are significant, and are materially attributable to renewable power, they are systemic costs and are not impacted by a single project or application in most cases. Yet, as the cumulative RE share of the overall grid increases, these integration costs become critical (Duane et al. 2016; OECD/IEA and IRENA 2017) as well as imminent to avoid losses for power generators (who may be forced to operate at lower-than-optimal load factors) as well as optimally utilize RE (with minimum curtailment). Studies suggest that integration costs for the current RE targets are achievable with low to moderate integration challenges and costs, and they increase significantly as the share of variable renewables increases (Chaturvedi et al. 2018; Palchak et al. 2017; Sen et al. 2018). Accordingly, we include the available estimate of grid-integration costs by the Central Electricity Authority (CEA) in our scenarios to understand the impact of these costs on the overall returns.

Methods and data use

The quality of the estimates depends on the data and assumptions used for the analysis. For estimating the ERR for RE power technologies in India, we use conservative assumptions and reliable data to the extent possible. Finally, this framework does not prescribe impact estimation methods, which may be adopted as per the specific context using locally relevant data and the best available methods and tools.

Step 6: Report the Assessment Results

This step involves transparently disclosing the assumptions, boundary, data, technology specifications, and assessment methods used to assign economic values to impacts along with the results of the impact assessment and ERR estimates. Disclosing this information will help decision-makers and stakeholders correctly interpret the results and use them constructively.

Estimates for India

Based on the impact estimation methods, we arrive at the estimates for each of the impact categories throughout the assessment period. A summary of impact estimates for each category and RE technology is summarized in Table 8. For detailed annual impact numbers, please refer to Appendix E.

Based on these, the ERR estimates for RE technologies in India are summarized in Table 9.

Understanding the Results

The ERR estimates in Table 9 represent the SD returns of investment to the society for the different RE power technologies in India. These estimates are based on the impact categories included, the available data, the assumptions, and the methodologies applied, and they cover impacts only during the generation phase. These calculations are based on the current norms for each of the technologies (details are provided in Appendix D) and relative to the baseline (see Section 3.2.2). These estimates indicate that among the RE technologies considered, ground-mounted

Table 8 | **Impact Estimates for RE Technologies in India**

RE TECHNOLOGY	IMPACT CATEGORY	IMPACT (₹/MW) (IN CONSTANT 2017 PRICES)	
		YEAR 1	YEAR 25
Solar—ground mount	Health impact	10,648,806	953,805
	Water impact	2,071,841	2,013,411
	Climate impact	321,506	653,555
	Land impact[+]	537,740*	-15,769
Solar—rooftop	Health impact	10,648,806	953,805
	Water impact	2,071,841	2,013,411
	Climate impact	321,506	653,555
	Land impact[+]	561,049.14*	7,541
Wind	Health impact	15,132,513	1,355,407
	Water impact	3,038,034	2,952,355
	Climate impact	456,876	928,736
	Land impact[+]	-739,683*	-9,942
Biomass	Health impact	16,679,175	1,338,994
	Water impact	1,631,342	1,242,614
	Climate impact	1,066,045	1,698,573
	Land impact[+]	-479,537*	-6,445
Hydro	Health impact	16,645,765	1,321,183
	Water impact	3,341,838	2,877,807
	Climate impact	502,564	905,285
	Land impact[+]	-1,764,535*	-8,193

Notes: RE = renewable energy.

* Here, land impacts represents the land impacts in year zero, where all other impacts are zero due to no generation. Land impacts are estimated as a sum of the net present value of forest land diversion (considered only when land is procured) and the opportunity cost due to loss of agricultural income. As the value of forest land diversion is the present value of all future impacts, it occurs only once in year zero. Remaining years only include the annual loss of agricultural income across the lifetime of the project.

+Land impacts are measured as Indian rupee per megawatt (₹/MW) because they depend on the land requirement per MW of power installed and do not depend on electricity generated—that is, megawatt-hour (MWh). Other impacts are measured as the product of impact per MWh generated and the annual net generation for 1 MW installation.

Source: WRI authors.

solar provides the highest ERR for India, and biomass and small hydropower provide inconclusive returns due to their nonstandard cash flows (see 3.7.4). These estimates are illustrative and may not be directly used for policy planning without specific data on the technology costs, location and capacity, and, where possible, additional impacts as relevant to the policy or project under consideration.

Beyond the ERR itself, these results provide insights into the drivers of economic return to the society. In the case of biomass and small hydro, the high operational and maintenance costs relative to the baseline, combined with the significant costs related to land diversion, outweigh the economic benefits associated with improved health outcomes, lower water consumption, and climate change benefits. On the other hand, with decreasing capital costs and significant benefits across health, water, and climate, solar power provides high SD returns on investment to the society. Finally, despite much lower land requirements, and all else being equal, rooftop solar provides lower economic returns than ground-mounted solar due to its high capital costs compared to ground-mounted or utility-scale solar PV, which are larger installations and thus offer economies of scale.

These results thus depend on the key inputs that may vary based on the specific technology deployed, the location of the deployment, the baseline chosen, or the size of the units under consideration. The estimates presented here are based on the average or benchmark power sector norms in India. Where more region-, technology-, and project-specific data are available, the results would provide a more accurate estimate of returns to society as well as the drivers of costs and benefits.

Sensitivity Analysis

In the absence of specific project or policy data, it is recommended to conduct a sensitivity analysis for key assumptions that materially impact the results. This provides a potential range of estimates that may account for the uncertainty in the assumptions and also indicates the key variables that can significantly impact the estimates. In our sensitivity analysis, we only include scenarios where key inputs significantly impact our estimates.

Sensitivity analysis for RE technology assumptions

Across all RE technologies included in this study, we find that the economic returns increase when a smaller proportion of agricultural or forest land is diverted and when less water is consumed per unit of power generated. Moreover, as expected, economic returns increase with lower technology costs and operational costs (see Table 10). This can be expected with larger projects that offer economies of scale or improvements in technology, allowing lower investment costs per MW. Additionally, the value of ERR is significantly impacted by the cash flows in the initial years. As the results show, capital costs, which occur at the outset, have a much higher impact on the ERR estimates than O&M costs, which increase over the lifetime of the project.

Table 9 | **Estimates of ERR for RE Technologies in India**

RE TECHNOLOGY	SUBCATEGORY	ERR (%)
Solar	Ground mount	33.93
	Rooftop	25.53
Wind		19.65
Biomass		NA
Small hydro		NA

Note: ERR = economic rate of return; RE = renewable energy.

Source: WRI authors.

Sensitivity analysis for baseline technology assumptions

Results also are driven by the baseline technology chosen. With a baseline that offers better pollution abatement, higher water efficiency, and lower GHG emissions per unit of electricity generated, the relative returns of RE technologies are lower (Table 11).

Scenarios with alternate key inputs

Additionally, we also look at alternate scenarios that significantly affect the estimates, including the following (see Table 12):

- The mortality risk value (MRV) or economic value per life saved in India, based on Majumder and Madheswaran (2018) (upper-bound range), and a lower-bound estimate from Cropper et al. (2019)
- The SCC (Ricke et al. 2018)
- The integration costs from estimates by India's CEA (2017)

Table 10 | Sensitivity Analysis for RE Technology Assumptions

RE TECHNOLOGY	ERR- BASE CASE	LESS AGRICULTURAL LAND DIVERTED (-10%)	LESS FOREST LAND DIVERTED (-10%)	LOWER WATER CONSUMPTION INTENSITY (-10%)	LOWER CAPITAL COSTS (-10%)	LOWER O&M COSTS (-10%)
Solar PV—ground mount	33.93%	33.93%	33.97%	33.97%	39.98%	34.36%
Solar PV—rooftop	25.53%	25.53%	25.56%	25.56%	30.73%	26.00%
Wind	19.65%	19.74%	19.65%	19.65%	23.69%	19.90%

Note: ERR = economic rate of return; O&M = operation and maintenance; PV = photovoltaic; RE = renewable energy.

Source: WRI authors.

Table 11 | Sensitivity Analysis for Baseline Technology Assumptions

RE TECHNOLOGY	ERR—BASE CASE	BETTER POLLUTION ABATEMENT IN BASELINE (LOWER EMISSION FACTOR [-10%])	LOWER WATER CONSUMPTION INTENSITY IN BASELINE (-10%)	LOWER EMISSION FACTOR FOR GHG IN BASELINE (-10%)
Solar PV—ground mount	33.93%	29.78%	32.86%	33.76%
Solar PV—rooftop	25.53%	22.02%	24.56%	25.37%
Wind	19.65%	16.92%	18.84%	19.51%

Note: ERR = economic rate of return; GHG = greenhouse gas; PV = photovoltaic; RE = renewable energy.

Source: WRI authors.

Table 12 | Scenarios with Alternate Key Inputs

RE TECHNOLOGY	ERR—BASE CASE (MRV: US$305,545/LIFE SAVED; SCC IN 2020: US$3.41/TCO$_2$)	MRV—UPPER BOUND (US$638,428/LIFE SAVED)	MRV—LOWER BOUND(US$90,834/ LIFE SAVED)	SCC (IN 2020: US$85.36/TCO$_2$)	GRID INTEGRATION COSTS INCLUDED (₹1.5/KWH)
Solar PV—ground mount	33.93%	79.40%	6.27%	69.64%	19.80%
Solar PV—rooftop	25.53%	64.10%	2.49%	56.93%	11.73%
Wind	19.65%	50.64%	2.56%	45.99%	8.22%

Note: ERR = economic rate of return; MRV = mortality risk value; PV = photovoltaic; SCC = social cost of carbon, TCO$_2$ = tonnes of carbon dioxide.

Source: WRI authors.

For our base case, we use the MRV based on the approach by Parry et al. (2014), where the values from the Organisation for Economic Co-operation and Development (OECD) are adjusted based on relative per capita income to estimate the value for India (OECD 2012). This value is also comparable with the midrange estimate provided by Robinson et al. (2019). We also use an upper-bound estimate from Majumder and Madheswaran (2018) and a lower-bound estimate of MRV from Robinson et al. (2019) to estimate the impacts. As the MRVs vary widely, we also see a significant impact on the ERR in the direction of the change. Similarly, whereas we use Nordhaus's estimate for the SCC in our base case, a recent study by Ricke et al. (2018) provides SCC estimates based on a country's vulnerability to climate change impacts and their related costs. These estimates are 20 times higher and reflect the costs of climate change, more than doubling the economic returns for all RE technologies (except biomass and small hydro). The economic value assigned to impacts thus has a critical impact on the estimated returns; therefore, it should be selected carefully and should be relevant to the region and purpose of application.

Although the costs of integrating RE in the present electricity grid infrastructure are not well established—in terms of the costs attributable to each unit of renewable power generated over time—preliminary estimates by the CEA for two Indian states (Gujarat and Tamil Nadu) with high RE shares, indicate a cost of about 1.5 Indian rupees per kilowatt-hour (₹1.5/kWh) (CEA 2017). Applying these costs to RE power generated almost halves the ERR compared to the base case.

In the case of small hydro, it leads to net negative cash flow across the project's lifetime, and with rooftop solar PV, the returns are lowered to 10 percent of the base case. Although these results are not conclusive by themselves, with better grid-integration cost estimates, they may indicate low returns of grid-connected RE power for some technologies, which may better serve off-grid networks.

A Note on Estimates for Biomass and Small Hydro Technologies

As shown above, our assessment does not provide a conclusive estimate of ERR for biomass and small hydropower in India. In this section, we discuss the potential reasons for this in the context of the parameter itself, ERR, as well as the broader scenario of the biomass and small hydro sector in India.

Returns from biomass technology

Biomass power in India has traditionally been unfeasible primarily due to inadequate information on biomass availability, its sporadic and seasonal nature, the competing demand for biomass, and its high costs, including the logistical costs of procuring and storing biomass and the high capital and O&M costs. Thus, it has been provided capital and tax subsidies and preferential tariffs (MNRE 2016). Based on the industry benchmark data, we observe that the increasing O&M costs outweigh the potential benefits from lower water consumption, lower pollutant emissions, and the avoided GHG emissions from biomass power generation. This leads to a cash flow with an inconclusive ERR estimate. In such cases, it is recommended to assess the economic net present value (ENPV) (Sartori et al. 2015), which uses the same cash flow approach but provides a clear indication of the present value of the future costs and benefits. In this case, we see that the ENPV for biomass-based power is -₹340,765,189, and is therefore much lower than zero. Hence, based on the current analysis, we can conclusively say that biomass-based power does not provide net benefits to society. This is because we observe that biomass technology exhibits negative cash flows for the majority of the project years, indicating very low or no economic feasibility for biomass power in India (MNRE 2016, n.d.a). However, in regions with predictable availability, such as in Maharashtra and Uttar Pradesh, where sugar mills provide bagasse for power production at lower logistical costs, biomass-based power generation may provide net positive economic returns. It also has the potential to help agricultural waste management by avoiding open crop burning, which would otherwise lead to acute air pollution, as seen in India's northern states. Although not part of the current scope, an assessment of biomass power conducted in a regional context considering the specific capital and operating costs, the local crop residue availability, and the potential to abate crop burning (and the associated health benefits), would provide a more accurate estimate of its economic returns to society. Accordingly, given that biomass power generation has a large potential (18 GW)(MNRE 2016), using a comprehensive framework to assess the SD impacts can help implementation in areas or regions where the technology provides net benefits to society.

Returns from small hydro technology

Our analysis also indicates inconclusive economic returns from small hydro in India due to increasing operational costs as well as high up-front costs. The ENPV for small hydro is estimated at -₹16,654,101, again much lower than zero. Thus, indicating no net benefit to society. However, given the limited scope of the assessment and the lack of data, it excludes the potential costs and benefits of small hydro that may be reflected in regional studies. For example, depending on local priorities, hydropower may not only be a power-generation technology but also could be adopted in order to irrigate surrounding agriculture. On the other hand, depending on the region of installation, a hydro project may entail displacing settlements as well as diverting rivers or considerable deforestation. Although small hydro (less than 25 MW) is considered to be renewable because its social and environmental impacts (from resettlement, river diversion, or deforestation) are low enough to be excluded, where relevant and significant, these social and ecosystem impacts are recommended to be included. Therefore, economic returns from small hydro would be better assessed in a specific context with all related costs and benefits included in order to provide conclusive insights.

Step 7: Report the SD Impacts Not Included in the ERR

In this step we will describe how to report the impact categories from Table 3 that cannot be assigned an economic value and how the indicators can be reported to frame the results from the ERR calculations.

Impact Category: Employment

Economic development and job creation are among the key priorities for India. Deployment of RE technologies is expected to create employment through direct job creation during the design, erection, and commissioning activities as well as during the operational and maintenance phase. Indirect job creation is also expected from the manufacturing of RE equipment and the services and material provided for RE deployment and generation as well as induced job creation due to the deployment. Employment benefits are also correlated with impacts on poverty alleviation, skill development, and overall economic development.

We can estimate job creation by using the employment factor approach or through macroeconomic input-output models that consider economic pathways, investment in RE, and thus the contribution to jobs. Employment factors have been studied for RE technologies in India, which suggest higher employment requirements across RE technologies relative to conventional power generation, including coal power plants. The latest studies suggests employment (across engineering, procurement, and commissioning, or EPC, and operations) to be highest in rooftop solar (24.72 job years/MW) compared to 3.45 for ground-mounted utility solar, 1.27 for wind, and 1.5 for coal power plants (Kuldeep et al. 2017; TERI and IASS 2019). And although a comparison of employment factors across RE technologies relative to the baseline may provide us an indication of the relative employment potential of RE technologies, the net effect of employment will depend on the larger macroeconomic scenario and alternate employment opportunities to ascertain whether RE technologies would displace employment from other sectors, including coal-based power generation, or would create new employment. Economic modeling does answer some of these questions, and estimates for the employment effects of RE technologies indicate the potential for job creation and a net employment increase due to RE in India (TERI and IASS 2019). Modeling by the Council on Energy, Environment and Water (CEEW) and the Natural Resources Defense Council (NRDC) suggests that if India achieves its 2022 RE targets, it could result in the creation of 1 million jobs between 2017 and 2022, and it could provide new employment to 331,000 workers (Kuldeep et al. 2017), which includes jobs created across the value chain of RE deployment. However, these macroeconomic employment creation estimates may not translate proportionally to a regional, project, or unit level where the impacts are being assessed due to different local economic activities and, hence, employment opportunities. Therefore, we do not include employment effects in our impacts. Furthermore, the economic impact of jobs created also vary depending on the number of permanent and temporary jobs created, the quality of employment thereof, and the impact on poverty reduction (Jairaj et al. 2017). Finally, RE jobs can also be targeted toward women, by building capacity and skills to promote better opportunities for the female workforce, thus contributing to SDGs on gender quality (Jairaj et al. 2017). The energy sector as a whole is traditionally male dominated. The survey by the International Renewable Energy Agency (IRENA) suggests that women currently represent about 35 percent of the labor force in the modern RE sector, which is higher than in the conventional fossil fuel–based energy sector (IRENA 2017b). Where methodologies are available to make such an assessment, and where local data are available, including such employment impacts is recommended.

A Note on Energy Security

Energy security is defined as the uninterrupted availability of energy sources at an affordable price (IEA, n.d.b). Although India does not presently have a shortfall of power, the grid is highly dependent on fossil fuels. Fossil fuels like natural gas and crude oil are largely imported due to domestic unavailability. Even though coal is available domestically and at low cost, it is of lower quality. Therefore, imported coal makes up 10 percent of total coal consumption in power production (CEA 2019a). Imported coal, which has a higher caloric value and lower sulfur content compared to domestic coal, can also reduce health-related costs. India is also a net importer of PV panels as well as other components for solar power and is a net exporter of wind equipment. Although the traditional narrative of energy security focused on import independence, imports alone do not imply energy insecurity. This especially holds in cases of critical goods that boost efficient consumption, thus positively affecting economic growth. Imports help make these goods available at a cheaper cost while local manufacturing capacity improves. Here again, the implementation and effectiveness of policies to boost manufacturing in the medium to long term would determine the overall impact of import dependence.

Based on the definition above and in the context of India, energy security also means providing reliable, affordable power. By definition, RE uses resources that are available in nature. Therefore, unlike fossil fuel–based power, it is not as vulnerable to fuel price fluctuations. However, although RE exploits inexhaustible resources like sunshine or wind, it still depends on components such as panels, spare parts, or rare earth minerals for power production, which may be imported or may be available in limited quantities domestically. Finally, energy security may be enhanced by diversifying the energy mix to reduce risk exposure to price or availability shocks. With the variety of RE technology options, energy security may be improved by increasing the share of RE. This is also important in the context of the intermittent nature of renewable power, where different RE technologies may compensate or complement generation patterns, thus enhancing the grid's reliability.

As shown above, the impact of RE deployment on energy security depends on the overall effect on domestic availability, reliability, and affordability. In the absence of a rigorous methodology to measure the direction or level of impact, we exclude energy security from ERR estimates. However, the discussion above highlights the need to broadly consider factors such as energy mix diversification, domestic manufacturing improvements, the impact of imports on domestic consumption, the exposure level to external shocks, and the ability to optimize generation patterns to conclusively substantiate the impact of RE on energy independence and improve energy security.

4. FRAMEWORK GUIDANCE AND POLICY APPLICATIONS

Guidance on Applying This Framework

This paper provides a methodological framework to estimate the socioeconomic and environmental costs and benefits of prevalent commercial-scale technologies and the impacts from technologies such as solar thermal, offshore wind, and geothermal. The framework may be used to assess economic feasibility where these technologies are important in the local context and where data is available.

The scope of this study is limited to the generation phase due to the lack of data on other aspects of the RE value chain. It does not include the upstream and downstream impacts of RE deployment, including, but not limited to, the mining of minerals required for RE equipment, the manufacturing of RE equipment, the construction and commissioning of RE units, the building of access roads to RE power plants, and the end-of-life disposal of RE equipment. Some of these impacts may be critical in eco-sensitive areas as well as when considering a large project or a large number of small projects. Therefore, where possible, it is recommended that the assessment boundary include wider aspects of the value chain, including upstream and downstream operations, to ensure that the costs and benefits of RE deployment are better represented.

This paper applies the framework, as an illustration, to the national context to arrive at generic or average estimates of SD impacts and the ERR for various RE technologies in India, based on available impact quantification methodologies and power sector norms. However, this framework is recommended to be applied with technology- and location-specific data as far as possible. This is because deployment costs and benefits vary widely depending on the location and region of the project, and national averages may not apply to specific contexts. Where more relevant methodologies are available to estimate impacts or assign an economic value to impacts, they should be used to arrive at more accurate estimates.

The current estimates do not include the impacts of employment or energy security in the ERR due to the lack of a standardized methodology to arrive at the economic value of these impacts. Yet where possible, it is recommended to include these in the assessment to provide more comprehensive estimates. Additionally, any costs or benefits relevant to the local context, such as land diversion, employment generation, the resettlement of people, air pollution abatement (from crop burning), irrigation, flood management, ecosystem impacts, and so forth, are recommended to be included for better representation of the economic returns.

With the increasing rate of renewable deployment, it is integral to account for the social, ecological, and grid-integration costs, where available. For a large number of small hydro projects in a region, a large utility-scale project (such as an extremely large solar power plant), or a large RE goal, the socioeconomic and environmental costs may materially affect the economic returns to society. These projects also may have greater cumulative impacts than estimated using these methods alone. It is thus recommended that the wider ecological or integration impacts for such cases be assessed and included in the estimates.

Finally, since the framework provides an approach for ex ante assessment of future policies, projects, or initiatives, it is recommended that users consider the latest available data. This is especially relevant for RE assessments given the dynamic nature of the sector in terms of improvements in the efficiencies and performance of existing RE technologies and the development and commercialization of newer technologies, such as offshore wind, floating solar, or hybrid wind and solar systems. Where possible and relevant, assessments must incorporate the latest developments and norms.

Guidance on Interpreting the Estimates

Inputs and assumptions, including capital costs, O&M costs, and land-use patterns, significantly impact the magnitude of the ERR. Yet the estimates should be interpreted within the larger context of the RE projects under consideration. These are some of the key guiding principles:

- The ERR, like the IRR, is not a decision-making tool or an indicator by itself and should be interpreted as a comparative summary statistic to support decision-making. The ERR for an RE technology may be compared with the financial IRR to indicate or estimate the level of policy support required for a project, where the ERR is higher than the financial IRR. The ERR may be compared with a social discount rate (SDR) to justify public investment for socioeconomic and environmental benefits to society. The ERR across different RE technologies may also help policymakers prioritize investments across RE alternatives.
- The ERR as a mathematical computation may not always provide conclusive estimates, as shown in the cases of biomass and small hydro for India. In such cases, it is recommended to use a related indicator ENPV that provides the economic present value of future costs and benefits, using the same parameters and methods for the ERR.
- The estimates depend on the baseline chosen, the available RE alternatives, and the economic valuation of the socioeconomic and environmental impacts. These inputs vary greatly with the local context. A few examples of the key variables that influence the returns include, among others, the prevalent baseline technology, which may be natural gas or one of the RE technologies; the potential of RE power generation (e.g., the unavailability of renewable biomass); the expected costs of potential land diversion (eco-sensitive areas may have greater impact on land-use costs); and the level of local water availability or stress. Therefore, the results depend on the contextual data and the specific applications. Results at the national level may not apply to all contexts. For example, whereas an increase in forest land diversion for wind energy deployment reduces the economic return to society, deployment of wind power in a location with high wind potential on fallow land would provide better returns. Additionally, the availability of fallow land in a water-stressed region with equal wind

and solar potential may offer greater returns from wind due to the technology's minimal or lower water requirement.

- The ERR estimates provided here vary based on the specific technologies deployed to reduce air pollutant emissions in the baseline. Likewise, the type of technology used in the project scenario (in the case of biomass) or the efficiency of the prevalent technology deployed in a region or state of study will also alter the corresponding health benefits.
- As mentioned earlier, these estimates do not include the grid-integration costs because we assume that a single project does not significantly impact the system as a whole. Within our calculations, including grid-integration costs of ₹1.5/kWh (CEA 2017) lowers the estimated returns with respect to the baseline case. As the share of RE in the grid increases, the integration costs may outweigh the economic case for grid-connected RE and may be a critical decision-making criterion for RE technology deployment.
- The calculations presented here include key assumptions on the land-use pattern. Location has a significant bearing on the returns because diverting forest land or cultivable land[11] results in a significant loss of biodiversity, ecosystem services, carbon capture potential, and economic opportunity costs for agriculture. Returns from RE can be improved significantly by deploying RE technologies on waste or fallow land.
- ERR estimates depend largely on the ability to quantify and assign an economic value to impacts. Including estimates of potential impacts, such as employment, energy security, and so forth, where available, is recommended and may change estimates. Additionally, the availability of region-specific, recent, and more accurate data on the economic valuation of impacts, such as intake fractions, MRV, water risk, and the costs of land diversion, may provide improved estimates and may significantly change results.
- Finally, as an assessment conducted to support decision-making or policy planning, the estimates provide insights on potential or expected SD impacts. However, the actual impacts realized would depend on the actual implementation parameters and to what extent deployment enhances the societal benefits, such as by creating local, permanent jobs versus temporary ones.

Policy Applications

Assessing the range of SD costs and benefits for RE technologies can provide policymakers with insights into the relative returns from available RE technology alternatives and identify the drivers of socioeconomic and environmental costs associated with their deployment in the region. This evidence, along with a deeper understanding of the impacts not assigned an economic value, can help RE planning and deployment at the most socially efficient cost.

As one of the tools to support decision-making, estimating the ERR can help policymakers identify projects where public intervention and investment are justified. When compared with an SDR,[12] which is the hurdle rate for public investments in welfare, the ERR can indicate where public funds should be invested. This means that an ERR higher than the SDR may help justify public investments because it provides a reasonable level of socioeconomic and environmental benefits to society.

Furthermore, in cases where investment is justified (ERR>SDR), it may or may not be financially viable. Where investments are economically beneficial to society, and financially viable, private and public investment takes place without public intervention. However, with relatively new technologies such as RE technologies (in comparison with long-standing fossil fuel technologies), financial viability may still not be competitive. In such cases, a comparison of financial IRR with market benchmarks for investment returns may indicate to policymakers which technologies need policy interventions in terms of subsidies or financial incentives and how much policy support may provide sufficient incentives for technology options valuable to society. Finally, in cases where the ERR is higher than the SDR and the IRR exceeds the benchmark investment rate, the investment provides societal benefits and is financially viable and, hence, may not require policy support. The decision-making framework (Table 13) summarizing the above draws on the recent study by the Ministry of New and Renewable Energy on estimating the justified level of incentives for promoting RE technologies (MNRE, n.d.a).

The framework can also be used to improve SD returns from policies or projects based on a comparison with financial returns. As demonstrated above, financial viability may be a hurdle in deploying socially beneficial projects. Nonetheless, projects or technologies that provide high financial returns take place irrespective of their SD

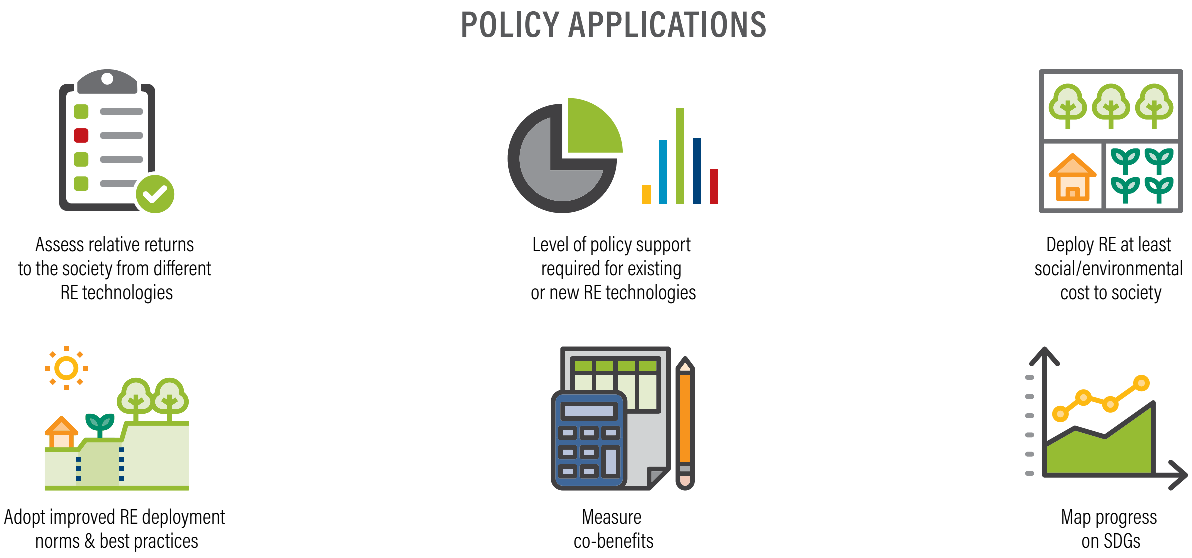
Table 13 | **Evaluation of the Economic Justification for Public Investment and Policy Support**

ECONOMIC VIABILITY	PUBLIC INVESTMENT JUSTIFIED	FINANCIAL VIABILITY	POLICY SUPPORT NEEDED
ERR>SDR	Yes	IRR<benchmark rate of return	Yes
ERR>SDR	Yes	IRR>benchmark rate of return	No
ERR<SDR	No	NA	NA

Note: ERR = economic rate of return; IRR = internal rate of return ; SDR = social discount rate.

Source: Adapted from MNRE, n.d.a.

Figure 5 | **Policy Applications**



Source: WRI authors.

implications. An analysis such as this can help policymakers and project proponents identify drivers that lower the ERR, including high economic, social, or environmental costs or low benefits. This can help develop practices or measures to alleviate the costs and increase the benefits to ensure that the financially viable technology also delivers SD benefits to society.

A regional analysis of these drivers can also support the adoption of improved norms and encourage the best practices for RE deployment in the region. Regional- or state-level assessments also provide nuanced insights based on context-specific data, local policy priorities and RE potential, and local ecological constraints. Such regional assessments can prove particularly valuable in the Indian context, given its wide geographical and economic diversity.

The application of the framework demonstrated in this paper assesses the costs and benefits for a new RE investment relative to a supercritical coal power plant in India. However, since the framework proposes an economic analysis, it may also be used to assess the impacts against existing power plants by considering the associated sunk or retrofitting costs and the potential benefits as the baseline. This may be helpful when considering whether to refurbish an existing inefficient power plant or replace it with a new RE power plant or installation.

Although this framework has been developed to more deeply consider the SD implications of RE in India, its flexible stepwise approach means that it also can be used in other countries and contexts. When applied to energy planning in other emerging markets, it can provide relevant insights on the cobenefits and SD categories relevant to local policymaking.

Power-generation projects are relatively long-term investments with potentially longer-term impacts on human well-being, environmental integrity, and climate change. Such an analysis can inform long-term policymaking by identifying and proactively mitigating the potential costs of RE technology deployment and optimizing the societal benefits. At the same time, because these assessments can inform future implementation, discretion is advised when using historical or past data for RE technologies. This is especially true for the RE sector, where technology is still evolving and newer technologies become available in shorter time spans. Where data are available, this assessment should be used for newer technologies, such as offshore wind, geothermal, hybrid solar and wind, and floating solar, to assess the policy support required for these options where their economic returns are higher than the social investment hurdle rate.

Finally, understanding and estimating the returns to society in the context of the various socioeconomic and environmental indicators can also help policymakers assess and report their progress on the SDGs and map the cobenefits in a more evidence-based manner.

5. CONCLUSION AND THE WAY FORWARD

This paper tries to address the lack of structured assessment of the SD impacts of RE technologies by developing a methodological framework to better support decision-making. The framework helps policymakers, researchers, and other users to systematically assess the socioeconomic and environmental impacts and estimate the ERR of various RE technologies.

The illustrative ERR estimates for RE technologies in India also highlight data gaps and research needs that can help improve the quality of such assessments in the future. Some of these include India-specific primary data for air dispersion modeling, regional mortality data, improved and regularly updated mortality risk estimates, the SCC for the country, power plant–specific emissions factors for pollutants, and land diversion data for RE deployment. Additionally, although national-level estimates exist for some of these, relevant regional-level data is also required for better estimating the local impacts and improving decision-making during deployment.

Power planning and deployment involves practitioners and decision-makers at various levels and departments of local, regional, or national governments. Efforts in sensitization of potential SD benefits and costs of RE and capacity-building exercises to better consider such assessments are therefore recommended. Where standardized data and assumptions are available, editable assessment tools can further enhance the use of such systematic assessments.

Based on the illustrative ERR estimates for RE in India, the SD benefits of RE technologies such as solar and wind outweigh the costs and can thus help strengthen the national ambition to increase RE deployment. However, this research also emphasizes the increasing importance of incorporating the costs of RE, including grid-integration costs and the impacts across the value chain of RE technologies, as well as the potential benefits that may not be assigned an economic value. Given the pace and scale of RE deployment and the lock-in of technology, it is increasingly critical to assess the benefits and costs of various technologies and include these considerations in future decision-making and planning.

At the same time, although an ex ante assessment of SD implications of RE deployment indicates the potential costs and benefits, planning and implementation also need to consider the indirect impacts on socioeconomic and environmental well-being. This would require identifying potential indirect impacts that could exacerbate existing damages or reinforce losses. This includes the loss of tree or forest cover beyond what is required and included for deployment due to the indirect economic or operational activities that occur in the area over the lifetime of the installations, and the loss of livelihoods for landless, unskilled agricultural laborers who may lose jobs due to RE installations that divert agricultural land. Further studies may identify methods to incorporate such impacts and improve RE decision-making and implementation.

Finally, although our research uses current power sector norms to provide estimates for the national level, our results emphasize the importance of the regional context and the availability of location-specific data in estimating the costs and benefits of RE technologies. Therefore, as a next step, we plan to apply this framework at the state level in India to provide better insights and specific policy recommendations for improved RE planning and deployment.

APPENDIX A: KEY STUDIES ESTIMATING THE SD IMPACTS OF RE AND COAL POWER

Table A1 | **Summary of Key Studies Estimating SD Impacts of Renewable and Coal Power**

IMPACTS	SOURCE	STUDIED	KEY FINDINGS
Multiple	IRENA 2017b	Economic impacts based on consumption and investment; social impacts based on expenditure on health and education; environmental impacts, measured as greenhouse gas (GHG) emissions and materials consumption; impacts on employment	▪ Doubling the share of renewables in the global energy mix by 2030 would increase global gross domestic product (GDP) by up to 1.1% or US$1.3 trillion ▪ Doubling the share of renewables by 2030 has a positive impact on global welfare, which increases by 2.7% compared to a 0.6% GDP improvement ▪ Doubling the share of renewables increases direct and indirect employment in the sector to 24.4 million by 2030
Multiple	OECD/IEA and IRENA 2017	The REmap program explores the energy transition to decarbonize the energy system in line with the Paris Agreement's goal of limiting global temperature rise to less than 2°C above preindustrial levels with a 66% probability	▪ Global carbon dioxide emissions in line with the Paris Agreement would boost GDP by 0.8% (US$1.6 trillion) in 2050; this translates into a cumulative gain of US$19 trillion ▪ In the Reference Case, global renewable energy (RE) jobs (direct and indirect) would reach 15 million by 2030 and 17 million by 2050; in comparison, in the REmap Case, the number of jobs would increase to 24 million by 2030 and 26 million by 2050; overall, the increased employment from renewables alone would offset job losses in the fossil fuel sectors (which would be around 7 million in 2030 and 8 million in 2050) ▪ When reduced air pollution externalities are considered, total benefits would be between two and six times greater than the incremental system costs of decarbonization, which are estimated to be US$1.8 trillion per year worldwide in 2050. Outdoor air pollution is a major externality, and it accounts for about two-thirds of this total
Water	Chaturvedi et al. 2017	Water consumption across different socioeconomic pathways	▪ Even assuming all thermal power plants shift to technology based on cooling towers by 2020, water withdrawals by 2055 under the high fossil fuel scenario are highest among all scenarios, indicating the need for improved water efficiencies and cooling technologies
Water	IRENA and WRI 2018	In its REmap study for India, the International Renewable Energy Agency (IRENA) formulated two scenarios for the power sector's development to 2030: the Reference Case and the REmap Case; in the former, 38% of the installed capacity would be based on renewable sources (including hydropower), and REMap has 61%; Central Electricity Authority (CEA) Scenarios 1 and 2 have RE at 38% and 54%, respectively	▪ In the Reference 2030 scenario, water withdrawal intensity would decrease by 83%, freshwater withdrawal would decrease by half in 2030, consumption intensity would decrease by 7% ▪ In the IRENA REmap 2030 scenario, water withdrawal intensity would decrease by about 84%, and water consumption intensity would decrease by 19%; compared to the Reference Case, water withdrawal in this scenario is projected to decrease further by 813 million m^3 under the REmap scenario ▪ In the CEA Scenario 1, 2027, water withdrawal intensity would decrease by about 71%, and water consumption intensity would decrease by 22%; absolute withdrawals in this scenario are projected to reduce by 9.5 billion cubic meters under CEA Scenario 1 compared to 2014 ▪ In the CEA Scenario 2, 2027, water withdrawal intensity would decrease by about 76%, and water consumption intensity would decrease by 25%; absolute withdrawals here are projected to reduce by 12 billion m^3 under CEA Scenario 2 compared to 2014

Table A1 | Summary of Key Studies Estimating SD Impacts of Renewable and Coal Power (Cont.)

IMPACTS	SOURCE	STUDIED	KEY FINDINGS
Health and employment	Hakhu 2019	Preliminary results assessing impact renewable energy will have in the areas of clean air and health, and employment generation	▪ By the year 2020, mortalities attributable to thermal power plants would reach 36,174 under the business-as-usual (BAU) scenario; it estimates that by 2020, BAU will translate to a loss of 0.39 million healthy years of life, which worsens by 69% to reach up to a loss of 0.66 million healthy years in 2050; these figures reduce by 10% in the Ambition scenario; in economic terms, this loss totals up to ₹110 billion in 2020, and ₹838 billion by 2050 ▪ Rooftop solar and small hydro projects will create the maximum number of jobs for every megawatt (MW) of capacity installed—approximately 25 and 14 jobs per MW, respectively ▪ The study also notes higher employment in RE in intended nationally determined contributions (INDCs) and Ambition scenarios to the order of 25% higher employment in the Ambition scenario compared to Reference Case
Employment	SCGJ 2016	Skill gap for wind, solar photovoltaic (PV), and small hydro across engineering, procurement, and commissioning (EPC); operation and maintenance (O&M); and manufacturing	▪ Wind, EPC, and O&M: By 2022, 62,999 and 19,841 additional manpower is estimated to be needed, respectively; no additional employment in manufacturing is estimated ▪ Solar PV, EPC, and O&M: By 2022, 400,257 and 234,951 additional manpower needed, respectively, as per estimates Small hydro, EPC, and O&M: By 2022, 0 and 18,200 additional manpower needed, respectively
Health	Guttikunda and Jawahar 2014	The emissions were estimated for the individual plants and the atmospheric modeling was conducted; health impacts are estimated as mortality and morbidity due to exposure to air pollution from coal-fired thermal plants	▪ In 2010–11, 111 plants with an installed capacity of 121 gigawatts (GW) consumed 503 million tons of coal and generated an estimated 580,000 tons of particulates with diameters less than 2.5 millimeters (mm) ($PM_{2.5}$), 2.1 million tons of sulfur dioxide (SO_2), 2 million tons of nitrogen oxides (NO_x), 1.1 million tons of carbon monoxide, 100,000 tons of volatile organic compounds, and 665 million tons of carbon dioxide; these emissions resulted in an estimated 80,000–115,000 premature deaths and 20.0 million asthma cases from exposure to $PM_{2.5}$ pollution, which cost the public and the government an estimated ₹160–₹230 billion (US$3.2–$4.6 billion)
Multiple	IRENA 2017a	In the REmap Case, modern RE's share of India's total final energy consumption (TFEC) increases to 25% in 2030, more than double the Reference Case level of 12%; RE's share in power generation increases to 35% in REmap, from 14% in 2010, compared to 18% in the Reference Case	▪ A higher uptake of renewables could result in reduced external costs of US$59–$224 billion annually by 2030 ▪ The benefits of modern renewables far outweigh the slight increase in cost to the energy system; most of the benefit, ranging from US$46 billion to US$161 billion per year, is related to reduced costs associated with a lower detriment to human health, including indoor and outdoor air pollution; the remaining US$13–63 billion relates to reducing costs associated with climate change ▪ Total investment needs in RE technologies in the Remap Case would average US$42 billion between today and 2030; this is made up of US$16 billion annually taking place in the Reference Case and an additional investment of US$26 billion due to the REmap options; of this US$26 billion, US$21 billion would be necessary new investment (incremental investment)

Table A1 | Summary of Key Studies Estimating SD Impacts of Renewable and Coal Power (Cont.)

IMPACTS	SOURCE	STUDIED	KEY FINDINGS
Health	CAT and Urban Emissions 2017	Health impacts from coal-fired thermal power plants (TPPs) where the total installed capacity is expected to increase three times from 159 GW in 2014 to 450 GW in 2030; under the proposed list of power plant projects	▪ The PM, SO_2, and NO_x emissions will at least double despite new plants being supercritical or ultra-supercritical; with no emissions regulations in place (at the time of study) for SO_2 and NO_x, these are assumed to be uncontrolled and are allowed to release through the elevated stacks for dispersion ▪ The total premature mortality due to the emissions from coal-fired TPPs is expected to grow two to three times, reaching 186,500–229,500 annually in 2030 ▪ Asthma cases associated with coal-fired TPP emissions will grow to 42.7 million by 2030
Health	Mahapatra et al. 2012	Estimate the damages to human health, crops, and building materials resulting from the operation of coal power plants and their associated mines; finally, economic values have been assigned to estimate the damage to human health, crops, and building materials	▪ The final external cost for generating 1 kilowatt-hour (kWh) of electricity from the coal fuel cycle is found to be ₹2.068 ▪ The annual welfare loss because of exclusion of external costs is closer to US$354 million (with ₹45 = US$1)
Health	Gupta and Spears 2017	Health externalities of coal plants using a panel of 40,000 households, matched to local changes in exposure to coal plants	▪ The average episode of cough resulted in an out-of-pocket expenditure of ₹550 on medical treatment and 4.09 days of missed work or school ▪ The average Indian district has just under 2 million people; if we assume a coal plant will last for 20 years and discount the future at the 3.81 rate at which the Government of India borrows money, then we find that the average coal plant will cause about 28 million discounted person years of exposure; combined with our cost estimates, this yields US$11.5 million (using 2011 International Comparison Program (ICP) exchange rate at health basket of goods, this increases to US$19 million) in out-of-pocket treatment costs and US$13.7 million as a conservative valuation of forgone days of work at the lowest wage paid by a government work fare program for poor rural Indians, for a total of US$25.2 million for each additional plant
Employment	Kuldeep et al. 2017	The Natural Resources Defense Council (NRDC) and Council on Energy, Environment and Water (CEEW) conduct annual surveys of India's solar and wind companies, developers, and manufacturers to collect accurate, market-based information on jobs created, workforce employed, and the skills required to achieve India's RE goals and arrive at actual full-time employment and workforce requirements	▪ Rooftop solar is more labor-intensive than other renewables, providing 24.72 job years per MW in comparison to 3.45 job years per MW for ground-mounted solar and 1.27 job years per MW for wind power ▪ Over 300,000 workers will be employed by 2020 to achieve India's solar and wind energy targets, mostly in the rooftop solar sector; a strong domestic solar module manufacturing industry has the potential to provide employment for an additional 45,000 people in India

Source: WRI authors.

APPENDIX B: POTENTIAL SD IMPACT CATEGORIES

Table B1 | **Sustainable Development Impacts**

ENVIRONMENTAL IMPACTS	
GROUP	IMPACT CATEGORIES
Air	Climate change mitigation (SDG 13)
	Ozone depletion
	Air quality and health impacts of air pollution
	Visibility
	Odors
Water	Availability of freshwater (SDG 6)
	Water quality (SDG 6, SDG 14)
	Biodiversity of freshwater and coastal ecosystems (SDG 6, SDG 14)
	Fish stock sustainability (SDG 14)
Land	Biodiversity of terrestrial ecosystems (SDG 15)
	Land-use change (LUC) (deforestation, forest degradation, desertification (SDG 15)
	Soil quality (SDG 2)
Waste	Waste generation and disposal (SDG 12)
	Treatment of solid waste and wastewater (SDG 6)
Other/cross-cutting	Resilience of ecosystems to climate change (SDG 13)
	Adverse effects of climate change
	Energy (SDG 7)
	Depletion of nonrenewable resources
	Material intensity
	Toxic chemicals released to air, water, and soil
	Genetic diversity and fair use of genetic resources (SDG 2, SDG 15)
	Terrestrial and water acidification (SDG 14)
	Infrastructure damage from acid gases and acid deposition
	Loss of ecosystem services from air pollution
	Nuclear radiation
	Noise pollution
	Aesthetic impacts

SOCIAL IMPACTS	
GROUP	IMPACT CATEGORIES
Health and well-being	Accessibility and quality of health care (SDG 3)
	Hunger, nutrition, and food security (SDG 2)
	Illness and death (SDG 3)
	Access to safe drinking water (SDG 6)
	Access to adequate sanitation (SDG 6)
	Access to clean, reliable, and affordable energy (SDG 7)
	Access to land (SDG 2)
	Livability and adequate standard of living
	Quality of life and well-being (SDG 3)
Education & culture	Accessibility and quality of education (SDG 4)
	Capacity, skills, and knowledge development (SDG 4, SDG 12)
	Climate change education, awareness, capacity building, and research
	Preservation of local and indigenous culture and heritage (SDG 11)
Institutions & laws	Quality of institutions (SDG 10)
	Corruption, bribery, and rule of law (SDG 16)
	Public participation in policymaking processes
	Access to information and public awareness (SDG 12)
	Compensation for victims of pollution
	Access to administrative and judicial remedies (SDG 16)
	Protection of environmental defenders
	Freedom of expression
Welfare & equality	Poverty reduction (SDG 1)
	Economic inequality (SDG 8, SDG 10)
	Equality of opportunities and equality of outcomes (SDG 10)
	Protection of poor and negatively affected communities (SDG 12)
	Removal of social disparities

Table B1 | **Sustainable Development Impacts (Cont.)**

ECONOMIC IMPACTS	
GROUP	IMPACT CATEGORIES
Overall economic activity	Economic activity (SDG 8)
	Economic productivity (SDG 8, SDG 2)
	Economic diversification (SDG 8)
	Decoupling growth and environmental degradation (SDG 8)
Employment	Jobs (SDG 8)
	Wages (SDG 8)
	Worker productivity
	New business opportunities (SDG 8)
	Growth of new sustainable industries (SDG 7, SDG 17)
	Innovation (SDG 8, SDG 9)
	Competitiveness of domestic industry in global markets
	Agricultural productivity and sustainability (SDG 2)
	Economic development from tourism and ecotourism (SDG 8)
	Transportation supply chains
	Infrastructure creation, improvement, and depreciation
Income prices & costs	Income (SDG 10)
	Prices of goods and services
	Costs and cost savings
	Inflation
	Market distortions (SDG 12)
	Internalization of environmental costs/ externalities
	Loss and damage associated w/ environmental impacts (SDG 11)
	Cost of policy implementation and cost-effectiveness of policies
Trade & balance of payments	Balance of payments
	Balance of trade (imports and exports)
	Foreign exchange
	Government budget surplus/deficit
	Energy independence, security, or sovereignty
	Global economic partnership

SOCIAL IMPACTS	
GROUP	IMPACT CATEGORIES
Welfare & equality (Cont.)	Climate justice and distribution of impacts on different groups
	Gender equality and empowerment of women (SDG 5)
	Racial equality and indigenous rights
	Youth participation and intergenerational equity
	Income of small-scale food producers (SDG 2)
	Migration and mobility of people (SDG 10)
Labor conditions	Labor rights (SDG 8)
	Quality of jobs (SDG 8)
	Fairness of wages (SDG 8)
	Quality and safety of working conditions (SDG 8)
	Freedom of association (SDG 8)
	Just transition of the workforce (SDG 8)
	Prevention of child exploitation and child labor (SDG 8, SDG 16)
	Prevention of forced labor and human trafficking (SDG 8)
Communities	City and community climate resilience (SDG 11)
	Mobility (SDG 11)
	Traffic congestion (SDG 11)
	Walkability of communities (SDG 11)
	Road safety (SDG 3, SDG 11)
	Community/rural development
	Accessibility and quality of housing (SDG 11)
Peace & security	Resilience to extreme climate change and weather events (SDG 13)
	Security (SDG 16)
	Maintaining global peace (SDG 16)

Source: Adapted from ICAT 2018.

APPENDIX C: IMPACT ESTIMATION METHODS

C.1. Impact Category: The Health Impacts of Air Pollution

Health impacts are typically measured as relative changes in mortality and morbidity attributed to a particular intervention. The process of producing energy from fuels such as coal, natural gas, or diesel emits air pollutants (such as particulate matter, $PM_{2.5}$; sulfur dioxide, SO_2, which reacts in the atmosphere to form $PM_{2.5}$; and nitrogen oxides, NO_x) and negatively affects the mortality and morbidity of the exposed population. In contrast, energy production from RE technologies (except biomass) do not entail direct emissions and thus avoid the negative health impacts related to conventional fossil fuel–based technologies. Therefore, a plausible approach to capturing the health impacts of deploying RE technologies is to estimate the avoided health impacts from avoided exposure to pollutants from the combustion of coal (baseline) or the difference in the health impacts relative to the baseline in the case of biomass. In order to quantify this, we refer to the approach used by Parry et al. (2014).

Based on the Parry et al. approach, this study estimates the health impacts of RE technologies in India as the difference in health damage from exposure to pollutant emissions from a conventional fuel, which is then assigned an economic value to the impacts. Given that the emissions and, hence, exposure from RE generation is zero, the health impacts of RE technology are the avoided negative health impacts from coal power generation.

In determining the health impacts, the following key assumptions adopted from Parry et al. (2014) apply:

- Health impacts are determined in terms of the increase in mortality risks (i.e., increased incidence of premature deaths due to pollution-related illnesses in the population exposed to $PM_{2.5}$, SO_2, and NO_x emissions from fossil fuel– or biomass-based power generation).
- The estimated health impacts in this study cover four adult diseases that are more prevalent when people intake pollution and that increase mortality risks: lung cancer, chronic obstructive pulmonary disease, ischemic heart disease (from reduced blood supply), and stroke.
- Exposure to the pollutants also cause a range of morbidity impacts, such as nonfatal heart and respiratory illnesses (increase in morbidity), adverse effects on local agricultural production, damage to local buildings, and increases in local water pollution. However, studies for China, Europe, and the United States find that mortality impacts typically account for 85 percent or more of the total damage from local air pollution (European Commission 1999; NRC 2010; World Bank and SEPA 2007; U.S. EPA 2011; Watkiss et al. 2005). Accordingly, we only focus on estimating the avoided mortality impacts due to RE technologies and thus provide a conservative estimate of health impacts.
- Health impacts are evaluated only for exposure during power generation. Upstream health impacts, such as health impacts from activities such as fossil fuel extraction by mining, during transportation of these fuels, and so forth, are not included.
- Only the population over 25 years of age exposed to pollutant emissions is considered for the calculations, thus excluding impacts on individuals younger than 25 years as well as impacts on infant mortality. This is because the valuation of mortality risk, or the MRV, for infants is contentious and incomplete because children have not been the subject of revealed and stated preference studies. Again, the estimated effects represent the lower bounds of the overall impact.
- We only estimate the ex ante economic value of the impacts over the lifetime of the installation, in terms of the impact of each unit of power generated.

Additionally, a significant number of deaths attributable to pollution in India occur outside the country (16 percent according to one study). This study does not cover the same and only accounts for impacts within the national boundary.

C.1.1. Level of Exposure to Pollutants

In order to quantify the avoided health impact of fossil fuels (coal), we first estimate the level of exposure to a pollutant, *p*. The level of exposure to pollutant *p,* at distance *i* from the source, is the incremental change in pollutant concentration. We use intake fractions[13] to estimate this, based on the work of Zhou et al. (2006) in China and Parry et al. (2014).

For the purpose of our study, we adopt the intake fraction estimated for SO_2, NO_x, and $PM_{2.5}$ in India by Parry et. al. (2014, 69), representing the pollution inhaled by the exposed population (based on proximity to coal power plants) to arrive at the overall level of exposure to pollutants from coal power generation. Thus, we calculate the **change in ambient concentration of pollutant *p,* per ton of *p* emitted at source, using the equation**

$$\Delta C_{i,p} = \frac{IF_p}{BR \times P_e}$$

where, P_e is the total population above 25 years of age exposed to the pollutant *p* within the boundary (calculated from UNSTATS and LandScan by Parry et al.); annual breathing rate, *BR*, is 7,300 cubic meters (m^3) (at 20 m^3 per day) per capita; and the *intake fraction* (IF_p) is the average amount of $PM_{2.5}$ inhaled per ton of pollutant emitted, weighted based on the plant's share in India's total coal usage.

C.1.2. From Exposure to Mortality

Using exposure, we now estimate the mortality risk due to the pollutant. Mortality risk, $Risk_{p,s}$, is the risk of premature death from illness, *s*, due to the incremental exposure to pollutant *p*, and is calculated as

$$Risk_{p,s} = (\Delta C_{i,p} \times \alpha_s) + 1$$

where α_s is the coefficient from the concentration-response function indicating the increase in mortality by illness *s* due to the increase in concentration of $PM_{2.5}$ (Burnett et al. 2014).

As outlined earlier, we focus on four illnesses (*s*) that increase mortality risks—lung cancer, chronic obstructive pulmonary disease, ischemic heart disease (from reduced blood supply), and stroke—all of which are more prevalent when people intake pollution.

Accordingly, the total mortality, MR_p, due to each ton of emitted pollutant *p,* which causes illness *s,* is calculated as

$$MR_p = \sum_s MR_{base,s} \times P_e \times \frac{Risk_{p,s} - 1}{Risk_{p,s}}$$

where $MR_{base,s}$ is the baseline mortality rate of illness *s* (Burnett et al. 2014) and ($Risk_{p,s}$ – 1) represents the change in the relative risk.

C.1.3. The Economic Value of Mortality Due to Pollutant

Finally, the health impact or economic value ($) of the mortality due to each ton of emitted pollutant *p*, $HI_{p,t}$, is estimated using the formula

$$HI_{p,t} = MR_p \times MRV$$

where *MRV* is the mortality risk value ($) per life saved. Here, we use the MRV calculated for India using the approach outlined by the OECD (2012). Since the MRV for India varies widely across studies, we also use two alternate values (Cropper et al. 2019; Majumder and Madheswaran 2018; Robinson et al. 2019) as additional scenarios.

C.1.4. From $ per Ton of Emissions to $ per kWh Generated from Coal ($H_{p,GJ,c}$)

The total health impact (in $) due to coal (gigajoule, GJ) is estimated as a sum of impacts due to all pollutants and the emission factors for the pollutant

$$HI_{p,GJ,c} = \sum_p HI_{p,t} \times EF_{p,c}$$

where $EF_{p,c}$ is the emissions factor of pollutant *p* per petajoule (PJ) of coal used, in kiloton/PJ, based on the current level of emissions control technology in India (PIB 2015; TERI 2016). Additionally, based on the latest regulations for emissions standards from power generation in India, we assume a 100 percent compliance by 2030 and thus use the consequent emissions factors based on the impact of the standards on the pollutant emissions, estimated in Srinivasan et al. (2018).[14]

Finally, to obtain the health impact ($) per unit of power generated (MWh), we use the CEA database's estimate of station heat rate or coal per kWh and obtain the health impact costs of RE technologies per MWh generated.

C.2. Impact Category: Availability of Freshwater

Conventional thermal power plants (TPPs) require large water withdrawals and are already losing a substantial amount of power generation due to water shortages (Luo et al. 2018). Even with newer regulations in India mandating a limit to water withdrawal intensities for old as well as new (post-2017) TPPs to 3.5 m^3/MWh and 3 m^3/MWh (GoI 2015; MoEFCC 2015b), respectively, water withdrawal and use remains a major impact for conventional power generation. Although most of the withdrawn water is returned to the source downstream and is available for use, water consumption within TPPs remains significant (Chaturvedi et al. 2017). In contrast, RE technologies such as solar and wind require zero to minimal water for power generation.[15] Water demand in solar PV power generation arises mainly from cleaning panels, and no water is withdrawn for wind technologies. Therefore, in order to estimate the water-use impacts of RE technology, we estimate the generation-related water use that would be avoided by deploying RE technologies compared to what would have been required for our baseline case, a new coal-based TPP.

C.2.1. Measure Avoided Water Use

We first estimate the avoided water use per MWh by deploying RE technologies and subsequently use the economic value of water to estimate the avoided economic cost of water due to RE technology *t.*

Water use in power plants differs greatly according to the cooling technology used. Currently, there is no mandate for power plants in India to monitor and disclose water withdrawal and discharge data and, consequently, no database for water-use statistics. Therefore, we use the estimates on India-specific water consumption from Chaturvedi et al. (2017).

The net water intensity of power generation, or the avoided water use per MWh, is the difference between the thermal water intensity and that of the RE technology under consideration. For estimates of water consumption benchmarks for the different RE technologies, we use estimates provided by Luo et al. (2018) and IRENA and the World Resources Institute (2018).

C.2.2. Determine the Total Economic Value of Water

For the total economic value (TEV) of water, we refer to the estimates from the Corporate Bonds Water Credit Risk Tool (Ridley and Boland 2015), which is a financial model to integrate water stress into corporate bond credit analyses by estimating the TEV or shadow price of water based on alternative uses of water (or the opportunity costs). This open-source, stand-alone tool helps users source the TEV that reflects local levels of water scarcity for each longitude and latitude during the years 2010, 2020, 2030, and 2040. The tool uses a hybrid approach to estimate the TEV of water, accounting for the alternative uses of the natural resource, including the external benefits that water provides to society and the environment, in addition to the private benefit gained by water consumers. This approach combines a value function for agricultural use alongside three additional components of value—municipal supply, impacts on human health, and impacts on the environment—as a function of *W* (the baseline water stress). Within the tool, we update the starting value of disability-adjusted life years (DALYs) for India, based on the World Bank for the year 2017, which the tool then projects across the years 2020, 2030, and 2040 (World Bank 2018a). All other assumptions from the tool have been retained as is. The hybrid valuation includes an additional weighting adjustment for the size of the local population.

The economic value of the water-use impact for RE technology *t* is thus estimated from the above as

$$WI_t = Net\ water\ intensity\ of\ power\ generation_t \times \sum_i Economic\ value\ of\ water$$

where $\sum_i$ *Economic value of water* is the total economic value of water and is a sum of the alternative uses of water (or the opportunity costs) and reflects the local levels of water scarcity estimated for India using the the Corporate Bonds Water Credit Risk Tool (Ridley and Boland 2015).

Net water intensity of power generation$_t$ is the difference in water intensity (m^3/MWh) of a coal-based TPP (baseline) with the water requirements per MWh for RE technology *t*.

C.3. Impact Categories: Climate Change Costs or Externalities

According to the latest Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), electricity production is the largest single sector emitting GHGs at the present and in future baseline scenarios (IPCC 2014). Therefore, it also follows that interventions in the electricity-generation sector can significantly mitigate climate change.
The combustion of fossil fuels across the value chain of electricity generation is responsible for the carbon emissions and the associated climate impacts from the electricity-generation sector. RE technologies replace the use of fossil fuels with renewable sources such as solar, wind, biomass, and hydropower for electricity generation, thus avoiding carbon emissions during power generation. Although other renewable sources do not involve the combustion of fuels, biomass-based power is generated from the combustion of agricultural or agro-industrial residues and urban or industrial wastes. Carbon in biomass returns to the atmosphere in some form regardless of whether it is burned for energy, is allowed to biodegrade naturally, or is lost in a forest fire; hence, it does not lead to additional GHG emissions.

C.3.1. GHG Emissions Avoided

To assess the climate impacts of RE technologies, we estimate the GHG emissions avoided due to RE technologies, relative to the baseline scenario in India, entailing coal as the primary fuel for power generation. Thus, the avoided carbon emissions per unit (MWh) of electricity generated from RE technologies is equivalent to the emissions factor for the baseline scenario (tons of carbon dioxide, tCO_2, per MWh).

The baseline scenario for our analysis is a coal-based power plant that would have been installed in the absence of the RE installation. Therefore, we use the emissions factor of the most efficient coal power plant in India (CEA, n.d.), 0.81 tCO_2e/MWh, which is also a conservative approach. Incidently, this is comparable to the emissions factor of the Indian grid, 0.82 tCO_2e/MWh, which is a weighted average of all power plants, including hydro, natural gas, lignite, diesel, and RE.

$$EA_{RE} = EF_{Baseline}$$

where EA_{RE} is the GHG emissions avoided per MWh due to RE, and $EF_{Baseline}$ is the baseline GHG emission factor, here 0.81 tCO_2e/MWh.

C.3.2. Estimate the Social Cost of Carbon (SCC)

Once we have the emissions intensity of power generation for RE technologies, relative to the baseline, we use the SCC to assign economic value to the associated emissions. The SCC is a key concept in environmental economics that captures the discounted economic value of the climate impacts associated with the emissions of one ton of carbon dioxide equivalent in the atmosphere. The climate impacts include the costs and benefits from carbon emissions, accounting for economic and agricultural productivity changes as well as impacts from the carbon cycle and climate change and the economic damages associated with climate change. Although various integrated assessment models estimate the SCC, these estimates vary widely due to model uncertainties, such as the differences across models, and structural uncertainties, which are uncertainties relating to the input parameters within the models arising from factors such as the timing and nature of the impacts as well as the SDR[16] adopted, leading to differences in productivity growth, equilibrium temperature sensitivity, and the damage function itself.

Here, we refer to updated SCC estimates based on a revised dynamic integrated climate-economy (DICE) model by Nordhaus (2017). These are the latest and most updated estimates available since the release of the Fifth Assessment Report by the IPCC, and they provide regional estimates for SCC, including for India, based on the proportional discounted value of output of the region. Also, we factor in an increase in the value, rising at 3 percent per year in real terms through 2050, for the SCC at the end of the RE technology's lifetime (Nordhaus 2017). Table C1 summarizes the SCC based on the Nordhaus revisions (2017), with alternate discount rates.

Table C1 | **SCC with Alternate Discount Rates**

	DISCOUNT RATES (%)	2015 (US$; 2010 PRICES)
	2.50	128.5
	3	79.1
	4	36.3
Baseline discount rate	4.25	31.2
	5	19.7

Source: Adapted from Nordhaus 2017.

This translates to an SCC of US$2.93/tCO$_2$ for India, based on an apportioning of 9 percent of the global output value as recommended by Nordhaus (2017).

Accordingly, the climate change impacts (*CI*) in year *i* for RE technologies is estimated as

$$CI_i = EF * SCC_i$$

C.4. Impact Category: Land-Use Change

Land is a key resource for all terrestrial energy technology and infrastructure deployment. The implications of land use depend on the quantity of land required, the type of land used, and the associated socioeconomic and environmental impacts. India's NDC target of 40 percent installed power from nonfossil energy sources by 2030 and 175 GW target from RE sources by 2022 (MoEFCC 2015a) will require considerable land and, consequently, may have socioeconomic and environmental impacts. To estimate impacts from land use due to RE technologies, we first estimate the land-use requirement for each of the RE technologies relative to the baseline. Subsequently, we estimate the socioeconomic and environmental impacts from land use for RE technologies and, finally, estimate the economic value for these impacts.

C.4.1. Estimate Land-Use Intensity

To estimate land-use impacts, we first use land-use requirement for different RE technologies. We use national standards and benchmarks to estimate the land-use requirements per MW of installations for RE technology *t*, or *land intensity*$_t$.

C.4.2. Identify Relevant Land Impacts

The primary land available and encouraged for RE projects is "wasteland." According to a study conducted by the National Institute of Solar Energy, the total solar potential on wasteland, which constitutes 8 percent of India's total land area (MoSPI 2017), has been estimated at 750 GW (MNRE 2017). Likewise, studies estimate the potential wind energy capacity on wasteland to be 153 GW. With this potential, it is unlikely that wasteland availability is an issue for India in deploying RE technologies to meet its goals or take up higher targets. Additionally, schemes such as the Kisan Urja Suraksha Evam Utthaan Mahabhiyan provide financial incentives to farmers to set up renewable power plants, including ground-mounted solar or solar pumps, on their barren or uncultivable land (CCEA 2019). The impacts of using wasteland are anticipated to be minimal because the land used does not have alternative cultivation or productivity potential, nor does it result in loss of biodiversity or ecological degradation. It may have an alternative economic use (such as commercial development); however, the economic value cannot be quantified without standardized data or information on the specific commercial application that is planned. Therefore, we assume the impact of RE deployment on wasteland to be zero. Where relevant and where such data is available, it is recommended to include it in assessing the land impacts.

However, RE projects such as solar parks require large, contiguous stretches of land. In such cases, it may be possible that the project encounters cultivable land or forest land. It may be noted that although the use of wastelands is encouraged for purposes of energy projects, most states allow agricultural or forest land to be used for energy and development projects by authorizing the necessary land-use changes. Additionally, as per the 2013 Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, the government can acquire land for its own use, for public purpose, for public-private partnerships with a public purpose or on behalf of private companies for a public purpose, such as infrastructure projects (physical and social) that may include the RE sector (within the power-generation sector). However, there is a ban on acquiring irrigated multicropped land, which can be acquired only as a last resort, with a condition to develop an equivalent area of cultivable wasteland for agricultural purposes. Thus, there may be scenarios where some agricultural or forest land is used for deploying RE technologies.

Land use in India is primarily classified as forest land; land not available for cultivation, which includes permanent pastures and land under tree crops; cultivable wasteland; uncultivable wasteland; and land under cultivation, which includes sown land and fallow land. Forest land accounts for 23 percent of India's total land area, and agricultural or cultivable land accounts for 59 percent (MoSPI 2017). Together, these two land types make up 82 percent of India's total available land (see Table C2). Wasteland, typically available for commercial development and renewable power installation, makes up 8 percent of the total land area available (MoSPI 2017).

In addition to wasteland, agricultural and forest land may be used for RE installations. Thus, to capture the land-use impacts from RE technology, we assess the impacts caused by diverting land from agriculture and forests to RE-related activities (assuming minimal impacts from using wasteland). We use data available for the land-use patterns and the percentage of RE capacity installed on the different types of land other than wasteland (MoEFCC 2017).

C.4.3. Estimate the Economic Value of Land Diversion

AGRICULTURAL LAND DIVERSION

We evaluate land-use impacts by calculating the opportunity cost of diverting land from a specific use to an alternative use (i.e., for RE technology). We can measure the opportunity cost/land-use impact by calculating a farmer's or farmworker's loss of agricultural income from being unable to use the land for agricultural purposes. This can be done by using national- and state-level statistics released by the Government of India. These statistics provide information about annual yield, total area, and total crop production. The Government also releases the prices of crops. The statistics released by the Government can be particularly helpful in case-by-case scenarios and if a piece of land is used to grow multiple crops.

Table C2 | Land Availability Pattern in India

1	YEAR	2013-14	%
2	Geographical area	328,726[a]	
3	Reporting area for land utilization statistics (row 4+5+9+12+13)	307,796	100
4	Forests	71,828	23
5	Not available for cultivation	43,860	14
6	Permanent pastures and other grazing lands	10,258	
7	Land under miscellaneous tree crops and groves (not including in net area sown)	3,187	
8	Cultivable wasteland	12,388	
9	Other uncultivated land, excluding fallow land (row 6+7+8)	25,832	8
10	Fallow lands other than current fallows	10,694	
11	Current fallows	14,154	
12	Fallow lands (row 10+11)	24,848	8
13	Net area sown	141,428	46
14	Total cropped area	200,859	
15	Area sown more than once (row 14-13)	59,431	
16	Agricultural land/cultivable land/arable land (row 7+8+12+13)	181,850	59
17	Cultivated land (row 11+13)	155,582	51

Source: Adapted from Nordhaus 2017.

We first calculate the average income per acre for each crop. This can be done by using the following formula:

$$P_c = \frac{\text{Total production of crop } c}{\text{Total area occupied by crop } c} \times \text{Price of crop } c$$

After having calculated the average income per acre for each crop, we calculate the average agricultural income per acre for a farmer in India. Statistics released by the Government of India include the weights that the crop yields hold in the market. Once we have P_c for all crops grown in the country, we can take a weighted average to determine the average agricultural income per acre for an Indian farmer (yield weights can be used to calculate this). This can be done using the following formula:

$$\text{Average income of a farmer (per acre) } I = (P_b \ Wt_b) + (P_c \ Wt_c) + (P_d \ Wt_d) \ldots . \sum Wt$$

where *P* is the average income per acre of crop *b,c,d,* and so on and *Wt* is the share in total area for crop *b,c,d,* and so on. *I* is the average agricultural income for a farmer per acre.

Considering the typical geographies where RE technologies are planned and installed, we assume the proportion of the total land requirement diverted from agricultural land, as shown in Table C3.

Table C3 | Assumed Agricultural Land Diversion

TECHNOLOGY	% OF LAND REQUIREMENT FROM AGRICULTURAL LAND DIVERSION	RATIONALE
Baseline	10	Although power installations are not planned or installed on agricultural land, we assume a 10% diversion of agricultural land as a conservative measure in case the project or installation encounters agricultural land. Rooftop solar does not involve any additional land requirement; hence, it is assumed that it will not require agricultural land to be diverted.
Solar PV—ground mount	10	
Solar PV—rooftop	0	
Wind	10	
Biomass	10	
Small hydro	10	

Note: No published data exists on the typical land diversion for RE technologies. Therefore, for the assumptions used here, we use recommendations and rationale provided by experts from the RE engineering, procurement, and commissioning industry through personal communications.

Source: WRI authors.

FOREST LAND DIVERSION

For estimates on the socioeconomic and environmental impacts from forest land diversion, we refer to the "Guidelines for Conducting Cost Benefit Analysis for Projects Involving Diversion of Forest Land under the Provisions of the Forest (Conservation) Act, 1980" (MoEFCC 2017). We also refer to the estimates provided for compensation by Verma et al. (2013). Based on these estimates, we arrive at the economic value of impacts per acre of forest land diversion.

Considering the typical geographies where RE technologies are planned and installed, we assume the proportion of forest land diversion, as shown in Table C4.

Table C4 | **Assumed Forest Land Diversion**

TECHNOLOGY	% OF LAND REQUIREMENT FROM FOREST LAND DIVERSION	RATIONALE
Baseline	10	Although power installations are not planned or installed on agricultural land, we assume a 10% diversion of agricultural land as a conservative measure in case the project or installation encounters agricultural land.
Solar PV—ground mount	0	Considering ground-mounted PV projects occur in flat, barren lands that rarely coincide with forests, we assume no forest land diversion.
Solar PV—rooftop	0	Rooftop solar does not involve any additional land requirement; hence, it is assumed that no forest land will be diverted.
Wind	10	Although power installations are not planned or installed on agricultural land, we assume a 10% diversion of agricultural land as a conservative measure in case the project or installation encounters agricultural land.
Biomass	10	Although power installations are not planned or installed on agricultural land, we assume a 10% diversion of agricultural land as a conservative measure in case the project or installation encounters agricultural land.
Small hydro	20	Considering the typical regions of small hydro installations, we assume a 20% forest land diversion.

Note: No published data exists on the typical land diversion for RE technologies. Therefore, for the assumptions used here, we use recommendations and rationale provided by experts from the RE engineering, procurement, and commissioning industry through personal communications.

Source: WRI authors.

C.4.4. Estimate Land-Use Impacts per MW of RE Technology Installed

Based on the economic value of land-use change, and using data on land-use patterns for RE technologies, we estimate land-use impacts per MW as follows:

$$LI_t = \sum_l Land\ intensity_t \times Economic\ impact\ per\ acre_l$$

where LI_t is the land-use impact for technology *t* per MW, $Land\ intensity_t$ is the per MW land requirement for technology *t,* and $Economic\ impact\ per\ acre_l$ is the economic impact per acre for land type calculated in Section C.4.3.

C.4.5. Economic Land-Use Impact per Unit of Electricity Generated

Based on the land-use impact per MW, we use the benchmark plant load factor (PLF) for the RE technologies to arrive at the economic impact per MWh for the technology, $Land\text{-}Use\ Impact_t$.

APPENDIX D: ASSUMPTIONS AND DATA FOR CALCULATIONS

Table D1 | **Technology-Based Assumptions for Economic Rate of Return Calculations**

	UNIT	SOLAR PV—GROUND MOUNT	SOLAR PV— ROOFTOP	WIND	BIOMASS	SMALL HYDRO
Project size	MW	1	1	1	1	1
Lifetime	Years	25	25	25	25	35
Plant load factor	%	19	19	27	70	30
Capital cost/MW	₹	26,200,000	31,015,560	52,500,000	62,220,000	77,900,000
O&M cost	%	2.92	2.92	1.47	6.13	4.16
Annual escalation	%	4.27	4.27	4.27	5.72	5.72
Auxiliary consumption	%	0	0	0	10	1
Residual value	%	10	10	10	10	10
Annual degradation	%	0	0	0	1	0.50
Source		In the absence of national government benchmark costs, we use the latest and most conservative state-level tariff order (among Karnataka, Rajasthan, and Tamil Nadu) KERC 2018; MERC 2018			CERC 2019	

Table D1 | **Technology-Based Assumptions for Economic Rate of Return Calculations (Part 2)**

	IMPACT ASSUMPTIONS							
	PARAMETER	UNIT	BASELINE—COAL	SOLAR PV— GROUND MOUNT	SOLAR PV— ROOFTOP	WIND	BIOMASS	SMALL HYDRO
HEALTH IMPACTS	**Emissions factor of pollutant—current**							
	SO_2	kg/MWh	7.3	0	0	0	0.46	0
	NO_x	kg/MWh	4.8	0	0	0	1.23	0
	$PM_{2.5}$	kg/MWh	0.2953	0	0	0	2.62	0
	Reduction in emissions factor in 2030							
	SO_2	%	95.57	NA	NA	NA	95.57	NA
	NO_x	%	87.50	NA	NA	NA	87.50	NA
	$PM_{2.5}$	%	93.00	NA	NA	NA	93.00	NA
WATER IMPACTS	Water intensity	m^3/MWh	2.59	0.08	0.08	0	1.994	0[a]
LAND-USE IMPACTS	Land-use intensity	ha/MW	0.247	2	0	1.5	1	1.35
LAND-USE PATTERN	Forest land diverted	%	10	0	0	10	10	20
	Agricultural land diverted	%	10	10	0	10	10	10
CLIMATE IMPACTS	GHG emissions factor	tCO_2/MWh	0.81	0	0	0	0	0

Note: [a]. Water use in hydropower generation is normally associated with evaporative losses (consumption) from the reservoirs. As the water for small hydro is used in stream, it does not contribute to water scarcity unless a dam is built, which is more likely in large hydro (great than 25 MW). Hence, it is considered zero.

Source: WRI authors.

Table D2 | Other Assumptions for Impact Calculations

	PARAMETER	UNIT	VALUE	SOURCE
HEALTH IMPACT	Average intake fraction for India (grams of $PM_{2.5}$ per ton of inhaled primary pollutant)			Calculated by **Parry et al. (2014)**, from Carbon Monitoring for Action (CARMA) and LandScan; coefficients from **Zhou et al. (2006)**
	SO_2	gm/ton	3.4196	
	NO_x	gm/ton	2.4812	
	$PM_{2.5}$	gm/ton	4.2666	
	Annual breathing rate	m^3	7,300	Zhou et al. 2006
	Total population above 25 years of age exposed to the pollutant *i* within the boundary		811,424,401	Calculated from UNSTATS and LandScan by Parry et al. (2014), 2018 update numbers
	COEFFICIENT FROM CONCENTRATION-RESPONSE FUNCTION			
	COPD		0.0050	Burnett et al. 2014
	Lung cancer		0.0068	
	Ischemic heart disease		0.0080	
	Stroke		0.0152	
	BASELINE MORTALITY RATE			
	COPD	Deaths/pop.	0.0050	Calculated based on **Burnett et al. 2014**
	Lung cancer	Deaths/pop.	0.0001	
	Ischemic heart disease	Deaths/pop.	0.0023	
	Stroke	Deaths/pop.	0.0019	
	MORALITY RISK VALUE ($)			
	Mortality risk value ($) midrange	US$	305,545.71	Mortality risk value for the Organisation for Economic Co-operation and Development (OECD) (**Parry et al. 2014**) updated to 2017 values, adjusted for India based on **OECD (2012)**
	Morality risk value ($) upper bound	US$	638,428.57	**Majumder and Madheswaran 2018**
	Morality risk value ($) lower bound	US$	90,384.38	Lower-bound and upper-bound estimates from **Cropper et al. (2019)**

Table D2 | Other Assumptions for Impact Calculations (Cont.)

	PARAMETER	UNIT	VALUE	SOURCE
WATER IMPACTS	Value of DALY (\$)	US\$	7,060	GNI per capita, PPP, in current US\$ from the World Bank's **World Development Indicators database**
	Total economic value (TEV) of water	US\$/m^3		Water valuations are sourced from the Natural Capital Declaration's project on integrating water stress into corporate bond credit analyses with a value of 1 disability-adjusted life year (DALY) set to US\$7,060 for India in 2017. Tool accessed from the **Emerging Markets Dialogue on Finance** website.
	2010	US\$/m^3	6.93	
	2020	US\$/m^3	7.08	
	2030	US\$/m^3	7.00	
	2040	US\$/m^3	6.89	
CLIMATE IMPACTS	Discount factor for SCC	%	4.25	**Nordhaus 2017**
	SCC attribution for India based on global output	%	9.41	
	Annual increase in SCC in real value	%	3	
	Country-level SCC for India—Nordhaus (2015 value)	US\$/tCO$_2$	2.9387	
	Country-level SCC for India—Ricke (2020 value)	US\$/tCO$_2$	85.36	**Ricke et al. 2018**
LAND IMPACTS	Annual agricultural income	₹/ha	116,547.73	Weighted average income per unit of land, weighted as per production share
	Social and environmental impacts of forest land diversion	₹/ha	8,555,000	**MoEFCC 2017; Verma et al. 2013**
COAL POWER PLANT SPECIFICATIONS	Station rate ton coal per unit electricity	ton/MWh	0.6282080	Calculated based on **CEA (2018a)**
	Biomass conversion rate	ton/MWh	1.25	**CERC 2019**

Note: COPD = chronic obstructive pulmonary disease; DALY = disability-adjusted life years; GNI = gross national income; SCC = social cost of carbon.

Source: WRI authors.

APPENDIX E: SUMMARY OF IMPACT ESTIMATES

Table E1 | **Summary of Impact Estimates for RE Technologies Considered (2019–2034)**

		2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
HEALTH IMPACTS																	
Solar PV—ground mount	₹/MWh	6,980	6,398	5,815	5,233	4,651	4,068	3,486	2,903	2,321	1,738	1,156	573	573	573	573	573
Solar PV—rooftop	₹/MWh	6,980	6,398	5,815	5,233	4,651	4,068	3,486	2,903	2,321	1,738	1,156	573	573	573	573	573
Wind	₹/MWh	6,980	6,398	5,815	5,233	4,651	4,068	3,486	2,903	2,321	1,738	1,156	573	573	573	573	573
Biomass	₹/MWh	3,022	2,440	1,857	1,275	692	110	-473	-1,055	-1,638	-2,220	310	310	310	310	310	3,022
Small hydro	₹/MWh	6,398	5,815	5,233	4,651	4,068	3,486	2,903	2,321	1,738	1,156	573	573	573	573	573	6,398
WATER IMPACTS																	
Solar PV—ground mount	₹/MWh	1,245	1,243	1,242	1,240	1,239	1,237	1,236	1,234	1,233	1,231	1,230	1,228	1,226	1,224	1,222	1,245
Solar PV—rooftop	₹/MWh	1,245	1,243	1,242	1,240	1,239	1,237	1,236	1,234	1,233	1,231	1,230	1,228	1,226	1,224	1,222	1,245
Wind	₹/MWh	1,284	1,283	1,281	1,280	1,278	1,277	1,275	1,274	1,272	1,271	1,269	1,267	1,265	1,263	1,261	1,284
Biomass	₹/MWh	296	295	295	295	294	294	293	293	293	292	292	292	291	291	290	296
Small hydro	₹/MWh	1,284	1,283	1,281	1,280	1,278	1,277	1,275	1,274	1,272	1,271	1,269	1,267	1,265	1,263	1,261	1,284
LAND IMPACTS																	
Solar PV—ground mount	₹/MW	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769
Solar PV—rooftop	₹/MW	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541
Wind	₹/MW	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942
Biomass	₹/MW	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445
Small hydro	₹/MW	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193
CLIMATE IMPACTS																	
Same for all RE	₹/mwh	193	199	205	211	217	224	231	238	245	252	260	267	275	284	292	193

Table E1 | Summary of Impact Estimates for RE Technologies Considered (2035–2050) (Part 2)

		2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
HEALTH IMPACTS																	
Solar PV—ground mount	₹/MWh	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573
Solar PV—rooftop	₹/MWh	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573
Wind	₹/MWh	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573
Biomass	₹/MWh	310	310	310	310	310	310	310	310	310	310	310	310	310	310	310	310
Small hydro	₹/MWh	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573	573
WATER IMPACTS																	
Solar PV—ground mount	₹/MWh	1,220	1,218	1,216	1,214	1,212	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210
Solar PV—rooftop	₹/MWh	1,220	1,218	1,216	1,214	1,212	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210	1,210
Wind	₹/MWh	1,259	1,257	1,254	1,252	1,250	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248
Biomass	₹/MWh	290	289	289	288	288	287	287	287	287	287	287	287	287	287	287	287
Small hydro	₹/MWh	1,259	1,257	1,254	1,252	1,250	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248	1,248
LAND IMPACTS																	
Solar PV—ground mount	₹/MW	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769	-15,769
Solar PV—rooftop	₹/MW	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541	7,541
Wind	₹/MW	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942	-9,942
Biomass	₹/MW	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445	-6,445
Small hydro	₹/MW	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193	-8,193
CLIMATE IMPACTS																	
Same for all RE	₹/MWh	301	310	319	329	339	349	359	370	381	393	404	417	429	442	455	469

Source: WRI authors.

ENDNOTES

1. Biomass is considered a renewable source only when it does not lead to a decrease in carbon stock. Examples of renewable biomass include scrap lumber, crop residues, rice husk, bagasse from sugar production, and so forth.

2. Only small hydro (less than 25 megawatt, capacity) is considered a renewable source of energy, as per the previous definition by the Ministry of New and Renewable Energy (MNRE). As of March 2019, large hydro (greater than 25 MW) is also considered to be renewable in India.

3. Biomass as defined as organic waste (husk, bagasse, and so on) is considered carbon neutral because it only emits GHGs that it has sequestered during its lifetime and which would also be released if it were left to decompose or otherwise be dumped in landfills or openly burned. Thus, it does not lead to any additional GHGs.

4. Includes power generated from the combustion of agricultural residues, agro-industrial residues and plantations, and urban and industrial wastes. Carbon in biomass returns to the atmosphere in some form regardless of whether it is burned for energy, is allowed to biodegrade naturally, or is lost in a forest fire; hence, it does not lead to GHG emissions.

5. At the time of drafting this paper, small hydro was defined as hydropower projects below 25 MW installed capacity (MNRE, n.d.c). Although large hydropower plants (more than 25 MW) use the renewable power of flowing water, they have large ecological and social impacts due to construction, reservoir creation, river flow diversion, human resettlement, and so forth; hence, they cannot be considered a renewable source of power generation. Small hydro plants are considered renewable because they involve relatively less civil construction work with no or small reservoirs and thus have a relatively low environmental and social impact compared to large hydro. Based on recent measures to promote hydropower, large hydro is now classified as renewable power (Union Cabinet 2019). However, in this paper we retain small hydro (less than 25 MW) as renewable power due to the impacts discussed above.

6. India has recently drafted rules about offshore wind due to its huge expected potential, particularly off the coasts of Gujarat and Tamil Nadu. Yet, while the framework can be used for assessing offshore wind, as of now, we do not have access to any operational or impact data; hence, it was excluded from the current national-level analysis.

7. Conventional coal-fired power plants boil water to generate steam, which activates a turbine. Supercritical and ultra-supercritical power plants operate at temperatures and pressures above the critical point of water, meaning above the temperature and pressure at which the liquid and gas phases of water coexist in equilibrium and there is no difference between water gas and liquid water. This results in higher efficiencies. In supercritical power plants, where temperatures reach 1,000–1,050°F (538–566°C), the turbine speed increases dramatically and requires advanced materials. In ultra-supercritical power plants, temperatures reach 1,400°F (760°C) and pressure levels reach 5,000 psi (340 bar), which allow for even more efficiency.

8. Assuming particulate matter emissions standards are met by 2030 and water-use efficiency is assumed to be that of the top five most water-efficient coal power plants, which are also in compliance with the latest water-use standards. There are no compliance requirements for GHG emissions. See Appendix C and Appendix D for details on the assumptions.

9. The technical lifetime for solar PV, wind, and coal power plants is 25 years. The lifetime for a biomass-based plant is 20 years, and the lifetime for a small hydro plant is 35 years. However, for better comparability with the baseline, the assessment of impacts and ERR is conducted over a period of 25 years.

10. "Climate change can affect human health directly (e.g., impacts of thermal stress, death/injury in floods and storms) and indirectly through changes in the ranges of disease vectors (e.g., mosquitoes), water-borne pathogens, water quality, air quality, and food availability and quality. The actual health impacts will be strongly influenced by local environmental conditions and socio-economic circumstances, and by the range of social, institutional, technological, and behavioural adaptations taken to reduce the full range of threats to health" (IPCC 2001).

11. The analysis presented in this paper estimates ex ante returns that include diverting land for the power installation. However, secondary activities during the installation's lifetime may lead to land diversion due to economic and maintenance activities around the power installation, including paved access roads, commercial establishments, and development near the power plant. Although these are not included in this analysis, it is important to note that such impacts may be significant and, where relevant, must receive due consideration in planning and implementation. Moreover, analyses that broaden the scope of the assessment to upstream and downstream impacts can provide more insights on the indirect impacts from RE power.

12. The SDR reflects society's relative valuation on today's well-being versus future well-being; that is, the SDR is the rate at which the whole of the community/society is willing to trade the current benefit for the future benefit (Palinko and Szabó 2012). The SDR can be interpreted as the minimum rate of return that the government expects from its investments in terms of the social opportunity cost of capital—that is, the rate of return that a decision-maker could earn on a hypothetical "next best alternative" to a public investment or a social rate of time preference approach, meaning the rate of return that a decision-maker requires in order to divert resources from use in the present to a public investment (Creedy and Passi 2018).

13. An intake fraction is the amount of pollutant inhaled by the exposed population compared to the total amount of pollutant emitted, based on the height of the stack, size of the exposed population, meteorological conditions, topography, and ambient ammonia concentrations.

14. These emissions norms are based on notification from the Ministry of Power in 2017. However, due to high technology costs, the level of adoption has been minimal (Srinivasan et al. 2018).

15. Although water may be required for site preparation and construction during the deployment stage, the scope here is limited to the generation phase; hence, the former is not included here.

16. This is a weight that society gives to benefits accruing in period t. Future benefits are valued less than present ones. One rationale for this is that societies prefer the present over the future. Reflecting this rationale, the SDR (s) is called the "social time preference rate" (EIB 2013).

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.