Clean Development Pathways for India: Evaluating Feasibility and Modeling Impact of Policy Options

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Abstract

Sustaining rapid economic growth and satisfying increasing energy demand while limiting greenhouse gas (GHG) emissions is a central challenge in India. Proposed policy solutions should be evaluated according to their impacts on the energy system and the economy to identify efficient policies. I have developed an energy-economic model for India that provides a comprehensive foundation for analyzing energy technologies and policies. This novel model based on a general equilibrium approach simulates the Indian economy, with detailed inter-sectoral linkages, and facilitates an understanding of economy-wide impacts of policies. The model allows for analysis of tradeoffs among different technology and policy choices in terms of their costs and efficiency in GHG emissions reduction.

While comprehensive carbon pricing is arguably the most economically efficient measure for emissions reduction, political considerations often favor technology-specific choices. Support for renewable energy factors prominently in India's climate change mitigation strategy. To study the impact of policies that promote renewable energy, the model represents renewable electricity in detail. Impact of incentives and scale factors are also incorporated in projecting renewables expansion. I simulate India's Nationally Determined Contributions (NDCs) to the Paris Agreement and compare their effectiveness, benchmarking them against the theoretical least-cost alternative of broad-based carbon pricing. Specifically, India's NDCs include targets on non-fossil electricity capacity expansion and CO_2 emissions intensity of GDP (GoI 2015a). This work provides valuable quantitative insights on the impact of these policy measures, and fills a critical knowledge gap in the design and implementation of effective climate policies in India.

My findings suggest that compared to a reference case of no policy constraint, the average cost of reducing a tonne of CO_2 is lowest in a scenario with an emissions intensity target implemented via CO_2 pricing, and more than 43 times higher in the pure non-fossil electricity target scenario. Further, emissions intensity targets result in a 6.3% drop in total electricity demand, as the cost of fossil fuel based electricity increases. As CO_2 emitting electricity sources become more expensive, non-fossil sources - particularly solar and wind - increase in the mix. Enforcing non-fossil electricity capacity targets leads to an additional 15.6% drop in total electricity demand as average electricity prices increase to account for a higher share of costlier non-fossil electricity. Non-fossil electricity capacity targets also result in leakage of emissions to non-electricity energy sectors. The magnitude of differences among these results depends on wind and solar electricity costs. Cheaper costs of wind and solar power lead to lower welfare losses and electricity demand levels that are comparable across scenarios.

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1. Introduction

India stands at a critical juncture in its development path. Economic reforms introduced in 1991 liberalized the domestic economy and opened the country to globalization. India has been the fastest growing of the world's major economies since 2015, when its growth rate surpassed China's, and many projections expect this growth to continue (World Bank 2016). Twenty-five years of strong economic growth have driven up energy consumption, with the electricity base alone quadrupling from 70 GW in 1992 to 272 GW in 2015 (CEA 2015). However, given a large population base and multiple challenges with the expansion of energy supply,[1] large sections of the population still lack access to reliable and clean[2] sources of energy.

India accounts for 18% of the world's population but uses only 6% of the world's primary energy.[3] Nearly 240 million individuals lack access to electricity (IEA 2015). Besides, as of 2012, nearly 76% of rural households depended upon traditional biomass for their cooking needs (Saptarsh 2012). Lack of energy access and poverty are mutually reinforcing – the poor are more likely to remain poor as long as they remain without access to modern energy, a situation termed Energy Poverty.

Satisfying the unmet energy demand as well as fueling the necessary economic growth implies energy consumption would need to rapidly increase in the coming decades. The India Energy Outlook of the International Energy Agency estimates India's energy consumption will more than double to 1900 Mtoe (million tonnes of oil equivalent) by 2040, relative to 2015, accounting for nearly a quarter of the worldwide growth in energy consumption during the period (IEA 2015). A major chunk of proposed growth is likely to occur in the electricity sector, which is expected to more than triple in installed capacity from current 281 GW to 1075 GW in 2040 (roughly equal to the installed capacity in the European Union today, IEA (2015)). Owing to India's large coal reserves, a significant portion of this increase is expected to be from coal based plants.

At the same time, to meet global climate mitigation goals outlined in the 2015 Paris Climate Agreement, every country will need to make significant emissions cuts. India's emission targets submitted in its Nationally Determined Contributions (NDCs) to the 21st Conference of Parties in Paris (COP21) promise

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[1] We discuss these challenges in greater detail in section 2.4, but put briefly, they include poor institutional and financial state of state distribution companies (DISCOMs), incomplete implementation of electricity reforms, low purchasing power of rural consumers, and high transmission and distribution losses etc.

[2] Here, I use clean to refer to sources of energy, primarily for cooking purposes, that do not adversely impact human health. Thus, while using biomass for cooking may qualify as cleaner than gas in terms of its CO_2 emissions, it could be considered "unclean" for its impacts on health.

[3] OECD defines primary energy consumption as "the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process" (United Nations 1997).

a reduction in carbon emissions intensity of GDP by 33 to 35 percent by 2030 from 2005 levels. This will be accompanied by an increase in non-fossil based power to about 40% of cumulative installed capacity in 2030 (GoI 2015a).[4] In 2015, the government increased its solar power installed capacity target for 2022 fivefold from 20 GW to 100 GW. Against current installed capacity of 12.28 GW (as of March 2017 - MNRE (2017)), the ambitions solar target is often seen as an indication of the commitment of India towards clean energy expansion. Simultaneously, India's leaders are also pushing forward reforms in coal mining[5] and aim to expand thermal power capacity, which, on one hand, appears to be at odds with climate commitments, but, on the other, is seen by policymakers as necessary for sustaining economic growth.

This constitutes the essence of what some call the Indian climate dilemma.[6] How does India improve the living standards of its populace and sustain strong economic growth while restricting carbon emissions to minimize the impact on climate change? There are multiple pathways to clean economic growth, each with associated costs and benefits, and comprehensive policies can be designed to suit priorities.

Economic theory suggests that pricing CO_2, either through an emissions tax or a cap-and-trade scheme, is the most efficient policy to mitigate CO_2 emissions (Coase 1960; Stavins 2008; Metcalf & Weisbach 2009). Owing to varied socio-political motivations and constraints, that we discuss later, policymakers however rarely opt for a pure carbon pricing policy[7] and rather pursue a mix of policies including, but not limited to, market mechanisms, regulations, and technology preferences.

Energy forms the foundation of any modern economy and policies affecting energy prices send shocks across the economy, leading to widespread impacts. Putting an appropriate price on CO_2 is expected to account for externalities associated with its release to the atmosphere, thereby increasing the price of fossil fuels and facilitating adoption of relatively expensive non-fossil energy sources.[8] Consequently, pricing CO_2 increases energy prices and the change is reflected in the price of goods and services as well as activity levels across the economy. Pursuing technology-specific policies along with, or independent of, carbon pricing also induces changes in the economy, either through direct increase in energy prices, or through transfers resulting from subsidizing non-fossil energy to keep its prices comparable to fossil energy.

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[4] With the help of transfer of technology and low cost international finance including from the Green Climate Fund (GCF)

[5] India has set a volumetric target to produce 1.5 billion tonnes of coal by 2020 (IEA 2015).

[6] For example, see Down To Earth (2015)

[7] While acknowledging the differences between price based (emissions tax) and quantity based (cap and trade scheme) instruments (Weitzman 1974), I refer to both as carbon pricing for the purpose of this work.

[8] Risking simplicity, I sometimes use non-fossil and renewable energy interchangeably. The usage should be considered in the context. Generally, when speaking about higher costs of non-fossil energy, I am chiefly considering solar and wind power, as the costs of nuclear and hydro power are almost comparable with the cost of fossil energy. Besides, while there is debate about considering nuclear as renewable, my general usage of non-fossil and renewable electricity assumes nuclear to be a renewable source of energy.

India’s energy and climate policies, including the targets proposed in its NDCs, also reflect a mix of alternate policy choices. The emissions intensity targets specify reduction in emissions level, with target stringency a function of GDP growth. These targets can be achieved through multiple policy paths, such as economy-wide emission pricing (through emission taxes or tradable permits),[9] technology standards, efficiency measures, and subsidies for cleaner energy sources etc. In principle, emissions-intensity targets would be pursued most efficiently if the least cost abatement options are adopted first, followed by successively costlier measures. Adopted abatement measures would include not only a shift to cleaner energy sources but also, and perhaps more importantly, energy efficiency measures. Studies suggest improvements in energy efficiency to be the low hanging fruit in CO_2 abatement (McKinsey 2009). In principle, emissions intensity targets are effectively a carbon pricing policy implemented via an emissions quota indexed to GDP growth.

In addition to intensity targets, India’s expansion plans for solar energy represent strong support for technology specific policies. This preference for what is arguably a second best policy option (Lipsey & Lancaster 1956; Bennear & Stavins 2007) is not unique to India. The decision processes favoring such preferences are driven by political-economic considerations emerging from the nature of the problem of climate change, and adaptation pathways favored by different sets of policies. At the same time, picking a winner among different abatement options drives changes in the economy through more restricted channels as compared to pure market based schemes, and may have differing impacts based on the transfer processes associated with subsidizing arguably more expensive measures.

Building off of these ideas and real-world policy scenarios, I develop my thesis in three steps. First, I discuss the problem of climate change along with widely accepted mitigation instruments, and the positioning of these instruments within the political economy challenges imposed by India’s electricity sector. Second, I evaluate India’s climate policy preferences by quantifying their impact on the economy, emissions, and electricity system, within a general equilibrium modeling framework. The development of this modeling capability for India’s climate policy evaluation forms the core of my work and constitutes the majority of this thesis. Third, I complete the analysis by identifying winners and losers under different policies, anticipating the interaction of expanding energy access with climate policies, and discussing implementation challenges within the existing electricity distribution sector of India.

My intent with this structure is to first qualitatively frame the setting of the problem faced by energy and climate policymakers in India. This helps identify the specific quantitative questions I deem important, and also motivates the choice of modeling framework. The utility of a model evaluating policy choices

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[9] We discuss emission taxes and permit trading in detail in Section 2.2.

should be gauged by the relevance of its analysis within the real world policy scenario, and I attempt to reflect that through the model structure and research questions. Finally, policy implementation entails impacts on winners and losers, and policymakers must grapple with these impacts if they wish to establish a level playing field. Expanding energy access while pursuing GHG mitigation policies makes designing effective policies more challenging. Besides, while model outcomes may suggest winning and losing policies based on specified evaluation criteria, actual implementation of policies is constrained (or facilitated) by the institutional setup within which they are enacted. This dictates the final piece of my inquiry where I identify winners and losers, investigate the access question, and discuss implementation challenges for preferred policies.

I briefly discuss these three components below, and expand upon them in the thesis.

1.1. Climate Change, Political Economic Constraints, and India's climate policies

Climate change and its impacts pose a grave challenge to the world as we know it. Developing countries are likely to face the worst impacts, with more frequent extreme weather events, floods and droughts, and shifting crop patterns, among other impacts (IPCC 2014). The threat of extreme impacts of climate change is widely recognized, motivating policy actions for mitigation and adaptation. Economists describe climate change as a problem of multiple market failures, which can be addressed by instituting appropriate policies. These market failures typically include non-accounting of negative externalities of burning fossil fuels (Hoeller & Coppel 1992; Stern 2007), the collective action problem (Olson 1984), and the principal agent problem (Eisenhardt 1989).[10]

Putting an appropriate price on CO_2 and including it in fossil fuel prices is widely argued as the most efficient means of adjusting for climate change induced market failures (Pigou 1920; Pearce 1991; Nordhaus 1992; Stavins 1997). Economic efficiency, however, is but one component of policy design. The nature of the problem of climate change in its temporal and geographical expanse, and widespread impacts of mitigation policies across varied stakeholders, give traction to several political economy constraints that make achieving a "first-best equilibrium"[11] especially challenging (Jenkins 2014; Jenkins & Karplus 2016). For instance, the collective action nature of the problem when combined with differing historical responsibility leads to stakeholders opting for different levels of action, an approach enshrined in the principle of common but differentiated responsibilities (UNFCCC 1992). Alternately, stakeholders with vested interests may seek to capture the process of designing and implementing climate policies (Stigler

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[10] I discuss these in detail in section 2.1.

[11] A first-best equilibrium is Pareto optimal, arising in the absence of any market imperfections or distortions.

1971). In India with its large government owned coal industry, the efforts to influence regulation may not be confined only to private industries.

Jenkins & Karplus (2016) note four important political economy constraints that are widely observed: (1) direct constraint on CO_2 price level, (2) constraint on the increase in final energy price, (3) constraint on decrease in energy consumer surplus, and (4) constraint on decrease in fossil producer surplus. Among these, constraints on final energy price and decrease in consumer surplus could be the primary driving factors behind India's reluctance to implement carbon pricing and subsidization of renewable electricity to keep prices comparable to fossil electricity. In my discussions with the Ministry of Power of India, "affordability" has been cited as one of the three defining dimensions of India's energy policy, along with "access" and "availability". With a GDP per capita (PPP) of US$ 6020 in 2015, India ranks 123 in the world (World Bank 2015b), making affordability of not only energy but also energy intensive goods an important political economic consideration while designing policies.

Arguably, more important than affordability is the dimension of energy access. Nearly 19% of the population of India lacked access to electricity in 2015 (IEA 2015). Opting for aggressive climate policies that impose costs on consumers when a large population lives without modern energy raises ethical concerns.[12] Further, lack of energy access also leads to productivity loss. The cost of productivity loss can be compared with the social and/or private cost of providing electricity to meet that demand. We do not cover this analysis in our present work, beyond acknowledging that energy access remains a cornerstone of energy policy design in India, and arguably the most important driving factor behind India's energy expansion plans.

These political economy constraints on climate change mitigation policies guide my research questions, and inform the modeling structure.

1.2. Analyzing the Impact of India's Climate Policies: A Computable General Equilibrium (CGE) Analysis

The core of this work is based on quantitative analysis of the impacts of India's energy policies using a General Equilibrium framework. In particular, I develop a computable general equilibrium model of the

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[12] By the virtue of its widespread impact, climate change undeniably stirs ethical debates in various forms. For example, Stern (2007) discusses ethical considerations in deciding discount rates for cost-benefit analysis of climate policies. Aggressive climate policies in developing countries with lack of energy access raises similar ethical questions. Is it ethical for the government to cease expansion of cheaper and technologically more reliable thermal power, keeping large portions of current population devoid of modern energy, for benefits accruing to future generations? As political decisions are generally unfavorable towards policies that harm large sections of the public in the short term, the ethical considerations, in essence, lead to political untenability of policies grounded on pure economic efficiency.

Indian economy with detailed representation of key industrial sectors, households, and their economic interlinkages. The general equilibrium structure captures feedbacks to changes in prices as they propagate across sectors in response to policy changes, while simultaneously preserving physical detail in the energy system and associated technologies (Wing 2004). Grounded in economic theory of general equilibrium formalized by Arrow & Debreu (1954), this component of my thesis seeks to evaluate relative impacts of different policy paths, benchmarking them against first best policy option of a comprehensive carbon price, simulated as targets on emissions intensity of the GDP, as stated in India's NDCs.[13] I introduce India's climate policy targets for 2030 as policy shocks and assess the resulting state of the economy, electricity use, and emissions under different scenarios. Benchmarking policy choices against a comprehensive emission intensity target that achieves similar levels of emissions reduction offers insights into relative efficiencies and impacts of different energy policies.

As argued earlier, energy policies lead to energy price adjustments. Owing to its deep integration in multiple industrial, commercial, and residential sectors, changes in energy prices propagate across multiple markets in the economy. By modeling the complete economic structure with underlying interactions, the general equilibrium approach attempts to enable better understanding of inherent complexities, within the limitations of modeling assumptions. Over time, CGE modeling has gained significant traction with climate policy researchers as a quantitatively rigorous tool for generating policy relevant insights.[14]

There exists a significant knowledge gap in quantitative assessment of the impacts of India's climate policies, and particularly of India's NDCs. Prior work either evaluates the impact of India's policies through a global general equilibrium setting (Shukla & Chaturvedi 2012), or is based on old data and strong assumptions about India's energy mix that are not appropriate to inform decision making today (Ojha 2009). This work offers significant improvements on both fronts. Compared to global modeling approaches, modeling India in a single country framework provides greater granularity in specifying country-level details. It facilitates, for instance, disaggregation of India's economy into domestically relevant sectors. Furthermore, I model technology specifications in electricity production in great detail, laying out seven separate electricity sectors embedded in the economy. The representation of renewable electricity sectors displays careful attention to domestic factors guiding their expansion. Reflecting India's ambitious solar targets and impressive cost declines, the model's representation of solar technology includes domestically calculated cost components. Further, I run sensitivity analyses to simulate various wind and solar pricing scenarios. This level of granularity in model specification enables analysis of impacts on energy use in greater detail and helps evaluate policy choices from the perspective of economic efficiency.

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[13] I discuss in section 2.5 how targets on emissions intensity essentially simulate a comprehensive carbon price

[14] See, for instance, the US Global Change Research Program: http://www.globalchange.gov/

1.3. Winners and Losers, and Institutional Challenges to Implementation

Different policy targets lead to differing economic impacts on industrial sectors and consumers, resulting in winners and losers. Policy implementation requires taking into account these stakeholder impacts to ensure level playing field as well as mitigate regulatory capture should powerful interest groups be exposed to negative impacts. Based on modeling outcomes under different policy scenarios and sensitivity analyses, I discuss projected winners and losers, and explore their impact on policy implementation.

Separately, the institutionally and financially weak electricity distribution system of India is widely recognized as the most important bottleneck in improving electricity access and reliability in India (Kumar & Chaterjee 2012; Pargal & Banerjee 2014; IEA 2015). Operationally and financially inefficient utilities have not only constrained electricity growth in India, but also stand to threaten implementation of climate policies. The high aggregate transmission and commercial (AT&C) losses,[15] to the tune of 22.70% in 2013-14 (CEA 2014), lead to huge efficiency losses as utilities do not get paid for more than a fifth of the electricity they supply. Combined with underpricing of tariffs for political purposes, unmetered electricity supply for rural consumers, and cross subsidies for agricultural and rural consumers, it is hardly surprising that state distribution companies (DISCOMs) are perpetually bankrupt and have to be bailed out every few years (Pargal & Banerjee 2014). The latest installment in such bailout schemes – Ujwal DISCOM Assurance Yojana (UDAY - Ministry of Power (2015)) – recognizes that financial turnaround of DISCOMs cannot be achieved without improving operational efficiencies, and takes several initiatives to that effect.[16] Implementation of India's climate policies thus have to take into account the constraint imposed by the institutional setup of electricity sector.

Building on these fundamental blocks, my thesis thus develops through the following sections. In section 2, I establish the context by outlining the problem of climate change, policy solutions, and political economy challenges that constrain efficient policies. In section 3, I specify the choice of method, describe CGE modeling principles, and subsequently delve in the modeling structure for India, policy scenarios, and sensitivity analyses. I present and interpret the modeling outcomes in section 4. Finally, in section 5, I conclude the thesis by discussing the implications of model outcomes on winners and losers, the interaction of declining wind and solar costs with the climate policies, the institutional challenges to climate policy implementation, and the implications of expanding energy access while mitigating GHG emissions.

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[15] AT&C losses in India go beyond traditional transmission and distribution (T&D) losses by also accommodating for losses resulting from theft, non/under-billing, non-payment of bills, and misclassification of subsidized consumers.

[16] Such as demand side management, smart metering, adaptive load shedding protocols etc. We discuss these in more detail in Section 5.

Along with filling critical knowledge gap on rigorous and reliable quantitative analysis of India's energy policy, this work's importance lies in developing a comprehensive foundation for understanding India's energy transition. The complexity of issues discussed earlier, and the growing body of literature on second best policies on mitigating CO_2 emissions, illustrate the importance of going beyond modeling outcomes to acknowledge the role of political economic constraints. Besides, policy recommendations should reflect awareness of institutional mechanisms through which they are to be implemented, and acknowledge the winners and losers. This attempt at understanding the electricity sector of India, its transformation through proposed policies within the institutional structure, and interaction with winning and losing stakeholders is a starting step in this direction, with significant scope for expanding on this research in future work.

2. Context and Literature Review

2.1. Climate Change as Multiple Market Failures

The problem of climate change is a classic example of multiple market failures, creating ground for policy action. A close look at the features of climate change outlines the existence of market failures.

First, burning of fossil fuels generates CO_2, which is the largest contributor to global warming (IPCC 2014). Traditional fossil fuel prices do not account for the externality costs of climate change impacts of GHG emissions (see, for example, Hoeller & Coppel (1992)). A negative externality occurs when the effect of production or consumption of goods and services imposes costs on others which are not accounted in the prices of those goods and services. In the context of climate change, as discussed earlier, the impacts are widespread both temporally and geographically, and affect vast and potentially unsuspecting populations, both in present and in the future (Stern 2007; IPCC 2014). GHG emissions from burning fossil fuels add to the global GHG stock, lead to rising temperatures, and consequently contribute to climate change events that result in multiple costs that should be accounted in the price of fossil fuels. Examples of externalities include loss of life and property in climate change induced extreme weather events, fall in crop yields,[17] and more indirectly, in violent conflicts (IPCC 2014). Besides climate externalities, fossil fuel combustion also adds to environmental pollution. Estimating costs of these externalities is extremely complicated and tedious, and barring carbon pricing policies in certain places,[18] fossil fuel prices have by and large ignored these externalities. In fact, the fossil fuel industry is heavily subsidized in many regions across the world (IMF 2013). Non accounting of these externalities is a major market failure. Termed Social Cost of Carbon, the estimates of these externality costs vary widely.[19] It is argued that if properly accounted, they would raise the price of fossil energy above renewable energy, correcting for the market failure (Epstein et al. 2011).

Second, climate change is a classic collective action problem (Olson 1984) as the effects are spread out across the globe and across multiple generations, while the actions to mitigate and adapt arguably lie with a few disparate institutions and jurisdictions,[20] owing largely to their disproportionate contribution to global

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[17] IPCC (2014) establishes that negative impacts of climate change on crop yields have been more common than positive impacts. Yields of wheat, maize, rice, and soya bean have been negatively impacted across the world.

[18] Examples of countries/regions that have a carbon pricing mechanism in place include certain European nations (Sweden, Switzerland, Norway, Finland, Denmark, France, Portugal etc.), Tokyo, British Columbia, Ireland, California's Cap and Trade, EU ETS (including nations from the previous parenthesis), US north-east's Regional Greenhouse Gas Initiative (RGGI), etc. (Jenkins & Karplus 2016)

[19] A review of literature on Social Cost of Carbon (SCC) suggests a median value of $75 per ton of CO_2, with a central range of $14 to $90, in 2015 USD (Tol 2011; Jenkins & Karplus 2016). The Interagency Working Group of the US government on SCC suggested four different estimates of $12, $43, $65 and $129 in 2007 USD (IAWG 2013). This illustrates the complexity associated with estimating the appropriate SCC.

[20] By institutions and jurisdictions, I mean corporate organizations, governments, multilateral organizations etc.

greenhouse gas stock, and negotiating authority derived from global political structures. Olson (1984) specified that in a collective action problem, each individual entity has little incentive to act as the benefits of the action diminish by spreading out across a larger group, and in the context of climate change, are uncertain and accrue mostly to future generations (Nordhaus 1992; IPCC 2014). IPCC (2014) particularly notes the "continuing uncertainty about the severity and timing of climate-change impacts". That several stakeholders do not see directly perceivable tangible benefits accruing to them makes them reluctant to act. Thus it becomes pertinent to frame policies that drive stakeholders to overcome collective action challenges.

Third, owing to the delayed and distributed impacts of climate mitigation, climate change also poses a classic intergenerational principal agent problem.[21] Eisenhardt (1989) discusses two broad categories of principal agent problem. The first type, agency problem, arises when the desires or goals of the principal and agent conflict and it is difficult or expensive for the principal to verify agent's actual actions. The second type – the problem of risk sharing – arises when the principal and agent have different attitudes toward risk, owing to which they may prefer different actions. It can be argued that risk perception in the present would differ from that of the future generations as they would face more damaging impacts of climate change[22] (IPCC 2014). Thus it is likely that future generations would have demanded stronger climate mitigation efforts than what are in place now.

Economists argue that appropriate policy measures can be adopted to correct for these market failures, particularly to correct for non-accounting of externalities. Putting an appropriate price on carbon is widely acknowledged as the most efficient policy measure to move away from fossil intensive economies.

Notably, studies also suggest that the tradeoffs in balancing climate mitigation with development objectives tend to be more acute in developing economies. Greenstone & Jack (2015) identify four explanations for the poor environmental quality in developing countries, and argue that these challenges may also seriously undermine efforts to limit climate change. The challenges include (1) high marginal utility of consumption, (2) high marginal costs of environmental remediation owing to weaker institutional capacity, (3) political economy and rent seeking behavior, and (4) market failures and behavioral biases.

2.2. Carbon Pricing: Addressing Market Failures of Climate Change

There are several pathways for shifting to a less carbon intensive economy. A broad classification could divide mitigation strategies into policy induced behavioral adaptations and technological modifications. However, this is not a strict classification as policy interventions inevitably interact with, facilitate, or

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[21] In agency theory, the agent is able to make decisions on behalf of, or that impact, the principal.

[22] Strong impacts of climate change are already appearing in certain regions. Bangladesh is at the center of attention for facing existential challenges arising from climate change. Rising sea levels are flooding low lying areas and are expected to inundate 17 percent of the land and displace 18 million people by 2050 (New York Times 2014).

restrict technological modifications. For instance, a policy intervention of carbon pricing may induce behavioral change in consumers to move away from carbon intensive commodities that may become expensive. It may also induce technological modifications in efficiency improvements in fossil electricity production, energy efficiency improvements in electronic devices, and innovations in renewable electricity production technologies.

The pathways towards GHG mitigation adopted by countries are officially reflected in their nationally determined contributions (NDCs) adapted under COP 21. While the objective is to limit global temperature rise to below 2°C, studies argue that the NDCs submitted by member countries do not add up to achieve the target (see, for example, Paltsev et al. (2016)). Jacoby & Chen (2015) discuss several measures, both within and outside the NDC framework, which would be required to limit global emissions growth beyond 2040. These include measures to retire coal fired capacity, improvements in energy efficiency, and reduction in deforestation etc.

Each of these measures have their associated costs. The costs vary significantly across regions and technologies. For instance, it may be more economical to produce the same kilowatt equivalent of solar power in India than in, say, the United Kingdom, owing to India's larger solar endowment. Even within India, geographical distribution of energy resources varies considerably.[23] It is a common concern, though, that most forms of non-fossil energy are expensive than traditional fossil based energy,[24] thus necessitating government support in the forms of subsidies and tax benefits. However, as discussed earlier, a comparison of renewable energy with fossil energy should account for externalities, which significantly add to the cost of fossil energy (see, for example, National Research Council (2000)).

Using taxation to account for externalities has long been recognized as an efficient method. Pigou (1920) is credited for first noting that taxes can help achieve efficiency in the presence of externalities. Pigou argued that negative externalities associated with an economic activity prevent a market economy from reaching an efficient equilibrium, when producers do not internalize all costs of production. If taxes amounting to externalized costs are levied, the negative externality might be corrected. Permit trading is another commonly used instrument in such cases, generally considered as efficient as taxes (Dales 1968). This creates grounds for using price instruments to internalize carbon's externalities.

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[23] Broadly speaking, the coastal southern and western regions are well endowed with wind, the mountains have considerable hydropower potential, and although almost the whole country has high solar potential, the dry western and central states are particularly well suited

[24] Nuclear and Hydro power are exceptions. However, they have constraints of their own, chiefly political, but also environmental, the two constraints being often interlinked.

Economists have for long acknowledged the climate externalities of fossil fuels and have advocated for pricing carbon. Pearce (1991) was among the first to emphasize that the uncertainty, irreversibility, high damage costs, and high joint benefits of climate change would require broad based instruments for climate mitigation. Arguing for a carbon tax and tradeable carbon permits as two potential economic instruments, he noted five advantages of a carbon tax: correcting for the environmental externality, double dividend in gaining cooperation of developing countries by recycling revenues, minimizing compliance costs for industries, continuous incentivizing of adoption of cleaner technology and energy conservation, and adaptation of the tax based on new information.

Several previous studies have evaluated climate policies either quantitatively or theoretically. Nordhaus (1992) used an intertemporal general-equilibrium model of economic growth and climate change to estimate the optimal path for GHG reduction, and found a modest carbon tax to be the most efficient approach. Stavins (1997) suggested that for the US a grandfathered tradable permits scheme in the short run and revenue neutral carbon tax in the long run would be preferable. Internationally, he noted the advantages of a global tradable permit system while acknowledging that no existing institution could run this system. Quite presciently, Stavins contended that the strength of "domestic political barriers" should not be underestimated in hindering the theoretical advantages of carbon pricing mechanisms. More recently, in a widely discussed study, Stern (2007) argued for a carbon price as an "essential foundation for climate-change policy", and discussed establishing a common global carbon price. Metcalf & Weisbach (2009) discussed designing a GHG emissions tax for the United States and argued for adjustments to income tax to ensure revenue and distribution neutrality.

In the economic modeling approach taken in this study, the two widely accepted pricing instruments of tax and permit trading are functionally equivalent.[25] Importantly, in a general equilibrium modeling framework, an emissions intensity target essentially represents a permit trading regime with emission levels indexed to economic output. An emissions intensity target will be most efficient if it is implemented along a marginal abatement cost curve, and a CGE modeling framework enables implementing emissions intensity target in this manner.

How does carbon pricing work? Assume an upstream carbon tax applied to three fossil fuels (coal, petroleum, and natural gas) at their entry in the economy (Aldy & Stavins 2012). As the fuel suppliers, essentially coal mining and upstream oil and gas companies, face a tax, they would raise the price at which they supply fuel to the market. This price increase will propagate through the energy system, and incentivize

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[25] Weitzman (1974) is widely considered a seminal work on deciding between price versus quantity instruments when political considerations or market failure necessitate government intervention. For other discussion on instrument preference, see Aldy & Stavins (2012), (Metcalf 2007), Parry & Pizer (2007), Pizer (2002).

shifts to low carbon technologies and investments in energy efficiency improvements. To be cost effective, the tax should cover all sources of fossil fuel production. Besides, to achieve efficient outcomes, the tax rate should be set equal to marginal benefits of emission reduction as represented by estimates of the SCC (Aldy & Stavins 2012; IAWG 2013).

Thus an appropriate carbon price can correct for externality costs of fossil consumption. Further, a carbon price may also partly address the collective action problem, but the interaction is complex. In the absence of a carbon price, energy producers and consumers have little incentive to shift away from a fossil base, as the transition costs would be direct but the mitigation benefits widespread and disparate. An appropriate carbon price would be expected to make fossil energy more expensive than non-fossil, directly incentivizing energy consumers to shift base. Falling demand and price competitiveness would also make production of fossil energy less profitable, incentivizing a shift on the supply side. However, the immediate costs of high fossil energy prices on consumers and declining profits for large concentrated producers make it difficult to introduce a carbon price in the first place.

While the efficiency of a carbon price in addressing multiple market failures is well established, actual climate mitigation policies shy away from price instruments and rather include a multitude of technology and policy interventions.[26] Even where carbon pricing exists, the prices are typically far lower than price estimates required to fully internalize the marginal cost of climate change. Jenkins & Karplus (2016) explain the remarkable lack of support for widespread carbon pricing by citing political economy constraints. A discussion of political economic factors influencing climate policies is important for this thesis as India, too, has a patchwork of diverse climate policies instead of an economy-wide carbon tax.

2.3. Political Economy Constraints on Carbon Pricing: Rationale for Multiple Policy Instruments

One rationale for existence of multiple policies on GHG mitigation stems from the theory of the second best which concerns with the non-attainment of a Pareto optimal outcome in a general equilibrium system, owing to the presence of one or more constraints (Lipsey & Lancaster 1956). In the presence of these constraints, the attainment of other Pareto optimal conditions is no longer necessarily welfare improving. Stated differently, if multiple constraints prevent the fulfillment of multiple Pareto optimum conditions, removing one of the constraints is not necessarily welfare improving. The implication of second best theory for climate change originates from the presence of multiple market failures that hinder Pareto optimum outcomes of carbon pricing.

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[26] See Stavins (1997) for detailed discussion on policy instruments.

Initial studies into the implication of the theory of second best for climate change looked at the interaction between existing “distortionary” labor and capital taxes and a carbon pricing scheme. Goulder et al. (1999) examine the second best setting of the effect of pre-existing distortionary factor taxes on multiple climate policy instruments, including carbon tax, technology mandates, performance standards, and fuel taxes. Particularly on carbon tax, they discuss two opposing welfare effects. First, carbon tax raises the prices of goods compared to leisure, compounding the factor-market distortions of pre-existing taxes. This negative welfare impact is termed “tax-interaction effect”. Second, the tax revenues can be recycled through cuts in marginal tax rates to reduce the distortions caused by pre-existing taxes. This results in a positive welfare effect, termed “revenue-recycling effect”. Using analytical and numerical general equilibrium models, they find that pre-existing taxes raise the cost of abatement under each instruments, relative to the cost in no-prior-tax world. The tax interaction effect is partly offset by revenue recycling, but overall impact is an increase in abatement costs.

In a similar analysis, Parry & Williams (1999) employ a numerical general equilibrium model in a second best setting with distortionary labor taxes, and compare costs of alternative carbon emissions mitigation policies. The specific instruments they analyze include a carbon tax, two energy taxes, and narrow based and broad based emissions permits and performance standards. Similar to Goulder et al. (1999), they find that pre-existing taxes raise costs of these instruments. In particular, they establish that the efficiency of carbon pricing instruments (both taxes and permit trading) in a second best setting depends on the extent of revenue recycling.

Bennear & Stavins (2007) offer theoretical justification for supporting a mix of policy instruments in a second best setting. They contend that the existence of multiple market failures in a second best world leads to constraints on the general equilibrium setting that justify policy coordination and use of multiple instruments on economic grounds. As environmental policies are usually executed in second best settings, employing multiple policy instruments may be justified. However, the authors note that there is little clarity on whether the actual mixes of implemented instruments are the economically efficient ones.

Jenkins (2014) formalizes certain key political economy constraints that bind climate policymaking and create “opportunity space” for combining policy instruments to achieve a second best optimum. In particular, Jenkins (2014) notes political economy constraints influencing producer and consumer behavior. On the producer side, industrial sectors with high asset specificity would likely oppose instruments that may require moving the assets (Murphy 2002). Insofar as policy instruments affect a concentrated group of economic agents (for example, large industries), regulatory capture for serving vested interests is likely (Stigler 1971). On the consumer end, as discussed earlier, collective action and principal agent problems pose constraints on implementing an appropriate carbon price that reflects the true social cost of carbon.

Certain recent works offer quantitative evidence suggesting that a sub-optimal mix of technology and pricing policies can keep ambitious emissions targets within reach. Bertram et al. (2015) employ an integrated energy-economy-climate model to analyze a mix of three policies: (1) a carbon price starting at US$7 per tonne of CO_2 in 2015 (significantly lower than the authors' quoted optimal carbon price falling between US$16 – US$73 per ton), (2) support for low-carbon technologies, and (3) a moratorium on new coal based power plants. While this policy mix is sub-optimal in achieving emissions reduction as compared to the optimal comprehensive carbon price, it is politically more palatable. They find that such a policy mix limits efficiency losses and lowers distributional impacts, while also building on policies already implemented in several countries, enhancing its political feasibility compared to a comprehensive carbon price.

Jenkins & Karplus (2016) employ a stylized partial equilibrium model of energy sector to study welfare impacts of combining carbon pricing with revenue recycling to address political economic constraints. They evaluate recycling carbon pricing revenues to subsidize clean energy and offset welfare loss of both producers and consumers, and find that this may lead to optimal first best carbon price levels. This suggests that a comprehensive policy package that accommodates interests of disparate stakeholder groups may be preferable, as it allows achievement of an optimal carbon price at lower welfare losses to specific groups or interests, motivating our analysis of alternative policy instruments.

As we would see in the next section, India offers additional unique political economic challenges along with the ones discussed so far. While this explains the patchwork of energy and climate policies, the arguments above suggest that any analysis of India's energy policies should give serious consideration to political economy, and not restrain itself to a study only of theoretically optimal carbon pricing.

2.4. India: Economy, Electricity Sector, and Access Issues

India is the second most populous country in the world, with a population of 1.252 billion as of 2013. A GDP of US $7.998 trillion (purchasing power parity) makes India the third largest economy in the world (World Bank 2015c). However, given the large population, GDP per capita (PPP) falls to US $6,101, putting India at 123rd position internationally (World Bank 2015b). The Indian economy is largely constituted of services sector (59%), followed by industry (27%) and agriculture and allied sectors (14%) (Planning Commission 2014). Among industries, certain energy intensive sectors within manufacturing are important contributors. In particular, iron and steel, cement, and petroleum and petrochemicals are major contributors to industrial output.

As of October 31, 2016, India had a total installed power generation capacity of 307.278 GW, fourth largest in the world after China, USA, and Japan. In recent years, the generation capacity has grown impressively, averaging 6.5% per year between 2009 and 2015. At the same time, due to significant existing unmet demand as well as rapid increase in demand, capacity additions have not been able to bridge the gap between requirement and availability, leading to supply being 2.1% short of demand, in financial year April-2015 to March-2016 (CEA 2016). Besides, this does not include the lack of access to electricity to a large section of the population. The actual shortfall could thus be significantly larger.

2.4.1. Electricity Production Mix

The electricity production mix is dominated by coal, followed by hydropower and renewables (**Figure 1**). While the installed capacity of coal is 61%, it had a 75.6% share in actual generation, compensating for the low plant load factors of hydropower and renewables (CEA 2015). India's electricity targets reflect a strong commitment to renewables going forward. India's NDCs submitted to COP21 note that 40% of installed electricity capacity in 2030 would be through non-fossil sources (GoI 2015a). Besides, the National Solar Mission of India targets expanding solar base to 100GW by 2022 (from current capacity of 12.288 GW, as of March 2017). These policy targets reflect strong commitment to technology specific choices for climate mitigation and must be considered in the analysis of India's energy policies.

2.4.2. Transmission, Distribution, and Commercial Losses

A major problem with Indian electricity sector is the extremely high losses between source and sink. The Transmission and Distribution (T&D) losses amounted to 23% of electricity generated in FY 2012-13 as compared to 6% in the US and 8.1% worldwide (CEA 2015). Further, India also estimates Aggregate Transmission and Commercial (AT&C) losses, mainly accommodating for losses resulting from theft, non/under-billing, non-payment of bills, and misclassification of consumers in the subsidized category. The AT&C losses were 25% in 2012-13 (CEA 2015). For comparison, India's AT&C losses amounted to 31% in FY2010-11 as compared with South Korea (4%), Japan (5%), Brazil (17%), China (5%), and Indonesia (10%). The total losses are estimated to be about 1.5% of India's GDP (IEA 2012). These losses distort the complete value chain of electricity and are considered a major bottleneck in expanding electricity access. I argue in section 5.3, how these operational challenges not only make the electricity sector highly inefficient, but may also hinder implementation of climate policies.

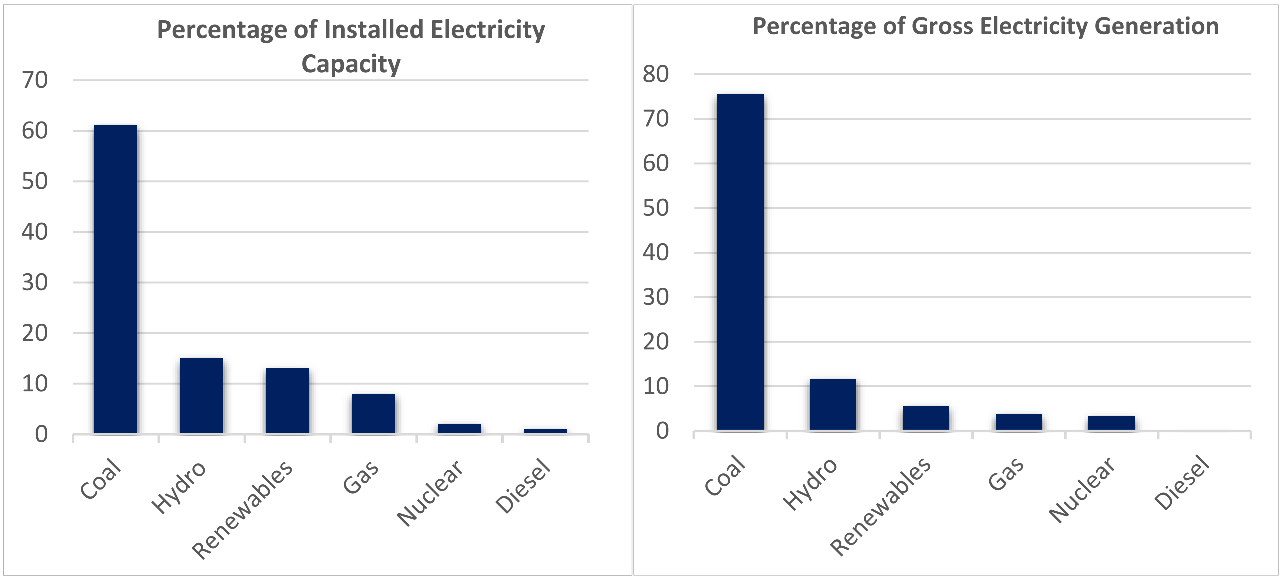

Figure 1*: India Energy Mix as of 31-March-2015 (CEA 2015)*

2.4.3. Growth Projections

The growth projections published by the International Energy Agency (IEA) under New Policies Scenario (NPS) point to sustained increase in India's energy demand. The New Policies Scenario take into consideration policy commitments and plans of governments, and not necessarily the existing capability to enact those plans (IEA Website). IEA forecasts that electricity demand in India would rise by an average of 4.9% per year, and would more than triple from 900 TWh in 2013 to almost 3300 TWh by 2040. Further, India would account for almost 17% of the increase in global electricity demand in this period, an amount that's "roughly equivalent to today's power consumption in Japan, Middle East and Africa combined". Although per capita consumption will reach more than 2000 kWh per year, it would still remain well below the world average in 2040. The unmet demand in electricity, which IEA roughly estimates to be equal to the current load shedding, is expected to disappear by mid-2020s. However, this may not be a good estimate, given the low rural electricity access discussed later. Overall, the increase in demand of various sectors over the projection period is shown in **Figure 2** below.

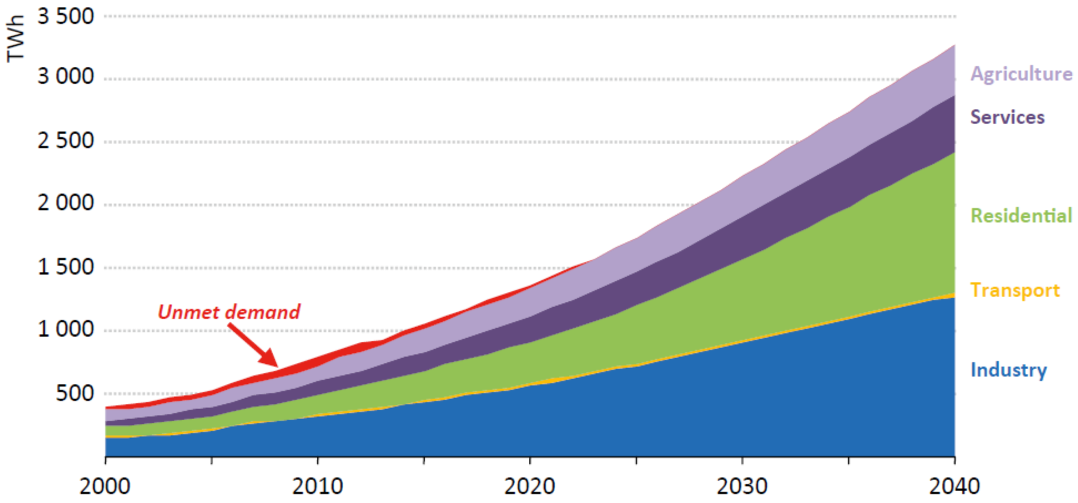

***Figure 2**: Electricity Demand by Sector in India in the New Policies Scenario. Source: IEA India Energy Outlook - World Energy Outlook Special Report 2015*

IEA (2015) forecasts that India would make impressive progress in energy access reaching universal urban energy access by mid-2020s. However, there would still be nearly 60 million people in rural areas without electricity in 2030 (**Figure 3**). Given the poor financial condition of state DISCOMs, which are responsible for building rural distribution networks, and also the difficulty in recovering costs of rural electricity consumption (Maithani & Gupta 2015), universal access would continue to be a challenge.

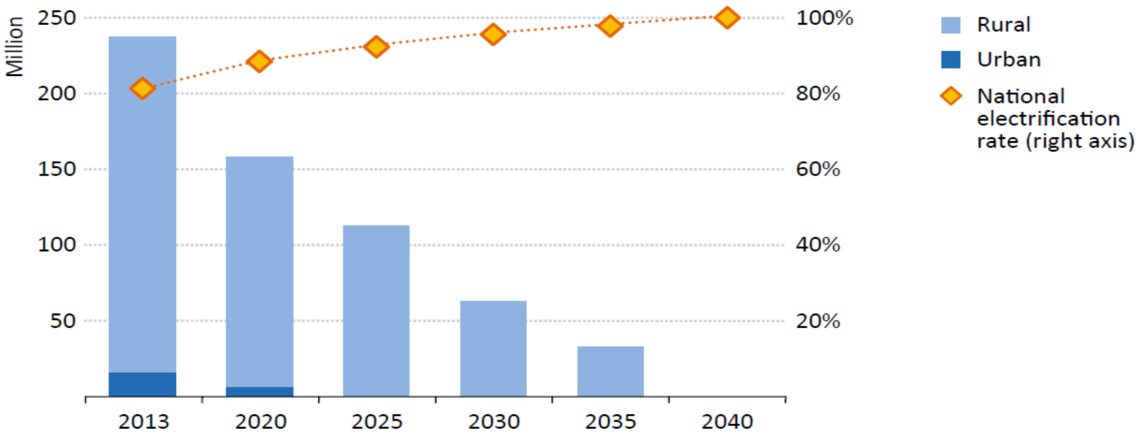

***Figure 3**: Population without access to electricity and electrification rate in India in the New Policies Scenario. Source: IEA India Energy Outlook - World Energy Outlook Special Report 2015*

The projected demand increase corresponds with projected increase in capacity, expected to grow from current 281 GW to 1075 GW in 2040, which is roughly equal to the current installed capacity in European Union. Further, coal will continue to dominate, reaching almost 440 GW by 2040, and possibly making India the second largest coal fleet country after China.

2.4.4. Electricity Act of 2003

The electricity sector in India has historically been plagued by several institutional problems that curtailed expansion. Electricity falls under concurrent subjects in India's constitution, with shared power between central and state governments, further complicating reforms. Nevertheless, a widely recognized need for strong institutional reforms lead to the Electricity Act of 2003 that aimed to make electricity sector competitive, transparent, investor-friendly and consumer-centric (Kumar & Chaterjee 2012). Certain major reforms included:

- Unbundling the monopolies of State Electricity Boards in separate generation, transmission, and distribution companies[27]
- Delicensing of generation and complete freedom and open access for captive generation
- Introducing competition in the distribution sector by the provision of multiple distribution licensees in the same area
- Institutionalizing short term electricity markets and trading
- Introducing Tariff Policy in 2006 with several forward looking changes, such as: procuring generation capacity and transmission services from the private sector only through tariff based competitive bidding, preferential tariff for renewable generation, reduction in cross subsidization of agricultural and rural consumers through industrial consumers

These reforms have arguably made the electricity sector competitive and lucrative to the private sector, particularly in generation. The share of private power generation has been steadily rising, reaching nearly 40% in 2014 (**Figure 4**). Besides, almost all investment in renewables in India over the previous decade, particularly in wind and solar, has been private (Kumar & Chaterjee 2012). Several targeted policies, such as renewable purchase obligations (RPOs),[28] renewable energy certificates (RECs),[29] along with subsidies and other forms of transfers are in place to facilitate investment in renewables. As last mile connectivity, especially in remote rural areas, continues to be challenging, standalone systems and microgrids have gained traction along with relevant support policies (Maithani & Gupta 2015).

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[27] The unbundling has arguably been ineffective in several states which have formed holding companies with complete control and common management over the transmission as well as distribution utilities (Kumar & Chaterjee 2012).

[28] RPOs aim to increase the demand for renewable energy by obligating distribution utilities to procure a percent of their electricity from renewable sources.

[29] REC mechanism aims to account for the differences in renewable capacities of the states, and consequently, their differing abilities and costs to decide and achieve renewable purchase obligations. RECs provide a market mechanism to overcome "geographical constraint of renewable energy resources" (Kumar & Chaterjee 2012).

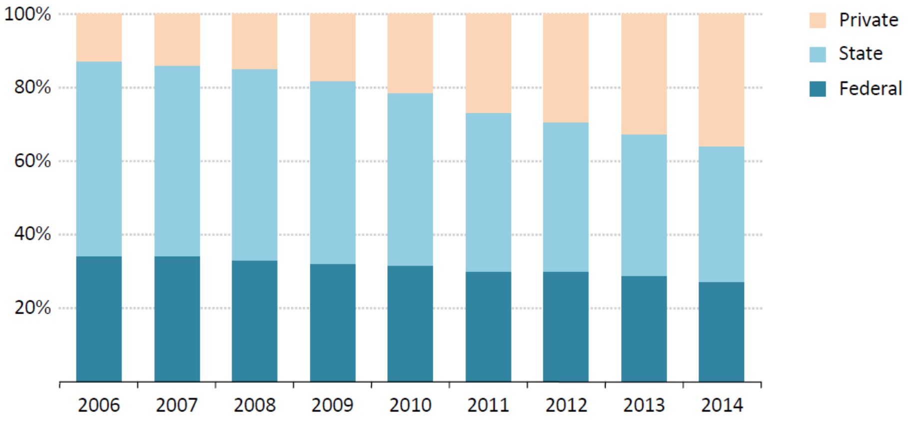

Figure 4: *Power generation capacity by type of ownership in India*

2.4.5. Low Electricity Access and Per Capita Consumption

An important energy policy challenge in India is the low levels of electricity access, particularly in rural areas. Several schemes over previous decades have focused on 100% rural electrification, always missing the target. While around 95% of the villages nationwide have been 'electrified', the weak definition of electrification can be misleading.[30] A better indicator is percentage of electrified rural households, which is as poor as 10% in Bihar and 24% in Uttar Pradesh. The total number of individuals without electricity access in 2015 was 240 million (IEA 2015).

Besides, while supporting around 16 per cent of the world population, India's share in world electricity consumption is only 3.5 per cent (Maithani & Gupta 2015). This reflects in low annual per capita consumption of 1010 kWh, which is a third of world's average (CEA 2015). Wide disparities between states in India lead to varying per capita consumption across the country. Owing to the differences in demographics, income levels, resource and industrial base, and also due to electricity being a concurrent subject with responsibility shared between central and state governments, these disparities are striking and important. For instance, **Figure 5** shows the variations in per capita residential electricity consumption across states. The annual per capita consumption of nearly 50 kWh in Bihar amounts to an average household use of a fan, a mobile telephone, and two compact fluorescent lamps for less than five hours per day (IEA 2015).

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[30] A village is said to be electrified when "basic infrastructure is provided to the inhabited locality as well as the dalit basti/hamlet, electricity is provided to public places, and at least 10 per cent of the total number of households are electrified" (Maithani & Gupta 2015).

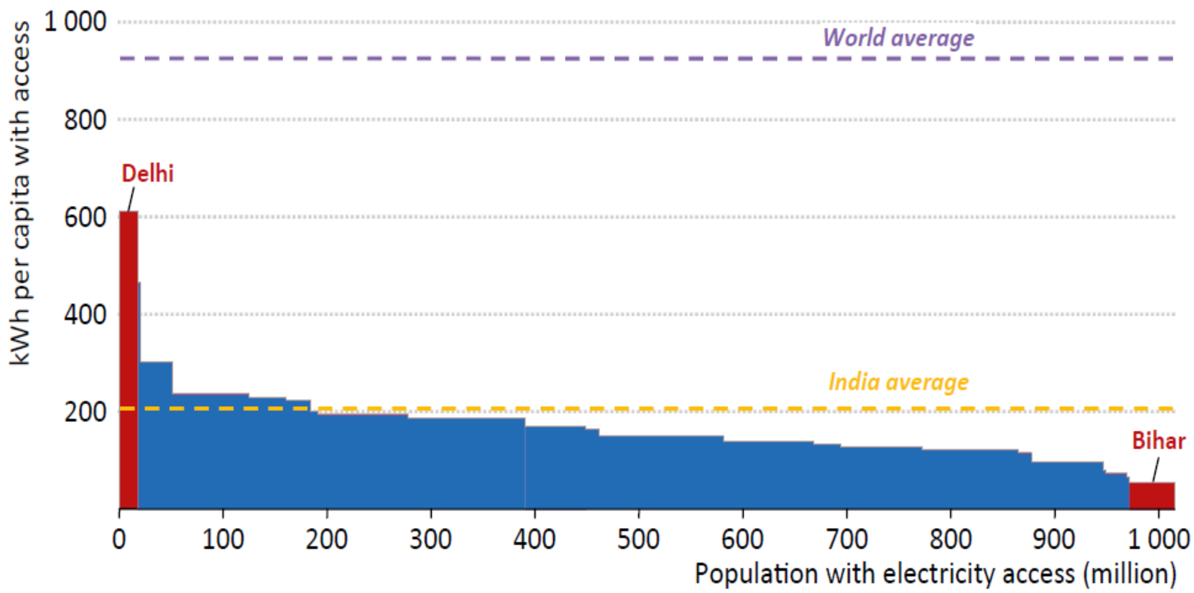

***Figure 5**: Annual **residential** electricity consumption per capita by state in India (for those with access), 2013. Source: IEA India Energy Outlook - World Energy Outlook Special Report 2015*

The gap between demand and supply discussed earlier, coupled with low levels of rural energy access, and significantly low per capita consumption point to tremendous growth potential for the electricity sector. Indeed, expanding electricity base and providing 100% electricity access is among the key policy priorities of the current government of India (Economic Times 2014).

2.5. Three Dimensions of India's Climate Policy Setup: Foundation of this Thesis

My analysis of India's climate policies is thus based on following three dimensions:

1) India's electricity base would see rapid growth with a strong policy mandate for renewables. This sector specific support is a classic example of technology-specific policy mandates. An evaluation of the impact of India's energy policy choices should pay special attention to the growth of renewables and its penetration in the electricity mix. Ambitious renewable targets motivate my study of the impacts of subsidies and other renewable support policies.
2) The NDCs of India promise a reduction in carbon emissions intensity of GDP by 33 to 35 percent by 2030 from 2005 levels. In principle, if this reduction spans all energy consuming sectors and follows the marginal abatement cost path, it is equivalent to an economy wide emissions permit trading mechanism. Thus, the emission intensity target allows for an actual benchmark of the optimal policy against which politically feasible alternatives such as pure technology instruments or a mix of technology and pricing instruments can be compared. Such a comparison would require representing the complete economy of India with detailed inter-sectoral linkages. As discussed in

the next section, a computable general equilibrium setting offers important advantages for such analysis.

3) Policy preferences inevitably lead to choosing tradeoffs in their impacts. India’s preference for non-fossil electricity targets over economy wide climate policies may reflect the distribution of impacts under these two policies. Besides, certain key institutional challenges in the electricity sector of India pose barriers to implementation of the ambitious non-fossil electricity targets. While the modeling exercise provides important quantitative insights on impacts of India’s climate policies, the implementation needs to be considered within these challenges and political economy factors. The conclusion of this thesis attempts to identify some of these constraints and proposes potential solutions.

3. Methodology

3.1. Computable General Equilibrium Analysis: Theory and Examples

I use a CGE model because of its ability to represent the complete economic structure, including the energy sector, with detailed inter-sectoral linkages: this enables capturing feedback loops as the economy adjusts to simulated policy shocks. Policy instruments targeting the energy system alter energy prices. As energy systems are deeply embedded within the economy, changes in energy prices are transmitted across multiple markets. For instance, an increase in the coal price due to a carbon tax will increase coal based electricity prices. Higher electricity prices shall increase the cost of production of steel and aluminum, as electricity is an important input to these industries. An increase in steel and aluminum prices shall propagate across several sectors of the economy, such as manufacturing, automobiles, and infrastructure, to name a few, and will eventually lead to increase in the prices of several commodities.

This highly stylized example illustrates the complexity associated with understanding the propagation of impacts of changing energy prices across the economy. Partial equilibrium approaches that consider the energy system separate from the rest of the economy fail to capture the feedback effects of varying energy prices. General equilibrium modeling approach attempts to enable a better understanding of these underlying feedbacks and complexities, within the limitations of modeling assumptions.

At its core, CGE modeling simulates the general equilibrium structure of an economy. This structure represents interactions between three agents: households, firms, and the government (see **Figure 6**). Households and firms primarily interact and transact through product and factor markets, while government collects taxes, provides certain goods, services, subsidies, and transfers. The functions of the agents are discussed below (based primarily on the MIT Economic Projection and Policy Analysis (EPPA) Model; see Chen et al. (2015)).

Households

Households are the owners of primary factors of production, chiefly labor, capital and natural resources. They provide factors to firms for production and receive income in return. For instance, households provide labor to firms and receive wages. Households also receive income from capital earnings, resource rents, and transfers from the government, and pay taxes to the government.

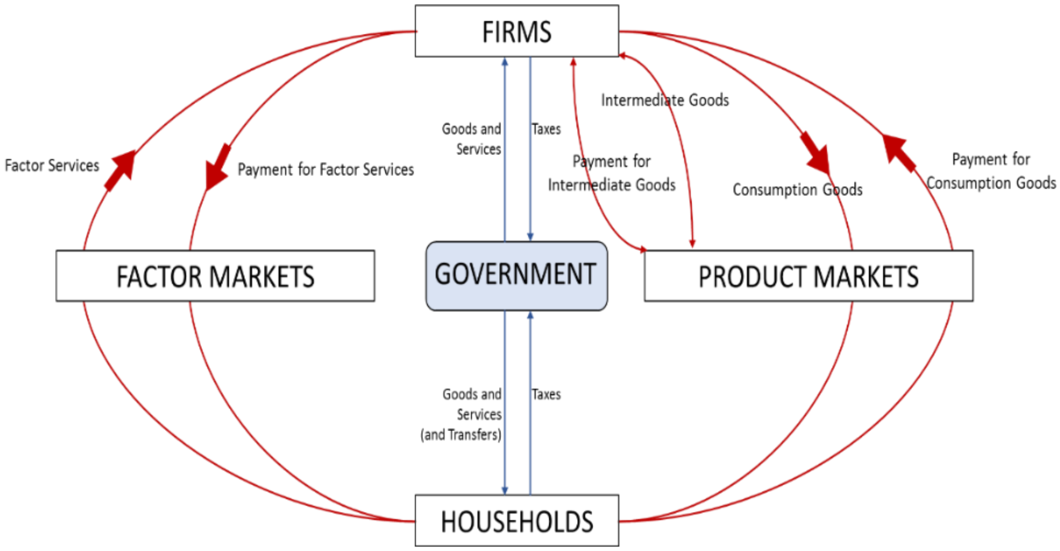

Figure 6*: Basic Structure of a CGE Model*

Firms

Firms transform primary factors and intermediate inputs into goods and services. They buy primary factors from households and intermediate goods from other firms, and sell goods and services to other domestic or foreign firms, households, and to governments. The production function of firms describes the possibilities of substitution both between intermediate goods and factors of production and within themselves. Generally, the production functions are modeled as nested Constant Elasticity of Substitution (CES) functions, and thus exhibit constant returns to scale (CRTS), implying that a doubling of all inputs would lead to doubling of outputs. See **Figure 7** as an example of a typical nesting structure.

Government

The government is a passive entity that collects taxes from households and producers to finance government consumption and transfers.

The activities of these agents and their interactions are defined by the following three conditions, primarily based on the Walrasian general equilibrium theory formalized by Arrow and Debreu (Arrow & Debreu 1954; Wing 2004):

1. Zero profit conditions represent the cost-benefit analyses for economic activities of the agents. Output and utility constitute the economic activity for firms and households respectively. Thus, in equilibrium, and under the assumption of perfect competition, the zero profit condition for a firm would imply marginal cost of production (MC) being equal to the marginal benefit (MB).

2. Market clearing conditions decide the equilibrium price levels that equalize supply and demand across all markets, reflecting Walrasian market clearing.
3. Income balance conditions decide the income levels of households and governments necessary to provide for their spending.

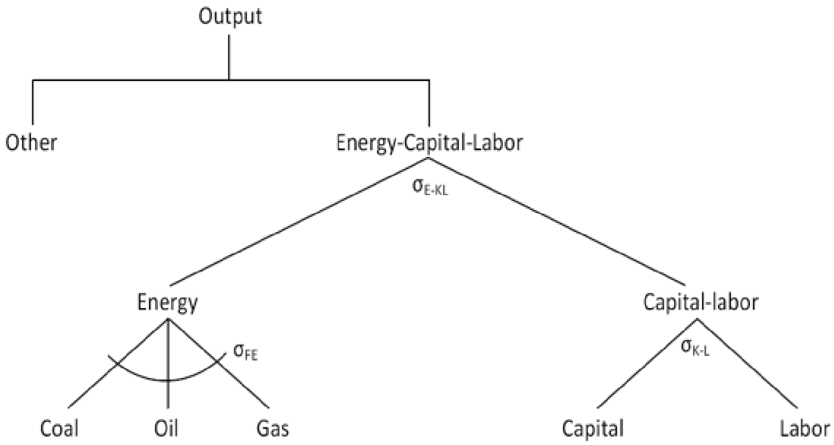

Figure 7*: Nesting structure for fossil based electricity generation in EPPA. (Chen et al, 2015)*

3.2. Equations governing a typical CGE model

The behavior of agents are specified by the following sets of equations:[31]

Firm behavior: Minimize production cost subject to zero profit condition

Minimize $\sum_{f=1}^{F} \boldsymbol{r_f K_{fi}} + \sum_{j=1}^{N} \boldsymbol{a_{ij} p_j}$ … (1)

subject to $Y_i = Y_i\,(Y_1, \ldots, Y_N, K_1, \ldots, K_F)$

⇨ $K_{fi} = K_{fi}\,(r_1, \ldots, p_F, Y)$ *(FxN equations)*

and $k_{fi} = K_{fi}\,Y_i = k_{fi}\,(r_1, \ldots, p_F)$ *(FxN equations)*

where r_f is the price of factor F,

K_{fi} *is* demand for factor f ($f = 1, \ldots, F$) by firm i,

a_{ij} is the input requirement of j per unit of good i

Y_i is the output of firm i,

k_{fi} is the unit factor demand function for factor f by firm i

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[31] Source: Winchester (2012): can be requested from the author.

Consumer behavior: Maximize utility subject to income constraint

Maximize $\boldsymbol{U = (C_1, \dots, C_N)}$ … (2)

subject to $\sum_{i=1}^{N} p_i C_i = M$

$\Rightarrow C_i = C_i\,(p_1, \dots, p_N, M)$ *(N equations)*

where C_i is demand for product i ($i = 1, \dots, N$),

p_i is the price of product i, and

M is consumer income

Under equilibrium, the following conditions hold:

Zero profit conditions

$$p_i = \sum_{f=1}^{F} r_f K_{fi} + \sum_{j=1}^{N} a_{ij} p_j \qquad \dots (3) \; \textit{(N equations)}$$

Consumer income

$$M = \sum_{f=1}^{F} r_f K_f{}^{*} \qquad \dots (4) \; \textit{(1 equation)}$$

Product market clearing

$$Y_i = C_i + \sum_{j=1}^{N} a_{ij} p_j \qquad \dots (5) \; \textit{(N equations)}$$

Factor market clearing

$$K_f{}^{*} = \sum_{i=1}^{N} K_{fi} \qquad \dots (6) \; \textit{(F equations)}$$

where *$K_f{}^{*}$ is the endowment of factor f*

Production and utility functions are usually described as constant elasticity of substitution (CES) functions. In calibrated share form (Rutherford 2002), a typical CES production function for commodity Y can be specified as below (for the sake of simplicity, the equation describes a commodity produced using only factors, and not intermediate inputs, although the functional form can be easily extended to include intermediate inputs as well):

$$Y = \bar{Y}\left(\sum_{f=1}^{F} \theta_f K_f^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \qquad \dots (7)$$

Where $\theta_f = \frac{(\bar{r}_f \bar{K}_f)}{\sum_{f=1}^{F} \bar{r}_f \bar{K}_f}$ (cost share of factor f)

$\bar{Y}$ is benchmark value of commodity Y σ is the elasticity of substitution between different factors of production

A model of the economy based on the structure described above is numerically calibrated using benchmark data form the target economy. For CGE analysis, benchmark data is usually represented through a Social Accounting Matrix (SAM). Generally speaking, a SAM represents a snapshot of inter-industry and inter-activity equilibrium flows of value (quantity times price) within an economy over a benchmark period (Wing 2004). It is composed of input-output accounts denominated in value units, typically in the currency of the benchmark year. Each cell represents the payment from the column account to the row account. Thus, for each account, its income from sales of commodity/factor appears along its row while the expenditure on purchase of inputs appears along its column (see **Appendix A**: Illustrative Social Accounting Matrix (SAM)).

For most of the Global and Domestic CGE Models, the underlying data is obtained from Global Trade Analysis Project (GTAP). Maintained by the Department of Agricultural Economics at Purdue University, the GTAP database combines detailed bilateral trade, transport and protection data characterizing economic linkages among regions, together with individual country input-output data bases which account for inter-sectoral linkages within regions (Aguiar et al. 2016; Peters 2016).

Beyond the parameters specified through the benchmark data, certain parameters, such as elasticities, have to be specified exogenously. Once baseline equilibrium has been established with the benchmark data, policy changes can be introduced in the model, and counterfactual equilibriums can be observed for new policies. The changes in prices, activity levels, income levels, and demands etc., in the new equilibrium over the baseline equilibrium specify the policy impact, subject to limitations of modeling assumptions (Wing 2004). For example, a carbon tax could be simulated by specifying tax rates on consumption of fossil fuels. Resulting changes in the equilibrium consumption of various quantities, household income, etc., could be compared to baseline values to estimate the impact of the tax.

Application of CGE Modeling for climate policy analysis could be global or confined to specific regions, depending on various factors such as the purpose of the model, required granularity, scope, and so on. The MIT Economic Projection and Policy Analysis (EPPA) model is illustrative of an elaborate global CGE model that has been applied to study policy impacts on the economy and emissions, as well as environmental feedbacks on the economy through human health and agricultural productivity (Chen et al. 2015). The latest version of the model, EPPA6-L (L denotes “light”), is a multi-region and multi-sector recursive dynamic CGE model. Recursive approach involves determination of consumption, production, savings, and investment by current period prices, and provides savings plus capital remaining from previous periods as the capital for next period's production. The model is solved at 5 year intervals from 2010 to 2100 and provides details on GHGs, aerosols, and other air pollutant emissions from human activities.

An illustration of applying CGE modeling for country specific analysis includes the China Regional Energy Model (C-REM) of the Massachusetts Institute of Technology (Zhang et al. 2013). C-REM is a multi-commodity, multi-region static numerical general equilibrium model of the world economy with representation of China's 31 provinces. Illustrative applications of the model include simulation of emissions intensity constraint in different regions of China (Zhang et al. 2013), and evaluation of the impact of a national carbon constraint on regional transportation demand in China (Kishimoto et al. 2014).

3.3. Prior CGE Analysis for India

Prior CGE work on India involves application of both global and regional models. Fisher-Vanden et al. (1997) used the Indian module of Second Generation Model to determine comparative costs of stabilizing GHG emissions through two alternative policy instruments – carbon tax and global tradable permits. The Second Generation Model was a set of 14 multi-sector regional CGE models that could be run independently or as a system for international trade in international permits. The regional models were recursive dynamic with a time frame of 1990 through 2050 in five-year time steps (Edmonds et al. 1993). The authors found that a global tradable permits system with grandfathered emission allocation (based on 1990 emission levels) and equal per capita allocation of emission allowances would be less costly than carbon taxes for India to stabilize emissions.

Bussolo and Connor (2001) employ a recursive dynamic CGE model of the Indian economy to estimate air quality and health co-benefits of limiting GHG emissions. The model represents 4 regions (broadly coinciding with the 4 regional power grids, with East and Northeast combined) and 35 sectors. Having multiple regions provides sufficient geographic resolution to examine the impacts of climate policy on regional air pollution as well as the possibility of different abatement costs across regions.

Among more recent works, Shukla et al. (2008) use an integrated modeling framework, including a CGE model, to study two alternative pathways for low-carbon growth in India – a pure carbon policy instrument in the form of a carbon tax, and a combination of sustainable policies with a carbon tax. The sustainability scenarios incorporate assumptions on the introduction of significant behavioral, technological, institutional, governance, and economic measures which promote sustainable practices in resource use, demographic transition, urban planning, land use, infrastructure, innovations, and technology transfer, etc. The suite of models includes a global multi-region and multi-sector CGE model included in the Asia-Pacific Integrated Model (AIM) family. The top-down AIM-CGE model is soft-linked to a bottom-up MARKAL model, which is soft-linked to AIM-SNAPSHOT tool (an accounting tool to calculate energy balance table and CO_2 emissions table). AIM-CGE provides GDP estimates for different scenarios, which are used as exogenous inputs to the MARKAL model, which, in turn, provides inputs to AIM-SNAPSHOT for factor analysis (Ibid.).

Realizing the heterogeneity in households and the expectation that climate policies have different impacts on households belonging to different income and expenditure groups (Poterba 1991; Bull et al. 1994; Hassett et al. 2009), Ojha (2009) employs a single country CGE model of India to study distributional impacts of climate policies. Specifically, multiple households segregated by income levels are incorporated in the model to study the impact of carbon policies on shifts in consumption patterns. Simulated climate policies include carbon tax and permit trading, with various revenue recycling options.

A limitation of these works I address here is that none of them simulate policy designs currently under consideration in India. The policy scenarios reflected in these models largely include implementation of a hypothetical carbon pricing or permit trading regime in India. This does not reflect reality as India's climate policies have shied away from a broad based carbon tax or permit trading scheme, and define targets in terms of CO_2 emissions intensity. As noted earlier, India's NDCs reflect strong technology specific support for solar and other renewables as well as emissions intensity targets, but do not mention a direct price based instrument. In my discussions with policymakers at several relevant Indian ministries, the consensus was that there is no plan for implementing a carbon tax in India. Our study takes this into account and simulates and compares India's declared policies. As a point of comparison, I include a theoretically least-cost path to achieving CO_2 emissions intensity targets that is implemented via a CO_2 price. This makes our work suitable for use by policymakers in that it fills a critical knowledge gap that they face.

This leads to another distinguishing feature of my work in the specification of electricity technologies. The core of India's climate mitigation policies define ambitious solar and other renewable targets. To gauge the impact of these targets and compare them with alternative policy choices, it is important to specify electricity technologies, particularly renewable technologies, in detail. Besides, solar prices in India have seen a sharp decline in the previous decades (see section 3.6), a trend which is expected to continue. My work reflects this trend in the model through sensitivity analyses to appropriately incorporate the variation in costs of solar and wind generation, and their policy implications.

3.4. India CGE Model: Structure and Parametrization

3.4.1. Model Structure

The CGE model I develop is based on the basic principles described above. In its current version, the model represents Indian economy through 18 sectors, obtained by aggregating 68 sectors in the GTAP Power database (**Table 1**). The sector description is flexible and can be specified in greater or lesser detail, as required. Notably, I specify energy system in significant detail by including 12 energy sectors, comprised of 8 electricity sectors (including T&D), and 4 other energy sources.[32] This disaggregation enables detailed technological specification of different electricity sectors and provides required flexibility in policy analysis.

The eighteen sectors are each described by a separate production function with nesting structures to provide for substitution between energy composite, electricity, capital, labor, resources, and other intermediate inputs. An additional production function describes advanced solar technology, introduced as "backstop", as the benchmark data comprises of negligible solar electricity. Nested CES functions are also used to describe consumer, government, and investment sectors. All industries are characterized by constant returns to scale and trade in perfectly competitive markets. Nesting structures are described in **Figure 8**. Horizontal lines indicate zero elasticity of substitution between inputs while slanted lines indicate a non-zero elasticity.

Figure 8(a) represents the nesting structure of all sectors except agriculture, electricity, fossil fuel, and consumption. Primary energy sources are grouped in the non-electricity energy nest and substitute with aggregate electricity. Final output comprises of an energy composite, land, labor, capital, resources, and other intermediate inputs. Agriculture is represented in **Figure 8(b)**, where land is moved from the value added nest to energy and other Armington input nest. Recognizing the importance of land for agriculture, a small elasticity of substitution limits the substitution of land with other inputs as price of land goes up.

Electricity production is represented by three separate nesting structures for benchmark electricity sources, and one for advanced electricity technology, primarily to facilitate new solar penetration in policy scenarios. **Figure 8(c)** outlines fossil electricity production, combining non-electricity energy composite with electricity, other inputs, and renewable permits. The permits are active in non-fossil target scenarios to enforce prescribed non-fossil electricity capacity targets. In principle, they simulate a renewable portfolio standard.[33] Every unit of non-fossil electricity output produces one permit, and every unit of electricity sold (fossil as well as non-fossil) requires utilities to turn in α permits, where α is the specified fraction of non-fossil production in electricity mix.

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[32] The model has three primary energy sources: coal, crude oil, and gas. They are inputs in different sectors, most significantly in producing fossil based electricity. Crude oil is also the primary input for refined oil, which is subsequently used as a fuel in other sectors. CO_2 enters the economy through these three sources.

[33] A renewable portfolio standard (RPS) is a regulatory mandate to increase production of energy from renewable sources such as wind, solar, biomass and other alternatives to fossil electric generation.

***Table 1**: Aggregation of GTAP commodities into sectors in the model*

GTAP commodity	Aggregated commodity	GTAP commodity	Aggregated commodity
Paddy rice	AGR	Ferrous metals	EINT
Wheat	AGR	Metals	EINT
Cereal grains	AGR	Metal products	EINT
Vegetables, fruit, nuts	AGR	Motor vehicles and parts	MANF
Oil seeds	AGR	Transport equipment	MANF
Sugar cane, sugar beet	AGR	Electronic equipment	MANF
Plant-based fibers	AGR	Machinery and equipment	MANF
Crops	AGR	Manufactures	MANF
Cattle, sheep and goats, horses	AGR	Transmission and distribution	TnD
Animal products	AGR	Nuclear baseload	ENUC
Raw milk	AGR	Coal baseload	ECOA
Wool, silk-worm cocoons	AGR	Gas baseload	EGAS
Forestry	AGR	Wind baseload	EW_S
Fishing	AGR	Hydro baseload	EHYD
Coal	COL	Oil baseload	EOIL
Crude Oil	CRU	Other baseload	ECOA
Gas	GAS	Gas peak	EGAS
Minerals	OMN	Hydro peak	EHYD
Bovine meat products	FOOD	Oil peak	EOIL
Meat products	FOOD	Solar peak	EW_S
Vegetable oils and fats	FOOD	Gas manufacture, distribution	GAS
Dairy products	FOOD	Water	SER
Processed rice	FOOD	Construction	SER
Sugar	FOOD	Trade	SER
Food products	FOOD	Transport	SER
Beverages and tobacco products	FOOD	Water transport	SER
Textiles	MANF	Air transport	SER
Wearing apparel	MANF	Communication	SER
Leather products	MANF	Financial services	SER
Wood products	MANF	Insurance	SER
Paper products, publishing	MANF	Business services	SER
Petroleum, coal products	OIL	Recreational and other services	SER
Chemical, rubber, plastic products	EINT	Public Administration, Defense, Education, Health	SER
Mineral products	EINT	Dwellings	SER

Figure 8(d) and **(e)** for non-fossil electricity display production of permits with electricity output. An additional difference from fossil electricity production is the limitation enforced by technology specific fixed-factors (TSF). The TSF, and the elasticity of substitution between the TSF and other inputs, control the penetration of non-fossil technologies (and also of backstop electricity, as we discuss later). In principle, this approach represents resource and other political constraints that may impose barriers to growth of certain technologies. These structures and their parametrization is based on interviews with stakeholders in India. **Table 2** outlines key characteristics of the four non-fossil electricity sectors, describing their current installed capacity, political economy factors constraining or facilitating their expansion, policy targets, and their specification in the model. These details are based on interviews and published reports (IEA 2015; Kumar & Chaterjee 2012).

I impose zero elasticity of substitution between TSF and other inputs for nuclear, hydro, and benchmark solar power, for two different reasons. For nuclear and hydro power, there is uncertainty in expected growth due to resource and political constraints. I represent these technologies by fixing targets for 2030, obtained from IEA Forecasts (IEA 2015). For solar, its representation in benchmark data (2011) is negligible, as nearly all solar capacity addition in India has been in subsequent years. I therefore assume that benchmark solar is not representative of cost of producing solar, and allow solar growth only as an advanced technology, restricting benchmark solar to its existing capacity.

I specify a separate production block for wind power, as the two rationales for fixing nuclear-hydro and benchmark solar do not apply to wind. Wind capacity is expected to grow considerably, with a target of 60 GW installed capacity for 2022. Studies project high wind resource potential (IEA 2015), and our interviews suggested no resource or political constraints. Besides, benchmark data includes 2% wind power production (24 TWh), suggesting a reasonable representation of cost estimates. I therefore allow for a non-zero elasticity of substitution between other inputs and TSF to offer flexibility in expansion. The elasticity is estimated from price elasticity of supply and wind cost shares, using methods specified in Rutherford (2002) and supply elasticity value of 12.66 outlined in Böhringer et al. (2012).

Solar expansion is represented as an advanced technology (McFarland et al. 2004) in **Figure 8(e)**, parametrized with bottom up cost estimates, described in section 3.4.2. Advanced solar is produced using capital and labor as key inputs, and constrained with a technology specific factor. The TSF represents real world constraints on capital, labor, or other inputs, as well as intermittency challenges, which may limit the growth of advanced technology. The elasticity of substitution between TSF and other inputs is kept similar to that in wind production. Estimated cost shares are normalized to one and multiplied with a markup to represent the relative cost of advanced technology over conventional technologies. The markup is varied to perform sensitivity analysis of solar penetration at different generation costs relative to those of conventional electricity.

Table 2: *Characteristics defining representation of non-fossil electricity sources in the model*

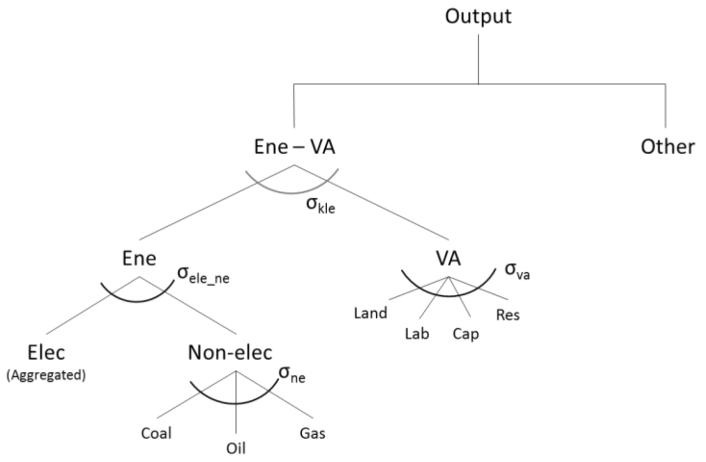
	Nuclear	Hydro	Wind	Solar
Current Capacity	5.8 GW	44.4 GW	28.7GW	12.28 GW
Political Economy	- Domestic opposition - International sanctions	- Displacement - Ecological impacts	- Near grid parity; - Favorable political and market environment	Very favorable political and market environment
Forecast	Policy target: uncertain; Production in 2030 = 164 TWh, compared to 32.28 TWh in 2011 (IEA 2015)	Policy target: uncertain; Production in 2030 = 253 TWh, compared to 165 TWh in 2011 (IEA 2015)	Policy target: 60GW by 2022; Flexibility in expansion	Policy target: 100 GW by 2022; Flexibility in expansion
Technology representation	Existing technology with TSF for resource/political constraint	Existing technology with TSF for resource/political constraint	Existing technology with TSF for resource/technology constraint	New technology
Parametrization	Sufficient presence in benchmark data; Zero substitution elasticity with TSF to enforce fixed targets	Sufficient presence in benchmark data; Zero substitution elasticity with TSF to enforce fixed targets	Sufficient presence in benchmark data; Small substitution elasticity with TSF to allow expansion	Negligible presence in benchmark data – cost shares specified based on LCOE analysis; Small substitution elasticity with TSF

Figure 8(e) also represents fossil fuel production, where top level nest is a CES aggregate of sector-specific resource and a composite of capital, labor, energy, and other intermediate inputs. This representation allows for exogenously specifying fossil fuel prices, assuming India to be a price taker in the international fossil fuel market.

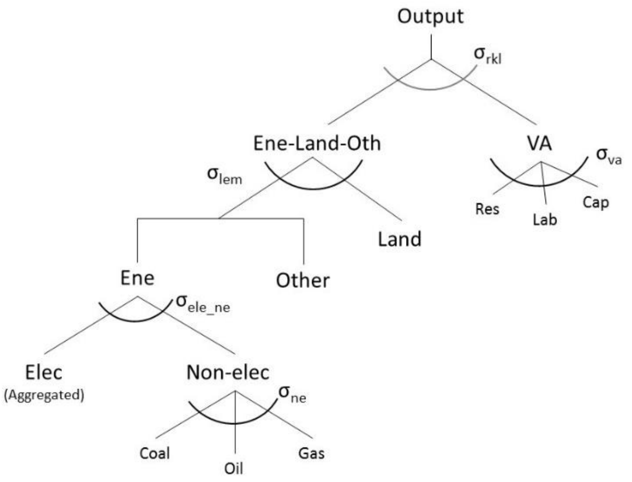
Finally, **Figure 8(f)** specifies CES functions for consumption, government, and investment sectors, where the top level nest is an aggregate of energy composite and other inputs. It essentially specifies value creation for consumer and government through direct consumption of inputs, and separately value of goods and services that acts as investment.

International trade is modeled following an Armington approach, where goods and services purchased by firms and households are composites of domestic and imported varieties. The elasticity of substitution between domestic and imported goods is set to zero reflecting the assumption that climate policies in India will not be implemented independent of the rest of the world, and thus domestic goods will not face competitive threats imposed by higher domestic energy prices.

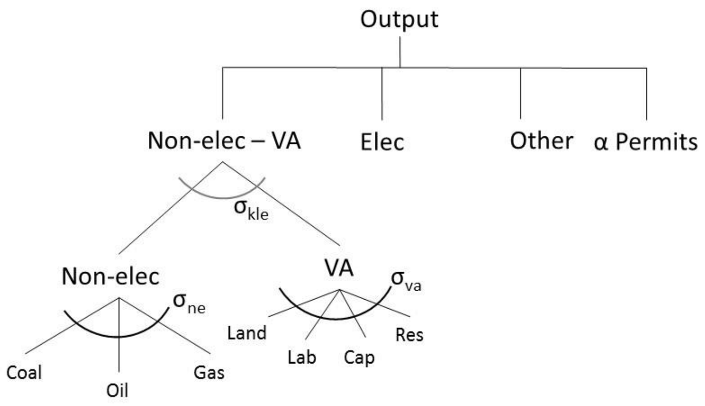
***Figure 8**: Nesting structures for production blocks in India CGE model*



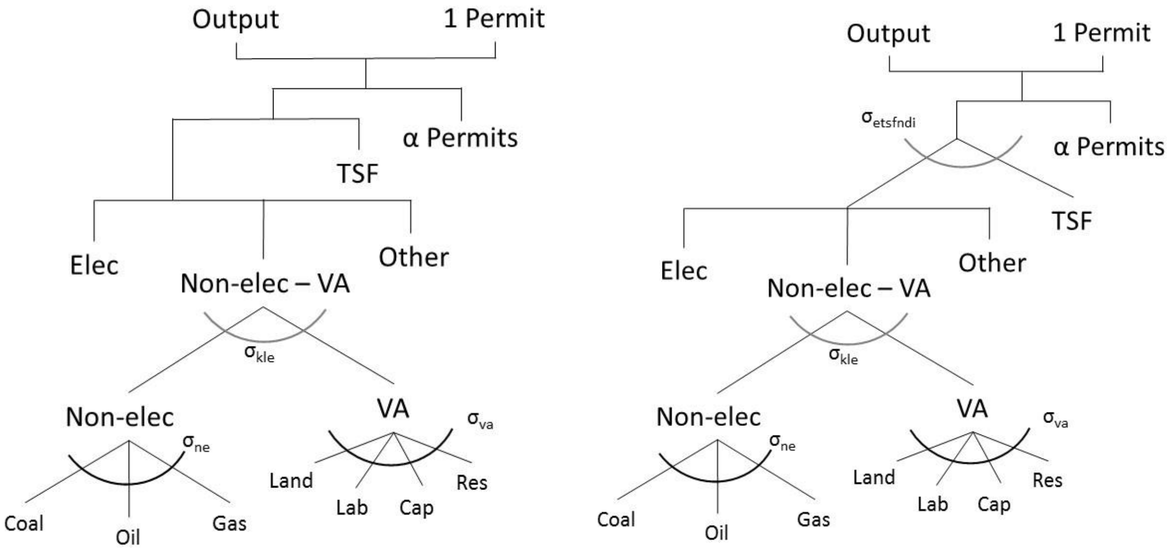
a) Production structure for all output except Agriculture, Electricity, Fossil Fuels, and Consumption



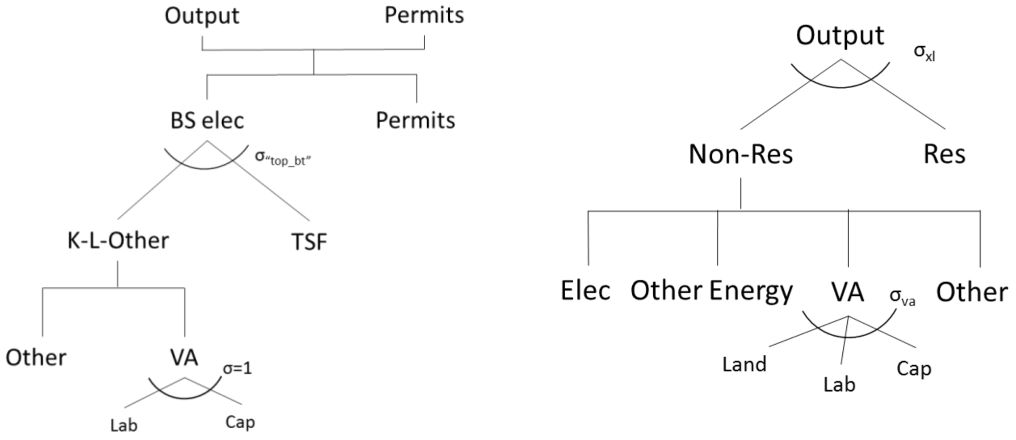
(b) Production structure for Agriculture



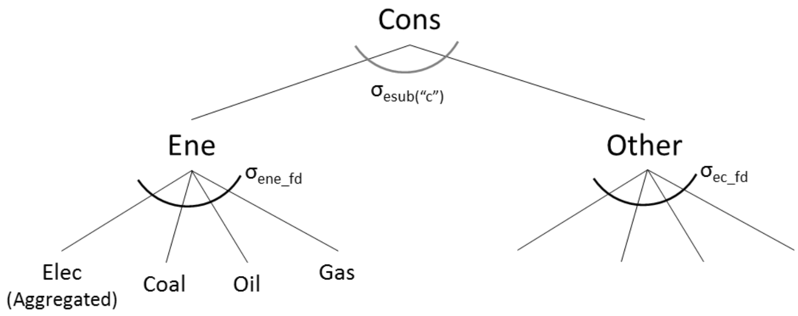
(c) Production structure for Fossil electricity (coal, oil, gas)



(d) Production structure for non-fossil electricity with dialed-in future capacities (left, representing nuclear, hydro, and benchmark solar), and flexibility in expansion (right, representing wind)



(e) Production structures for backstop electricity (left) and fossil fuel production (right)



(f) Production structure for consumer, government, and investment

3.4.2. Data Sources and Parametrization

The core data for parametrizing cost shares is obtained from GTAP Power database (Peters 2016), which is based on the ninth version of the primary GTAP dataset: GTAP-9 (Aguiar et al. 2016). GTAP Power provides global trade data across 68 industrial sectors for 140 regions. The data corresponds to the world economy in 2011. Constituent data sets belong to three reference years - 2004, 2007, and 2011, and the earlier reference years are extrapolated to 2011 using economic projection estimates, such as GDP projection. GTAP-Power is an electricity detailed extension of the GTAP-9 database, disaggregating electricity into coal, oil, gas, nuclear, hydro, wind, solar, and T&D (Peters 2016). Data for India in the GTAP database is derived from the Input-output transaction tables prepared by India's Ministry of Statistics and Program Implementation. Elasticity values for production blocks are provided exogenously. The elasticities in this model closely follow those in the MIT EPPA model (Chen et al. 2015), which are drawn from an extensive literature review.

Advanced solar is parametrized using levelised cost of solar estimates from NITI Aayog (2015). **Table 3** below lists relevant data and calculations. Operating and maintenance (O&M) costs over project life of 25 years are discounted to present value using the following formula:

$$PV\ of\ O\&M = \frac{P}{r-g} * \left(1 - \left(\frac{1+g}{1+r}\right)^{n}\right) \qquad \dots (8)$$

These are added to Capex to obtain PV of total costs, from which percentage capex and percentage O&M are derived. I assign 2.2% of the input cost share to a TSF for advanced solar**,** modeling advanced solar technology as similar to wind power. Treating wind and solar production equivalently is a widely followed approach in CGE modeling. For instance, the MIT-EPPA model includes a single production block for advanced wind and solar technologies. I distribute the remaining 97.8% cost between Capex and O&M (considering labor as the only O&M cost).

While these datasets parametrize the model to simulate the benchmark, additional data are required to simulate policy scenarios. The target year for policy scenarios is 2030 to facilitate evaluation of India's NDCs. **Table 4** lists additional required data, their sources, and calculation methods. The required parameters include factor productivity growth in India from 2011 to 2030 (GDP multiplier), expected exogenous growth in fossil fuel prices (fossil fuel multipliers), expected efficiency improvements in energy production technologies (AEEI multiplier), and factors for simulating India's NDCs on emissions intensity and non-fossil targets. Policy simulation is discussed in section 3.4.3.

***Table 3**: Calculation of Cost Shares for Advanced Solar*

Parameter	**Unit**	**Value**
Capex (15-16)	INR million/MW	60
O&M – 1st year (P)	INR million/MW/Year	1.23
Project Life (n)	Years	25
O&M Escalation (g)	%	5.72
Discount Rate (r)	%	11
PV of O&M	INR million/MW	16.41
PV of total costs (Capex + PV of O&M)	INR million/MW	76.41
Capex as % of PV of costs	%	79
O&M as % of PV of costs	%	21
TSF input to backstop	%	2.2
Non TSF inputs to backstop	%	97.8
Capital input	%	**76.8**
Labor input	%	**21.0**

***Table 4**: Additional parameters for policy scenarios*

Parameter	**Unit**	**Value**	**Source**
GDP Multiplier (2011-2030)	-	2.86	OECD (Ibid.)
Fossil Fuel Price Multipliers (2011-2030)			
Coal	-	1.00	
Oil	-	1.13	
Gas	-	1.13	U.S. EIA (2017)
AEEI Multiplier	-	0.826	Chen et al. (2015)
Emissions Intensity Target for 2030	% of Benchmark Emissions Intensity	74.16	GoI (2015) and calculations in **Table 5**
Non-Fossil Target for 2030	% of installed capacity	40	GoI (2015)
Non-Fossil Production Target for 2030	% of Electricity Production in TWh	28	Calculations in **Table 6**

The GDP multiplier is obtained from long term GDP forecasts prepared by OECD.[34] Reported in real terms in 2010 US$ PPP, India's GDP grows from $3.90 trillion to $11.16 trillion at a compounded annual

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[34] Source: OECD (2017), accessed on 03 April 2017

growth rate (CAGR) of 5.7%. This is a conservative estimate, considering that average annual GDP growth rate of India from 1992 (when large scale economic reforms were introduced) to 2015 has been 6.78%.[35]

Fossil fuel multipliers specify exogenous increase in fossil fuel prices in 2030. As coal is not a scarce resource in India, and domestic coal constitutes bulk of the consumption, the price is expected to remain constant. The multiplier for crude oil is based on historical data and long term projection of international crude oil prices in U.S. EIA (2017). The multiplier for natural gas price is the same as for crude oil, as natural gas prices are typically strongly correlated with crude prices (Brown & Yücel 2008).

Autonomous Energy Efficiency Improvement (AEEI) multiplier represents improvement in energy production technologies in the future, leading to lower inputs per unit energy produced. I base AEEI multiplier on MIT-EPPA model, which assumes 1% annual efficiency improvement, leading to 17.4% improvement from 2011 to 2030. Physically, this suggests that for the same level of electricity generation from coal, it would require 17.4% lesser amount of coal in 2030, than it does in 2011.

Calculation of emissions intensity targets is specified in **Table 5**, which is self-explanatory. Emissions intensity of the GDP for a year is the ratio of CO_2 emissions and GDP for that year.

***Table 5**: Calculation of Emissions Intensity Target*

Parameter	**Unit**	**Value**
Benchmark Emissions	Million MT CO_2	1771.2
Benchmark GDP	Billion USD (2011)	2034.6
Benchmark Emissions Intensity of GDP	MT CO_2/Thousand USD (2011)	0.8705
Base Year	Year	2005
Benchmark Year	Year	2011
Target Year	Year	2030
Total decrease in Emissions Intensity[36]	%	34
Yearly decrease (assuming linearity)[37]	%	1.36
Decrease from benchmark to 2030	%	25.84
Emissions intensity in 2030 as percentage of that in 2011	%	**74.16**
Target emissions intensity in 2030	MT CO_2/Thousand USD (2011)	**0.6455**

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[35] Source: World Bank (2015a)

[36] India's NDCs in GoI (2015) mention a reduction in emissions intensity of the GDP by 33-35% by 2030 over 2005 levels. We take the average value of 34% for our analysis

[37] The linear assumption is based on observed near linear trend in historical emissions intensity of the GDP of India reported in World Bank (2013).

Conversion of non-fossil electricity installed capacity targets for 2030 to production targets is specified in **Table 6**. First I calculate capacity factors for 2015 using installed capacity and production values for fossil and non-fossil electricity[38] from CEA (2015) through the following formula:

$$CF = \frac{Electricity\ Production}{Installed\ Capacity * n_h * d_y} \quad \ldots (9)$$

where, n_h = 24 hours, and

d_y = 365 days

To convert percentage capacity targets for 2030 to percentage production targets, I use the following equations, which can easily be derived from equation (9):

$$P_{nf}(\%) = C_{nf}\ (\%) * \left(\frac{CF_{nf}}{CF_{total}}\right) \quad \ldots (10)$$

$$P_{f}(\%) = C_{f}\ (\%) * \left(\frac{CF_{f}}{CF_{total}}\right) \quad \ldots (11)$$

where, $P_{nf/f}$ (%) = Percentage production level of non-fossil/fossil electricity

$C_{nf/f}$ (%) = Percentage capacity of non-fossil/fossil electricity

$CF_{nf/f/total}$ = Aggregate capacity factor for non-fossil/fossil/total electricity

***Table 6**: Conversion of non-fossil electricity capacity targets for 2030 to production targets*

	Fossil	**Non-Fossil**	**Total**
Installed Capacity in 2015 (GW)	188.898	82.824	271.722
Electricity Production in 2015 (GWh)	878320	227126	1105446
Capacity Factor (2015)	0.53	0.31	0.46
Assumed Capacity Factor (2030)	0.53	0.31	0.44
Installed Capacity Target for 2030	60%	40%	100%
Production Target for 2030	72%	**28%**	100%

I assume that capacity factors for fossil and non-fossil electricity sources will continue to be the same in 2030, but a higher percentage of non-fossil electricity will decrease aggregate capacity factor of the electricity sector.[39] This leads to a circularity problem, as calculation of non-fossil production levels for 2030 require total capacity factor, but total capacity factor depends on non-fossil production levels. To

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[38] To reiterate, fossil power includes coal, gas, and oil, while non-fossil power includes nuclear, hydro, wind, and solar.

[39] Strictly speaking, the fossil and non-fossil capacity factors will also change. Fossil and non-fossil electricity sources are aggregates of different power sources with varying capacity factors, hence the aggregate capacity factors will change as constituent source mixes change. However, for simplicity, and in the absence of more information, I assume that the aggregate fossil and non-fossil electricity capacity factors remain same.

address this, I iterate total capacity factor to arrive at percentage production levels for 2030 that add up to a total of 100%. This generates overall capacity factor of 0.44 (lower than 0.46 for 2015), and a non-fossil production target of 28%.

3.4.3. Solving the model

The model is formulated as a mixed complementarity problem (MCP) (Mathiesen 1985; Rutherford 1995) in the Mathematical Programming System for General Equilibrium Modeling (MPSGE) (Rutherford 1998) and the General Algebraic Modeling System (GAMS) modeling language. The system of equations described above is solved using the PATH solver (Dirkse & Ferris 1995) to determine prices and quantities for all factors of production as well as goods and services produced by respective economic sectors. Solving the model for different policy scenarios involves adjustment of relative prices of goods as economic activities adjust to reach new equilibrium that meets the policy constraints at least cost.

Currently, the model is structured to be solved statically in two stages, reflecting the economy in 2011 (benchmark period) and 2030. This allows for a simple comparison of the equilibrium states of the economy in 2030 under different policy scenarios, while not providing temporal information about how those states are reached. Future work on the model may involve converting it to a recursive dynamic model, along the lines of EPPA or C-GEM, where information about intermediate periods is also available.

3.5. Policy Scenarios

The model as described above is calibrated with benchmark data of the Indian economy in 2011. The calibrated model is used to compare the impacts of India's NDCs against a reference case that does not impose the climate policies. Reference as well as all policy scenarios for India's economy in 2030 are based on the same default assumptions about factor productivity growth, fossil fuel price in 2030, and autonomous energy efficiency improvement. The three simulated policy scenarios include:

3.5.1. Emissions Intensity Target

First, I simulate India's NDC objective of reducing emissions intensity of the GDP by 34% (taking mid-point of proposed 33-35 percent reduction) by 2030 from 2005 levels. As described in **Table 5**, this translates to a reduction by 25.84% from benchmark (2011) level. Based on the equivalence discussed earlier in section 1 and 2.5, emissions intensity target is simulated as an economy-wide cap-and-trade policy in the model. I evaluate the impact of this target on total and sectoral emissions, consumption, electricity mix, and also identify the corresponding carbon price.

3.5.2. Non-Fossil Target

The second policy simulation corresponds to India's non-fossil electricity capacity target for 2030. India aims to have 40% installed electricity capacity powered by non-fossil sources in 2030, which corresponds to a 28% electricity production target (**Table 6**). The impact of this target on emissions, consumption, and electricity mix is compared with reference and emissions intensity scenarios. Further, I also calculate the implicit subsidy required to achieve the target.

3.5.3. Combined emissions intensity and non-fossil electricity targets

In the third scenario, I combine the emissions intensity and non-fossil targets. While simulating these targets separately offers insights into comparing these widely different policy approaches to emissions reduction, in practical terms the two targets shall be implemented jointly. Simulating their combination offers insights into comparing the actual policy implementation with the two extremes. It also offers the possibility to explore synergies between two different policy instruments.

3.6. Sensitivity Analysis

The generation costs of wind and solar power are important in deciding the impact of different policy targets. As shown in **Figure 9,** solar prices in India have dropped significantly over the previous years. This motivates the sensitivity analysis where I compare policy outcomes under different costs of producing solar power. Cost variation is simulated by varying the markup on solar cost shares.

Figure 10 shows the decline in average LCOE of onshore wind and learning curve effects. In the model, beyond benchmark cost shares, the cost of wind expansion is controlled by the elasticity of substitution between other inputs and technology specific factor. I run sensitivity analysis with different elasticity levels and assess the impact of varying costs of wind power expansion.

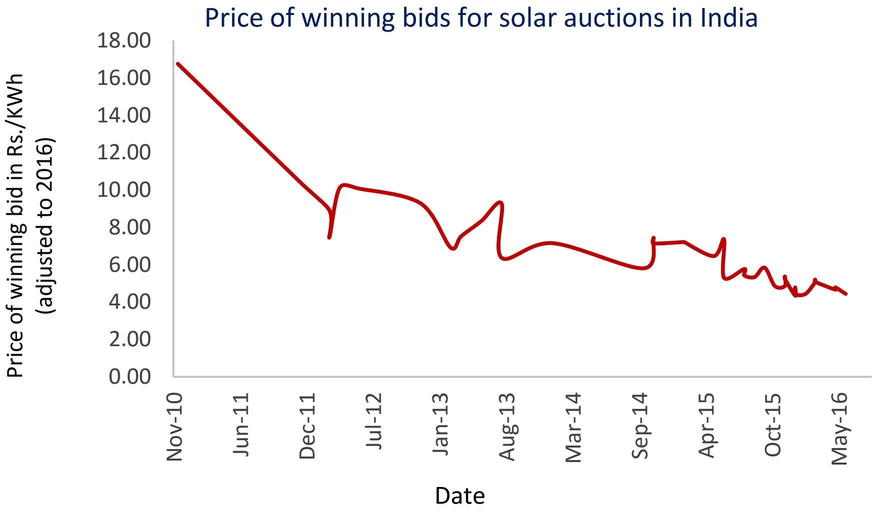
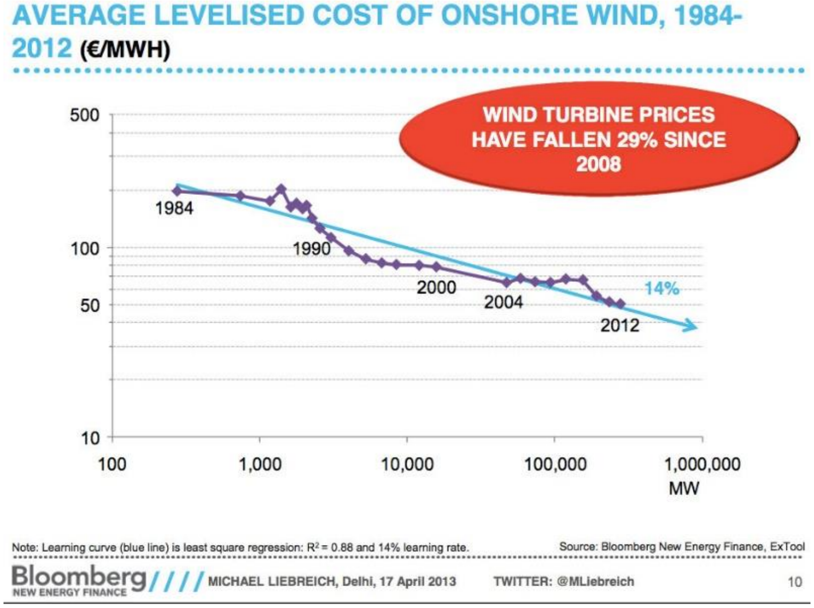


Figure 9*: Price of winning bids for solar auctions in India, adjusted for inflation to INR 2016. Source: MNRE, Status of implementation of various schemes to achieve 100 GW Solar Plan*



AVERAGE LEVELISED COST OF ONSHORE WIND, 1984-2012 (€/MWH)

Note: Learning curve (blue line) is least square regression: $R^2 = 0.88$ and 14% learning rate.

Source: Bloomberg New Energy Finance, ExTool

Bloomberg NEW ENERGY FINANCE MICHAEL LIEBREICH, Delhi, 17 April 2013 TWITTER: @MLiebreich 10

Figure 10: *Drop in cost of wind power. Source: Bloomberg New Energy Finance*

4. Results

4.1. Base Results

The base analysis is performed with an elasticity of substitution between non-TSF composite and TSF in wind production function set to 0.29, and solar cost share markup set to 1. These specifications provide a sensible comparison across policies without accounting for variation in cost of producing wind and solar power. For wind power, the base elasticity is obtained from Böhringer et al. (2012). For solar, a markup of one implies that the cost of solar power generation is equal to the cost of thermal power generation. Alternatively, a markup of 1.5 would imply that it costs 50% more to produce the same quantity of solar power compared to thermal power. Given the fall in solar prices in India, and that recent auctions have seen generation cost as low as that of thermal power,[40] this is a reasonable assumption. The sensitivity analyses discussed subsequently will offer more insights into comparisons across policies with varying wind and solar generation costs.

Table 7 summarizes key base results, which I discuss in detail below.

***Table 7**: Summary of key base results (All dollar values are in 2011 USD)*

			Scenarios		
Metric	**Unit**	**Reference**	**Emissions-Intensity**	**Non-Fossil**	**Combined**
Welfare Loss (w.r.t. reference)	USD/MT CO_2		0.27	13.01	11.35
Emissions	MT	4567.62	3751.14	3824.01	3728.62
Carbon Price	USD/MT CO_2		17.40		2.06
Total Electricity Production	TWh	3070.97	2877.17	2427.72	2424.04
Fossil Electricity	TWh	2678.54	2346.18	1756.00	1752.68
Non-Fossil Electricity	TWh	392.43	530.99	671.73	671.36
Non-Fossil Subsidy	Cents/KWh			20	19

I first compare the cost of emission reduction under different policies (**Figure 11**). The comparison metric is the decrease in consumer welfare from reference, measured as the Hicksian equivalent variation (EV) from economic theory.[41] Welfare loss is the lowest under the emissions intensity policy (0.01%), and significantly higher under non-fossil and combined policy scenarios (0.29% and 0.28% respectively).

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[40] As noted in LiveMint (2017), “at current rates, solar power generation cost is at par with that of thermal power generation”

[41] Hicksian equivalent variation is the maximum amount the consumers are willing to pay to avoid a price change. In the present context, it is equivalent to decline in household consumption due to emission reduction policies.

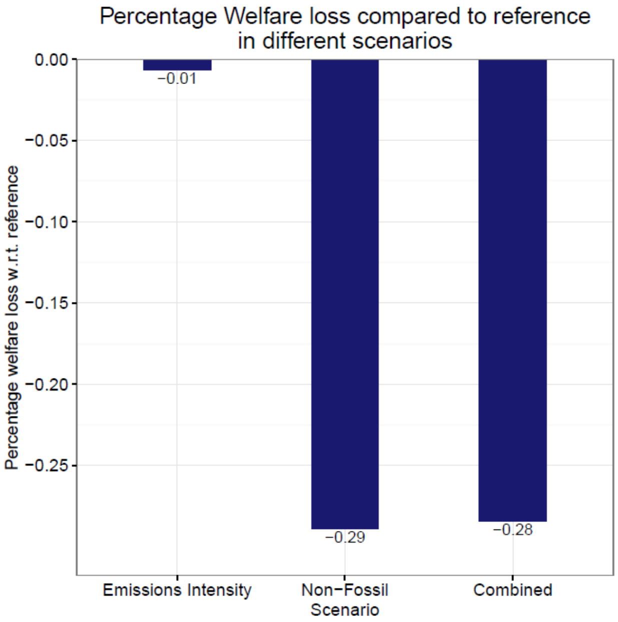

***Figure 11**: Change in consumption from reference under different scenarios*

A better metric to compare the efficiency of emission reduction of different policies is the welfare loss per ton of CO_2 reduced (**Figure 12)**. Compared to reference, the cost of reducing a ton of CO_2 is lowest in the emissions intensity scenario, and is more than 43 times higher in the pure non-fossil electricity target scenario. This resonates with economic theory's support for the efficiency of economy-wide emission reduction policies. Simulating both the non-fossil and emission intensity targets results in a decline in welfare loss over pure non-fossil scenario. This is because some low-cost emission reduction measures are incentivized by the economy-wide policy, which reduce the average cost of emission reduction.

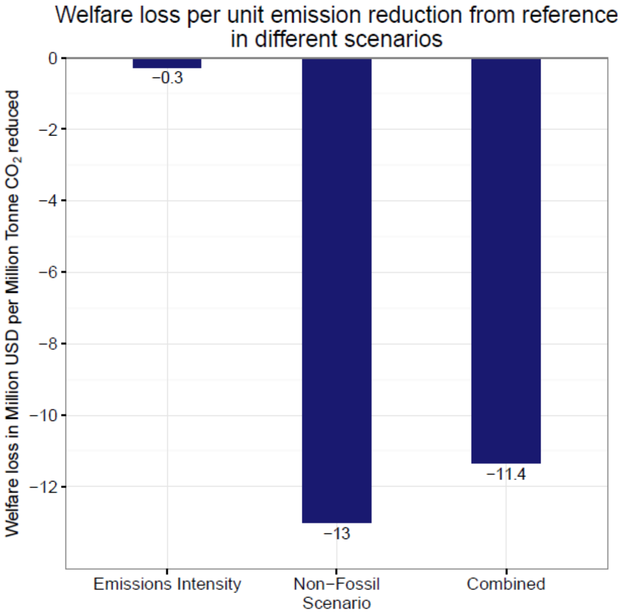

***Figure 12**: Change in consumption per unit emission reduction under different scenarios in 2030*

The change in emissions and emissions intensity under different scenarios is shown in **Figure 13** below. As expected, in all policy scenarios, total emissions as well as emissions intensity decrease relative to the reference. The emission intensity target scenario sees a drop of 18% in emissions over reference. Combining this with the modest drop in consumption per ton of emissions reduction illustrates the efficiency of economy-wide policies in reducing emissions. Non-fossil electricity targets result in 2% higher emissions than under emissions intensity target, while achieving 92% of the emissions intensity target of 34% (average of 33-35%) reduction. As non-fossil targets directly impact the electricity price but have little impact on other energy prices, energy intensive industries substitute expensive electricity with other cheaper energy sources.

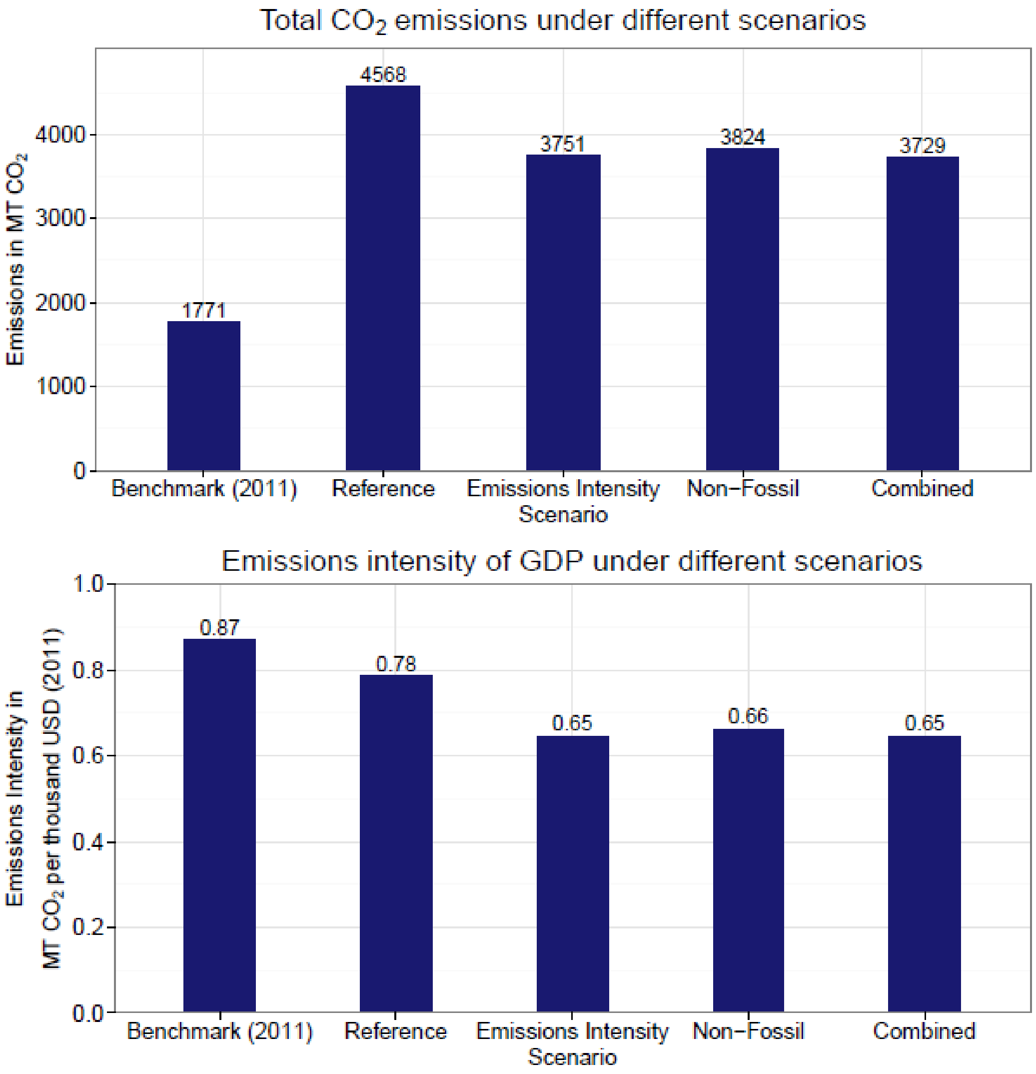

***Figure 13**: Total emissions and emissions intensity in 2030 under different scenarios*

This is clearly visible in **Figure 14** which shows emissions from the four highest emitting sectors. Emissions fall in absolute terms in all sectors under emissions intensity scenario, with coal power and energy intensive industries both seeing a significant drop. But under non-fossil scenario, while coal power sees further reduction in emissions, energy intensive industries emit more as they substitute electricity with other energy sources. This further underscores the advantage of an economy-wide emission policy relative to sector specific policies – which may lead to leakage of emissions.

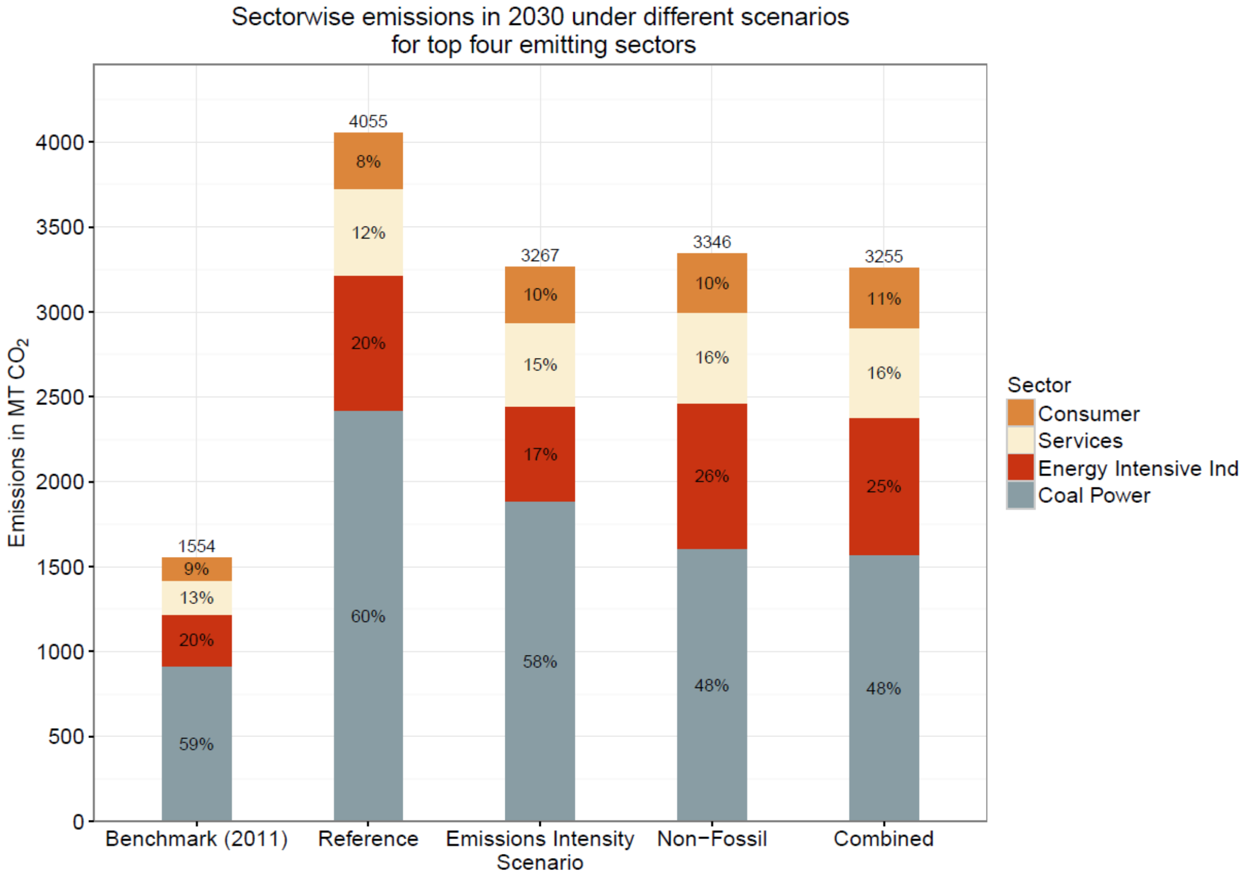

Figure 14: *Emissions by sector in 2030 under different scenarios*

Figure 15 describes the electricity mix under different scenarios in 2030. In the reference case, total electricity production in India is poised to be three times the level in 2011. Most of the increase comes from expansion of coal power, which more than triples in 2030. Other fossil based electricity sources also increase by varying amounts. Among non-fossil electricity sources, hydro power rises to its imposed target but nuclear power falls short. This indicates higher cost of producing nuclear power as compared to thermal power, which restricts its expansion in a no-policy scenario. Similarly, the share of wind power in the reference also does not rise significantly beyond benchmark level, suggesting that even though wind has a reasonable share in benchmark, the cost of producing wind power is still high relative to thermal power. Thus, without any policy constraint or subsidy support, wind power will see moderate expansion. Further, in the absence of any policy support, solar power will not see any growth.

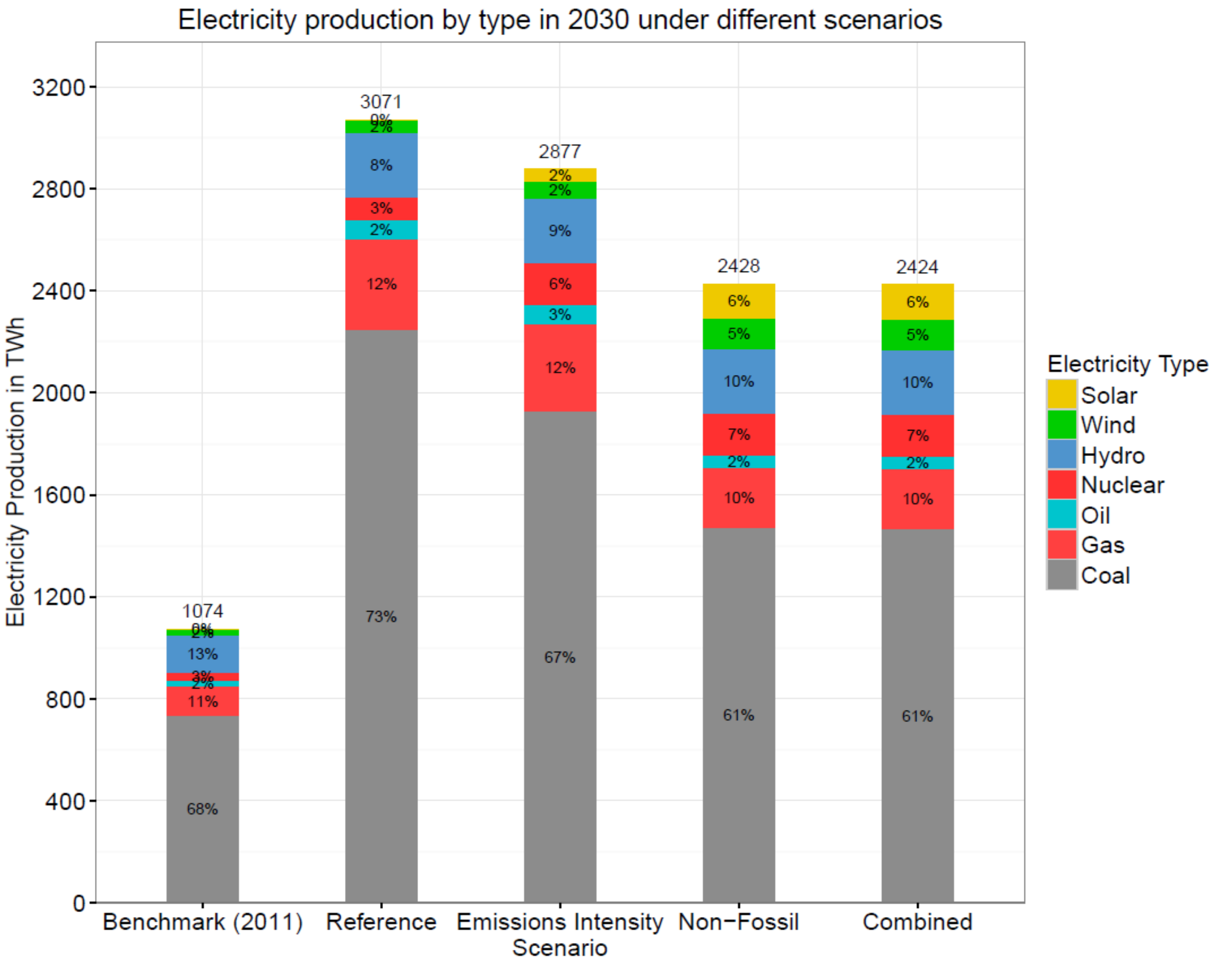

Figure 15*: Electricity mix in India in 2030 under different scenarios*

Imposing emissions intensity targets reduces electricity production in 2030 by 6.3%. This is indicative of the increased cost of CO_2 emitting economic activities. As emissions content per energy unit is highest in coal, most of the decrease is through reduction in coal power. This is confirmed by a relatively smaller drop in gas power due to lower emissions intensity of gas. Both nuclear and hydro power reach their dialed-in targets. Besides, wind penetration increases slightly, indicating that with fossil electricity sources becoming more expensive, renewable power will compete with them in adding to the total electricity production. A higher share of solar (driven by advanced solar technology) further underscores the competitiveness of renewable electricity under emission policy constraints. Overall, substitution of cheaper fossil based power sources with more expensive non-fossil sources, resulting from emission constraints, increases electricity prices and consequently leads to a drop in overall electricity demand.

Electricity level drops further in the non-fossil scenario, which enforces that a certain percentage of total electricity production be from non-fossil sources. Introducing a higher share of expensive non-fossil electricity in the mix (28% in non-fossil scenario compared to 13% in reference and 18% in emissions intensity scenarios) increases the price of electricity, consequently reducing demand by an additional 15.6% over emissions intensity scenario. All fossil electricity sources see a decline, whereas shares of non-fossil sources increase. The importance of subsidizing renewable electricity to ensure to ensure that electricity prices do not rise is clearly visible from this exhibit.

Under the combined policy scenario, the electricity mix is similar to that in non-fossil scenario, suggesting the dominance of the technology-specific policy in dictating electricity system. The trends in individual electricity sources are clearly illustrated in **Figure 16**, which plots the magnitude of increase or decrease in the production of electricity from all sources w.r.t. reference.

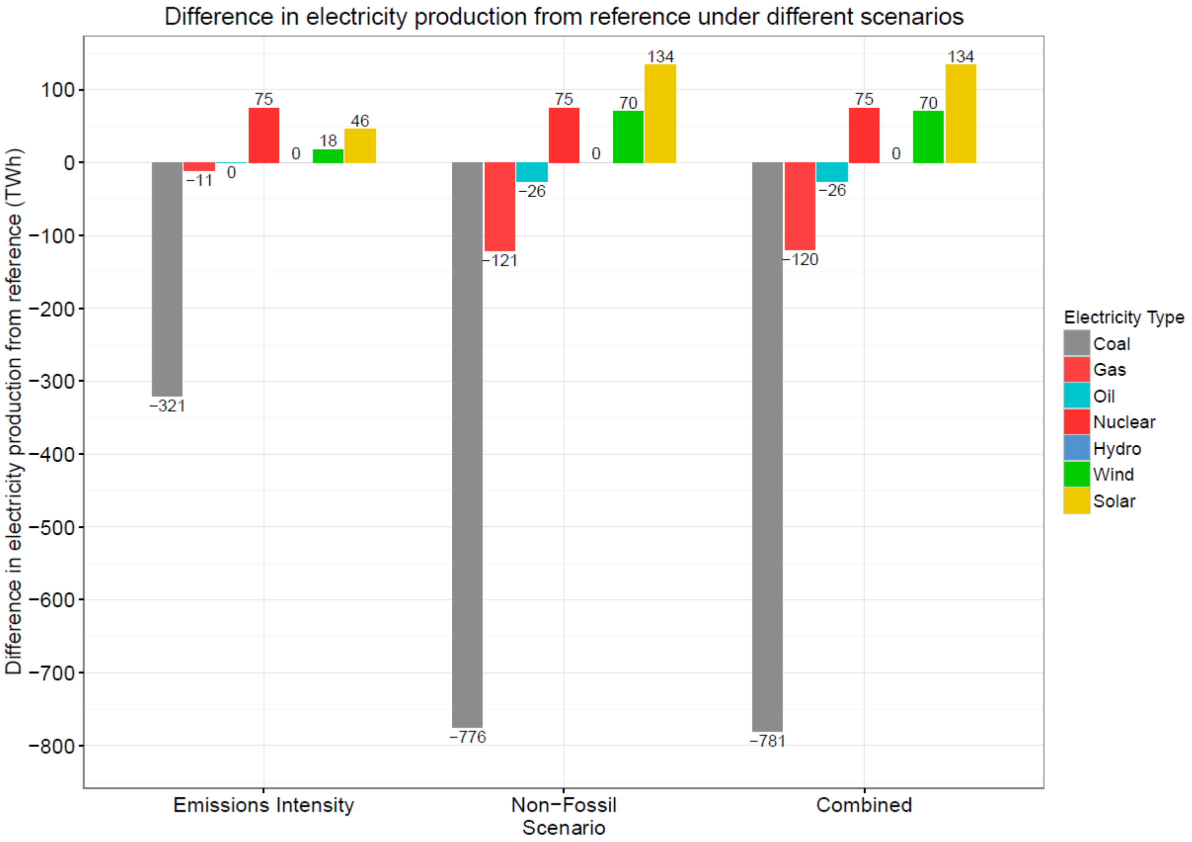

***Figure 16**: Source-wise difference in electricity production w.r.t. reference under different scenarios*

Figure 17 illustrates the change in production of various economic sectors under policy scenarios. The trends discussed earlier are further confirmed by observing changes in three key sectors – fossil electricity, non-fossil electricity, and coal. Fossil electricity drops modestly in emissions intensity scenario and sharply in non-fossil and combined scenarios. This is only partially compensated by a rise in non-fossil electricity, illustrating the observed fall in electricity levels. The evidence that non-fossil targets lead to leakage of CO_2 emitting sources from electricity to other energy intensive industries is evident from the trend in coal production, where a small increase is observed in non-fossil scenario over emissions intensity scenario.

Most other industries see relatively little change in production as they adapt to the changing energy mix by adjusting production methods.

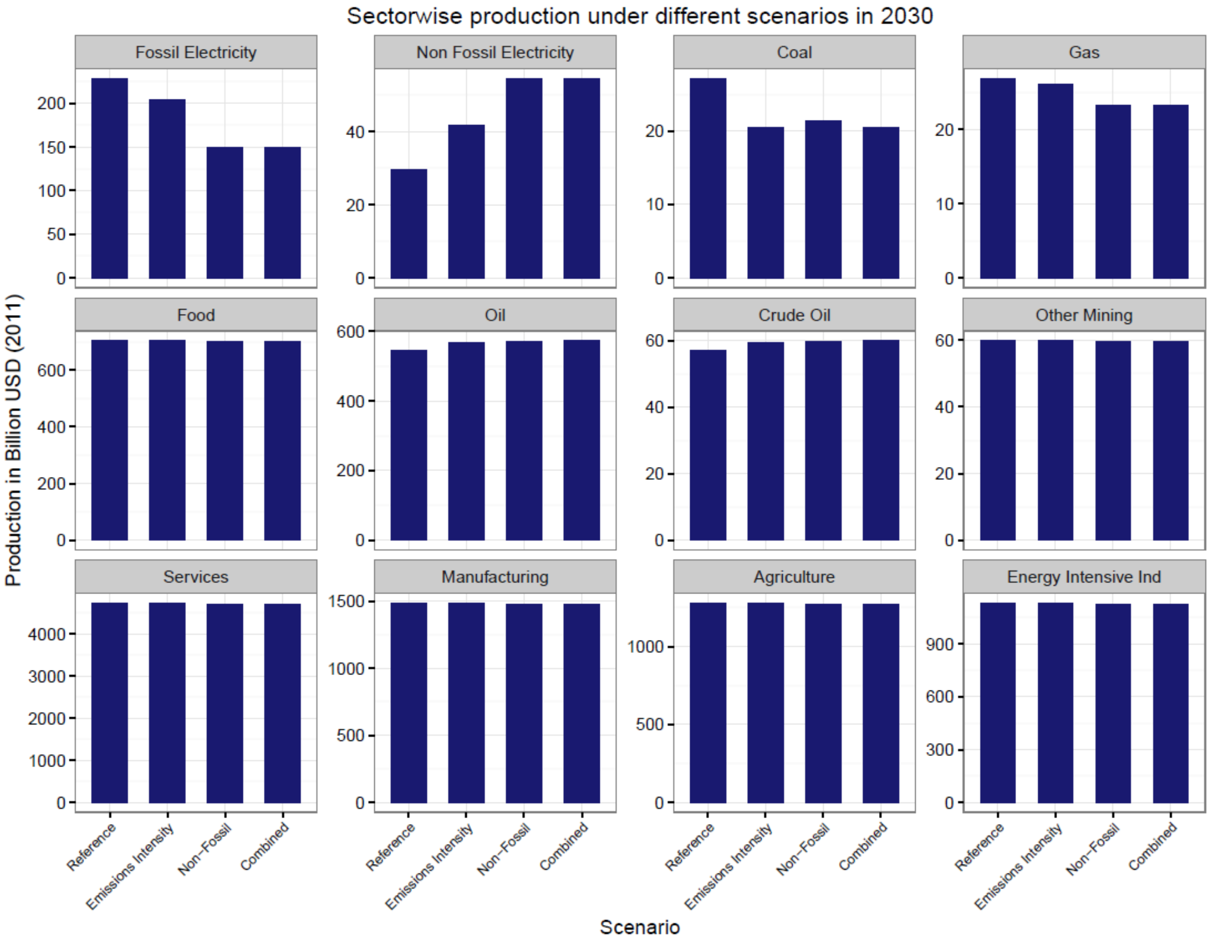

Figure 17: Production trends of different sectors in 2030 under reference and policy scenarios

4.2. The Impact of Alternative Wind and Solar Costs

While my base analysis suggests that technology specific policies prescribing non-fossil targets are considerably more expensive than economy-wide policies, the cost difference depends largely on the cost at which non-fossil electricity is available. Given the favorable policy and market environment for wind and solar power, and the drop in their generation costs over time, future costs remain uncertain. Studies suggest that by 2025 the global weighted average LCOE of solar PV could fall by as much as 59% and that of onshore wind could fall by 26% (IRENA 2016). Through the sensitivity analyses, I attempt to evaluate how varying wind and solar power costs would impact policy scenarios.

As wind power is reasonably represented in the benchmark data, the cost shares are considered representative and cost variation is simulated by varying the elasticity of substitution between the TSF and other inputs in the wind production block. Conceptually, a higher elasticity of substitution indicates reduced impact of the TSF constraint, leading to cheaper expansion of wind power capacity. The higher the substitution elasticity, the cheaper it would be to expand wind capacity. Variation in substitution elasticity thus serves as a proxy for the uncertainty in future wind power generation cost.

Simulating cost uncertainty for solar power is more straightforward. Following the advanced technology representation of solar, cost uncertainty is simulated by varying the markup on the cost of production. Conceptually, this may indicate availability of cheaper capital for building solar plants, a drop in solar panel prices, improvement through learning-by-doing leading to reduced labor inputs, decline in installation costs, and so on. Solar cost variation can also be simulated by varying substitution elasticity between TSF and other inputs, but the outcome will be conceptually similar.

4.2.1. Carbon Price and Welfare Loss under different scenarios and alternative renewable generation costs

Along with the reduction in consumer welfare as a metric for cost of climate policies, the model also provides estimates of the carbon price necessary to enforce the emissions intensity target in the emissions intensity and combined policy scenarios. **Table 8** illustrates both metrics as a function of varying solar and wind costs under emissions intensity and combined scenarios. The base results are highlighted. It is important to note that all scenarios listed here result in similar total emission levels in 2030.

***Table 8**: Comparison of carbon price and cost of emission reduction under different scenarios*

Scenario	**Carbon Price**		**Welfare Loss**	
	Emissions Intensity	**Combined**	**Emissions Intensity**	**Combined**
Wind Elasticity	USD (2011) per tonne of CO_2	USD (2011) per tonne of CO_2	USD (2011) per tonne CO_2 reduced	USD (2011) per tonne CO_2 reduced
0.10	18.38	0.00	0.48	24.48
0.20	17.96	0.00	0.38	19.24
0.29	17.40	2.06	0.27	11.35
0.35	16.89	4.29	0.18	6.55
0.40	16.34	6.24	0.08	3.71
0.45	15.66	7.67	-0.03	1.91
Solar Markup				
2	18.95	0.00	0.82	26.85
1.5	18.95	0.51	0.82	21.30
1.2	18.95	1.28	0.82	16.01
1	17.40	2.06	0.27	11.35
0.9	16.53	2.59	-0.36	8.57
0.8	15.68	3.25	-1.22	5.44

These results clearly highlight the tradeoffs between economy wide and technology specific policies. The following outcomes are noteworthy:

(i) Economy wide emission intensity targets lead to significantly higher carbon prices compared to those in combined targets. In combined targets, enforcement of a higher non-fossil electricity share and reduced electricity demand due to higher price brings total emissions close to the level required to meet emission intensity target. The remaining reduction can be met with much lower, or even zero, carbon prices. Thus, combined policies may result in politically feasible carbon prices.

(ii) In the emission intensity scenario, as expected, carbon price decreases with cheaper wind and solar power. Availability of cheaper wind and solar power lowers the marginal abatement cost, bringing down carbon price. On the contrary, and somewhat counterintuitively, increasingly cheap wind and solar power in combined scenario is associated with *increases* in the carbon price. This is explained by the opposing impacts of cheaper wind and solar power in a capacity based RPS policy. While cheaper wind and solar power facilitate emission reduction, they also increase total electricity demand due to lower average electricity costs. Higher electricity demand increases fossil electricity production (see **Figure 20** and **Figure 24**). The overall impact is dominated by higher total emissions (see **Figure 19** and **Figure 23**), resulting in higher marginal abatement costs, and consequently higher carbon prices.

(iii) Emissions intensity targets result in lower welfare loss, and may even lead to welfare gains, compared to combined targets. This follows directly from the efficiency of economy-wide carbon policies in achieving emission reduction. On the contrary, combined policy targets lead to higher welfare losses, higher by 42 times on a per ton CO_2 basis compared to the base case. Thus, while combined targets may lead to politically feasible carbon prices, the higher welfare loss highlights their inefficiency in reducing emissions.

(iv) The welfare loss decreases with cheaper wind and solar power in both scenarios. This follows directly from the availability of cheaper electricity, and consequently, comparatively lower reduction in consumption.

4.2.2. Impact of alternative wind costs on policy outcomes

As discussed in Section 3.4.1, wind power is specified in the model using a non-zero base elasticity of substitution between non-TSF composite and TSF, obtained from available literature. The cost of expanding wind power is sensitive to this elasticity, necessitating analysis based on alternative wind expansion costs. While the base case uses an elasticity value of 0.29, I analyze the interplay between wind expansion cost and policy scenarios by varying the elasticity. As discussed earlier, a higher substitution elasticity between TSF and other inputs facilitates a cheaper expansion of wind power.

Figure 18 shows the costs of emission reduction under different scenarios for varying cost of expanding wind generation in terms of elasticity. Owing to low levels of wind penetration in emissions intensity scenario, the welfare loss is generally very low, and further decreases at lower wind expansion costs. In the non-fossil targets scenario, the cost of emission reduction drops sharply with decreasing wind expansion costs. Low wind expansion costs result in low welfare losses in combined policy setting as well. These results illustrate that at low renewable energy costs, achieving both economy wide targets as well as technology specific targets can be relatively politically feasible. At high wind expansion costs, reducing emission is expensive in both non-fossil and combined policy scenarios. Further, as **Figure 19** shows, final emission levels in combined and emissions intensity scenarios are similar – an outcome ensured by the emissions intensity limits.

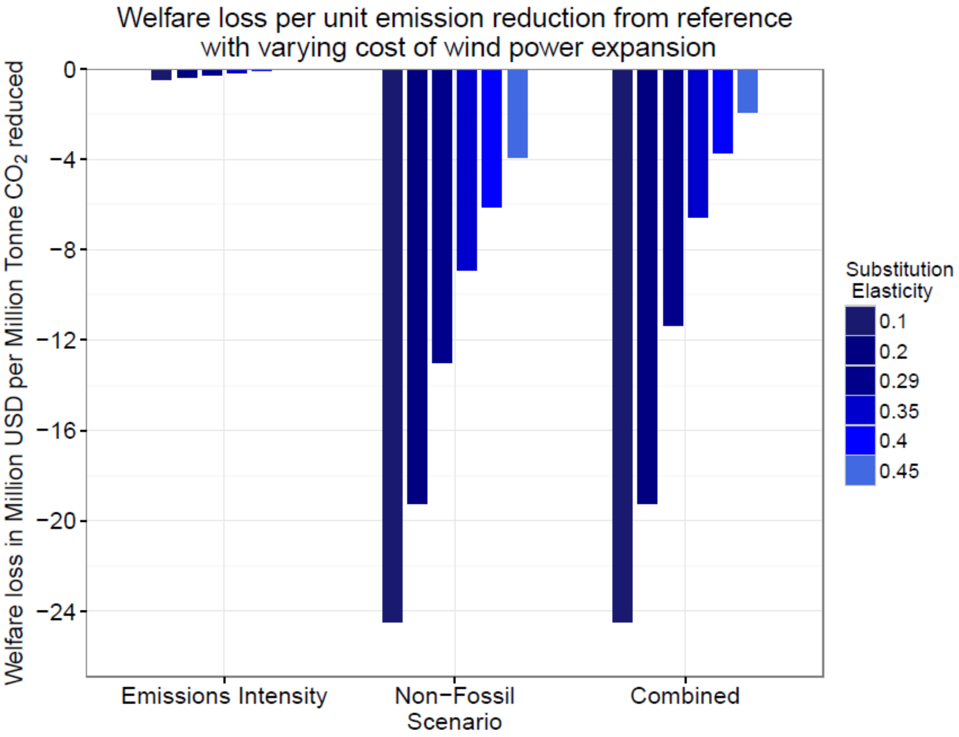

***Figure 18**: Variation in cost of emissions reduction with varying wind costs*

Electricity levels at different wind costs are plotted in **Figure 20**. At low wind costs, total electricity levels are comparable in all policy scenarios. In a pure carbon price setting, cheaper wind power drives down marginal abatement costs and leads to a decline in fossil electricity, compensated by higher levels of wind power in the non-fossil mix. On the contrary, when non-fossil capacity targets are included, the availability of cheap wind power in the electricity mix decreases the average electricity price, resulting in a demand pull, and consequently higher levels of fossil electricity as well, while maintaining the required non-fossil share of 28%. This ties in with the lower welfare losses and higher emission levels under the non-fossil scenario observed in **Figure 18** and **Figure 19** respectively.

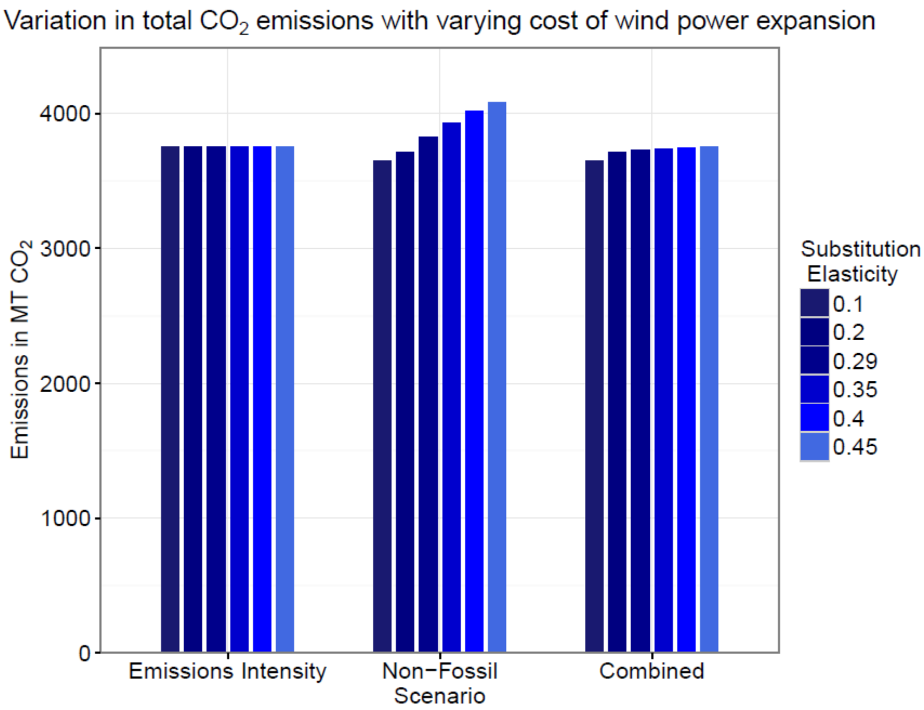

Figure 19*: Variation in total emissions with varying wind costs*

Figure 21 plots implicit subsidy required to enforce non-fossil targets in the electricity production mix. Higher wind expansion costs require higher subsidies per KWh of wind power production. Besides, subsidy requirement decreases slightly in the combined policy scenario, as putting limits on emissions intensity incentivizes non-fossil sources of electricity. It is important to note that these values reflect the subsidy for adding the last unit to realize the capacity target of 28%. Lower levels of non-fossil penetration will have smaller subsidy requirement.

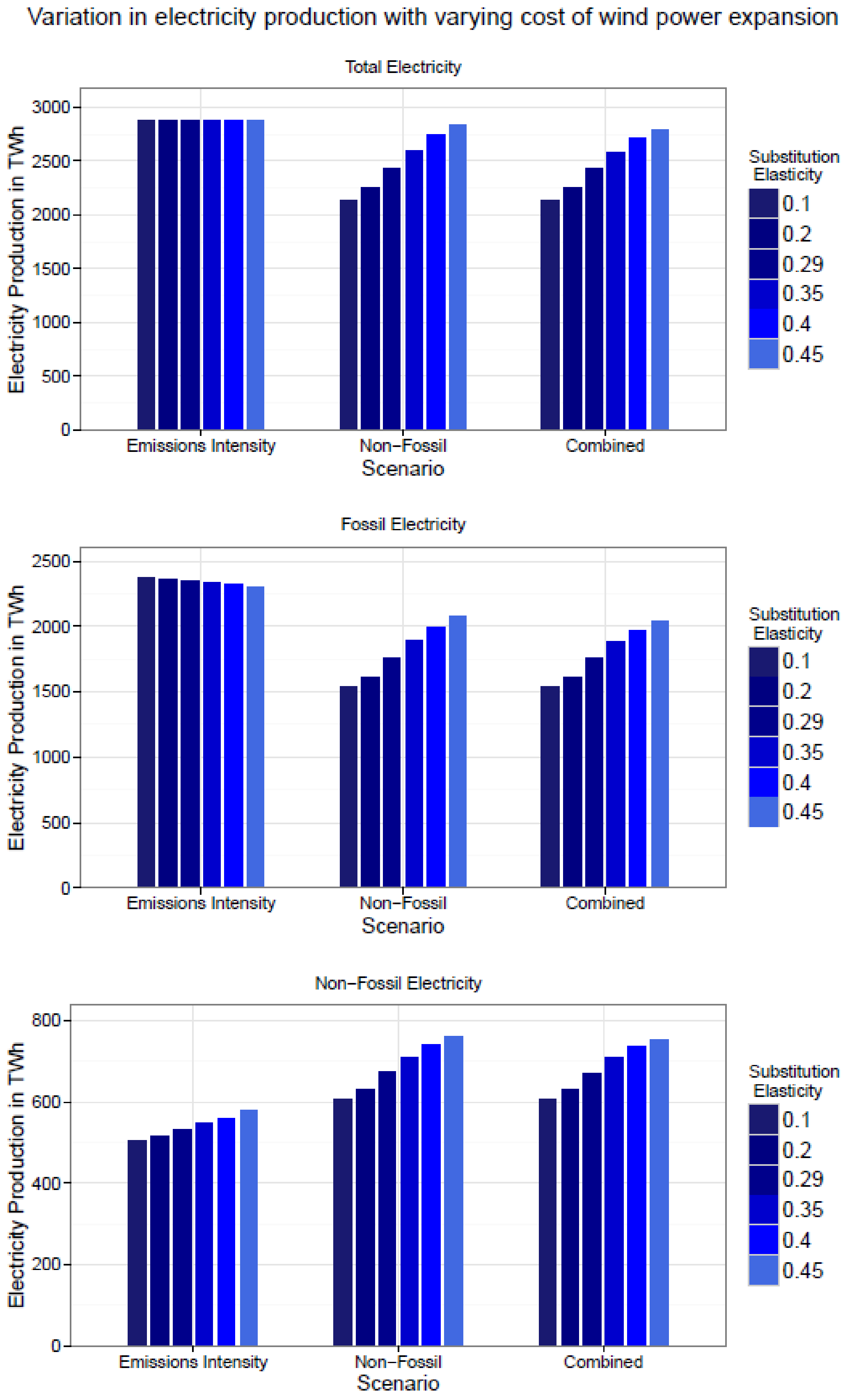

***Figure 20**: Variation in electricity levels with varying wind costs*

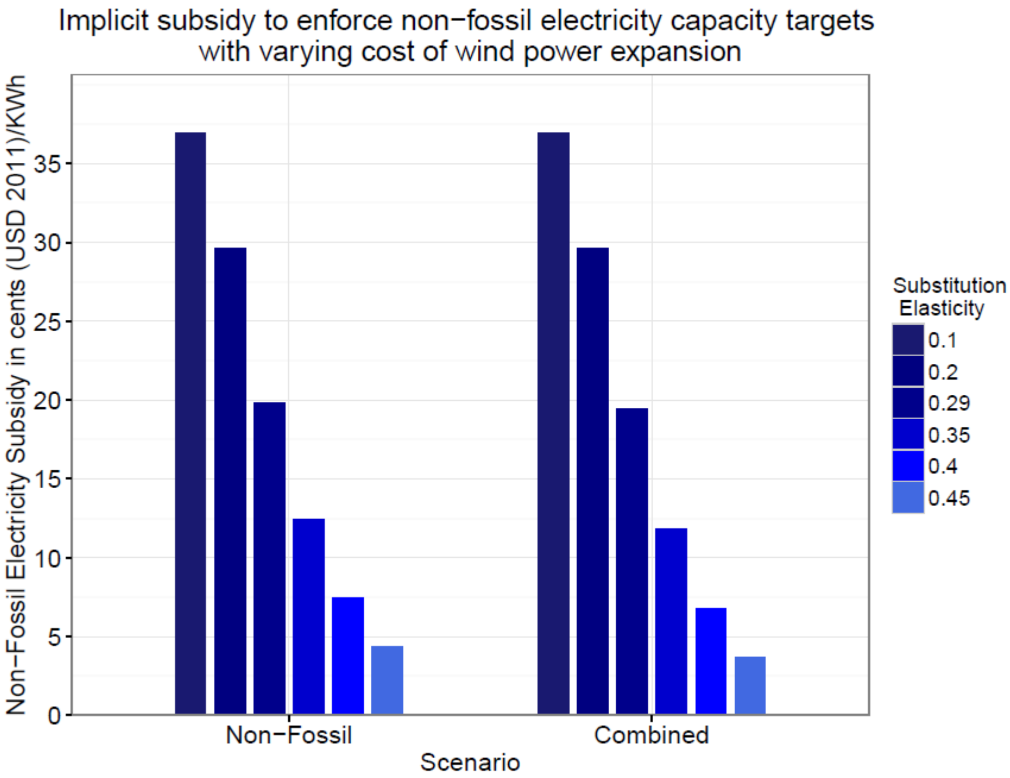

Figure 21*: Variation in non-fossil subsidy requirement with varying wind costs*

4.2.3. Impact of alternative solar costs on policy outcomes

The policy implications of varying cost of solar power is simulated by varying the markup on the inputs to solar production. In physical terms, a declining markup represents declining cost of solar production due to various factors as discussed earlier. In order to study the impact of cost of solar production independent of the cost of wind, the elasticity of substitution between TSF and other inputs in the wind production block is kept constant at 0.29 in the following scenarios.

Figure 22 compares welfare loss across policies with varying costs of solar production. Under the emissions intensity scenario, low solar prices may even lead to welfare gains, as cheaper solar power replaces expensive fossil power under a carbon price, leading to higher electricity levels (see **Figure 24**). Further, similar to wind power, at low solar costs, the welfare losses in non-fossil and combined policy scenarios drop significantly. Importantly, while I do not illustrate it for the sake of simplicity, the combined impact of lower solar and wind costs may decrease the welfare loss further, bringing it closer to that in the emissions intensity scenario.

Plotting CO_2 emissions with varying solar costs (**Figure 23**) also reveals a pattern similar to that with varying wind costs. Total emissions are higher in the non-fossil scenario, and increase with decreasing cost of solar production.

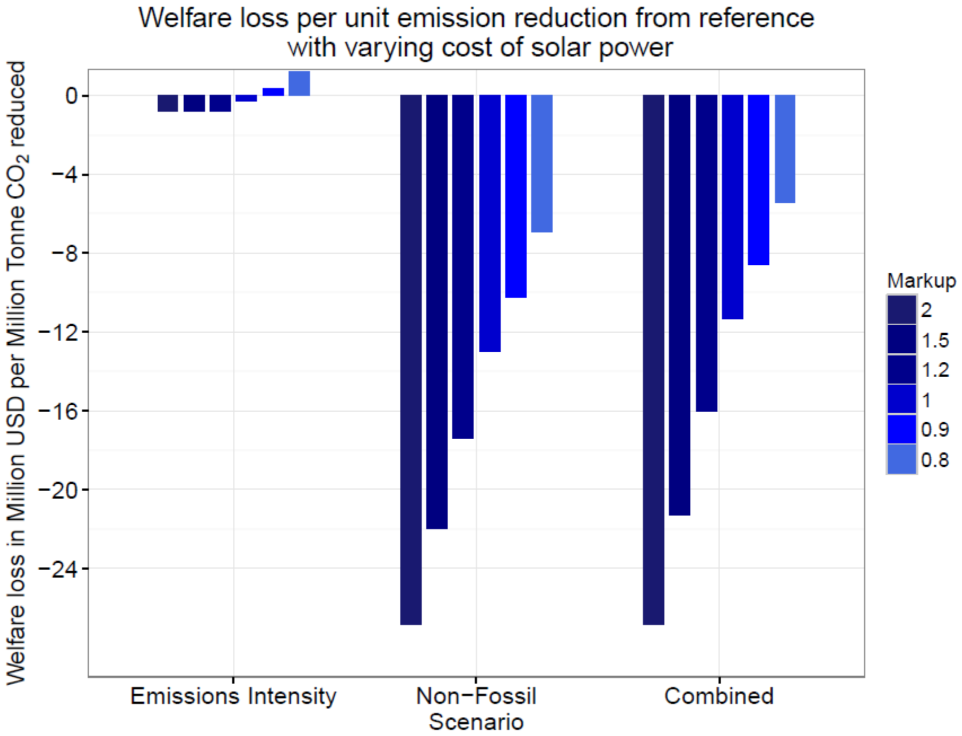

Figure 22: *Variation in cost of emissions reduction with varying solar costs*

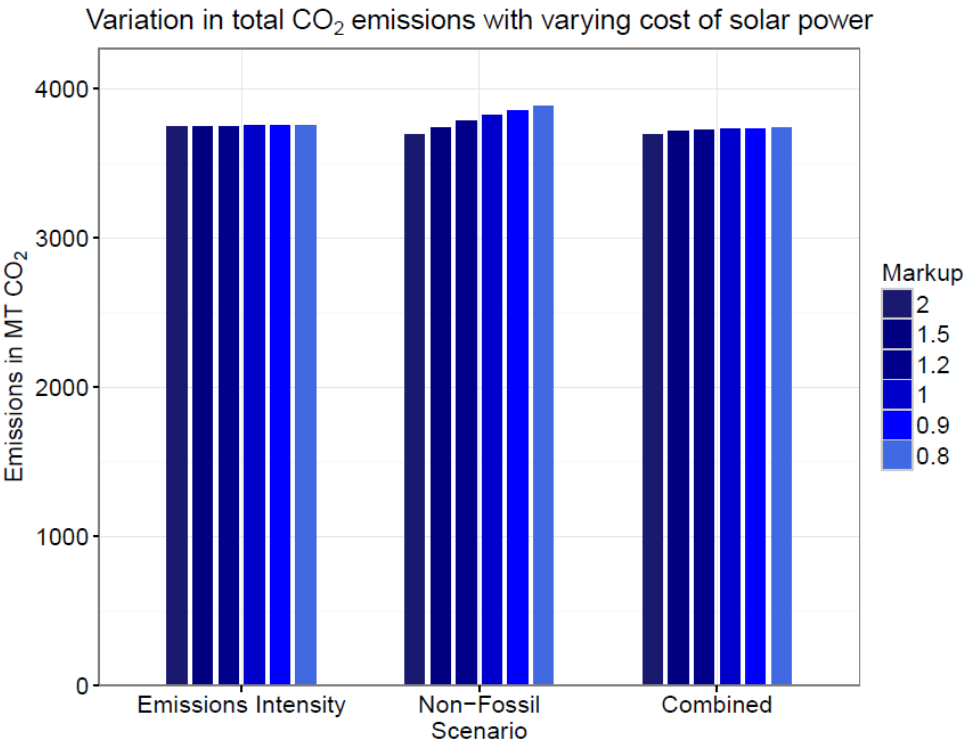

Figure 23: *Variation in total emissions with varying solar costs*

Further, as **Figure 24** and **Figure 25** illustrate, the patterns observed in electricity mix and non-fossil subsidy with varying solar costs are also similar to those observed with varying wind costs.

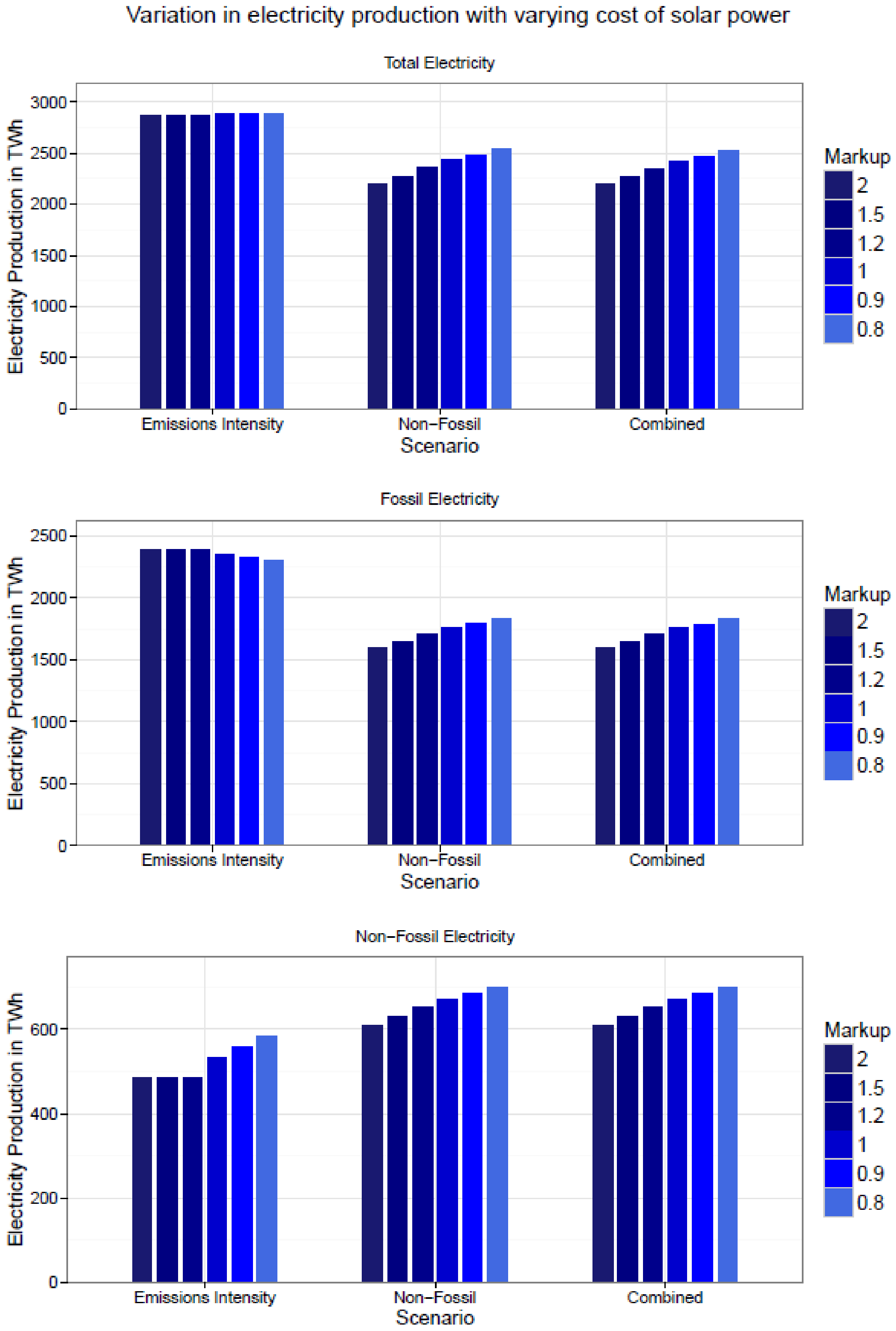

***Figure 24**: Variation in electricity levels with varying solar costs*

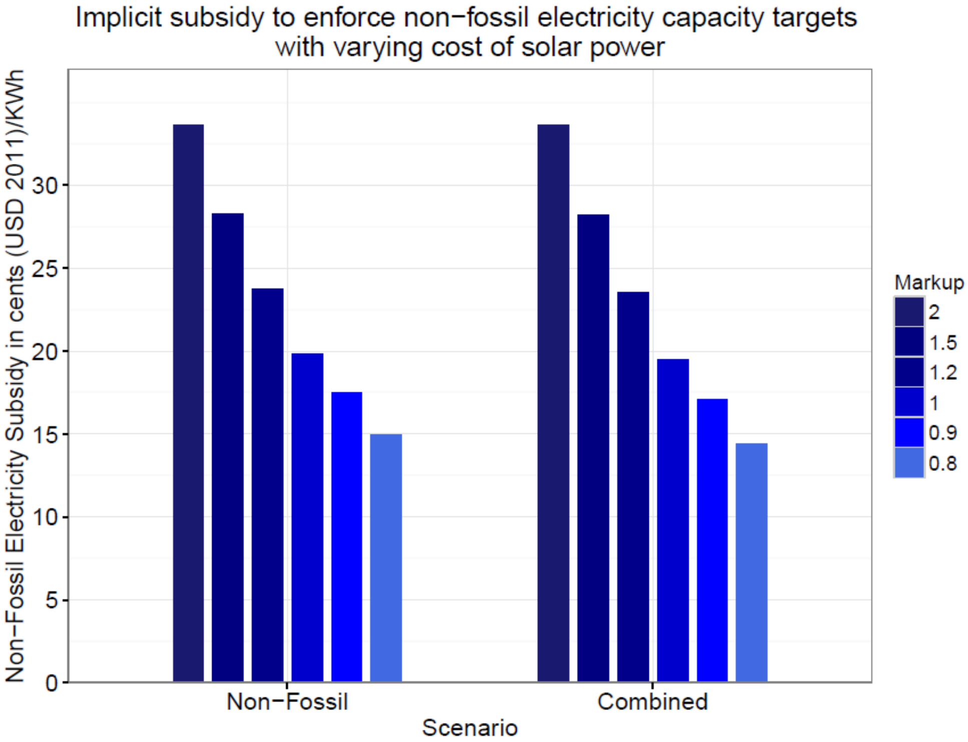

***Figure 25**: Variation in non-fossil subsidy requirement with varying solar costs*

5. Conclusion

In the preceding chapters, I have laid out the complexities arising from the interaction of climate change with country specific challenges faced by the policymakers in India. To address the dual challenges of maintaining economic growth while limiting GHG emissions, India's climate commitments to the Paris agreement include both economy-wide and sector specific policies. Analyzing the impact of these policies on emissions, consumer welfare, electricity system, and the interests of different stakeholder groups can help adjust policies to improve their efficiency in achieving desired outcomes.

I have explored theoretical arguments for addressing climate change when considered with and without political economy constraints such as the collective action problem (Olson 1984) and the capture of regulatory interests by large and concentrated stakeholders (Stigler 1971). Recognizing that political economy constraints render it difficult to achieve a Pareto optimal solution to climate change, the implications of the theory of second best as applied to climate change have been discussed (Lipsey & Lancaster 1956; Jenkins & Karplus 2016).

To analyze the efficiency and impact of India's climate policies within the theoretical framework of second best climate policies, I have employed a CGE model of the Indian economy with detailed representation of the electricity sector. The design of the model and the research questions are based both on theory as well as qualitative inputs on policy preferences and possibilities. In particular, I have endeavored to analyze how sector specific climate policies compare with economy-wide policies on a variety of parameters such as consumer welfare, electricity levels and mix, and sector-wise production, in achieving desired levels of emission reduction.

The modeling results provide important quantitative insights and help identify stakeholders that stand to benefit or lose, along with the extent of impact on them. An economy-wide emissions reduction policy simulated through a carbon price results in the lowest decline in consumer welfare. Further, emissions decrease across all fossil energy consuming sectors, and not only in the electricity sector. On the contrary, policies that enforce non-fossil electricity capacity targets are not only more expensive per unit of emission reduction, but are also less effective, as emissions leak from electricity to other energy intensive sectors. In reality, India's policies aim to achieve both economy-wide emission reduction and non-fossil electricity capacity targets. The non-fossil targets constitute one of the many measures that can help achieve economy-wide emission reduction.

Under a pure carbon pricing policy without non-fossil targets, the model predicts a carbon price of \$17.40 per tonne of CO_2 (in 2011 USD) to achieve India's NDC target of 33-35% reduction in emissions intensity of the GDP in 2030 over 2011 level. This price is higher than the carbon prices observed in most developed nations (Jenkins & Karplus 2016), suggesting its political intractability. Enforcing non-fossil targets brings down the price to US$ 2.06 per tonne of CO_2, which will likely witness decreased resistance from affected stakeholders. However, consumer welfare loss is higher in the combined policy setting compared to a carbon pricing policy. The implications of lower but concentrated carbon price and higher but dispersed welfare loss need to be considered while comparing the political feasibility of these policies.

The decline in wind and solar costs across the world motivates my inquiry into the interaction of above policy outcomes with varying costs of wind and solar power. As expected, welfare losses under non-fossil electricity targets decrease sharply at lower wind and solar costs and are only slightly higher than those under a carbon pricing policy at the lowest cost levels that I consider. This suggests that declining wind and solar costs may pave way for more aggressive decarbonization policies in the future.

While so far I have discussed the role of political economic factors in the choice of policies, equally important is the capability of existing institutions in implementing the chosen policies. In section 2.4, I briefly discussed the institutional challenges with India's electricity sector. These challenges, if not appropriately addressed, can jeopardize the implementation of well-intentioned policies. Further, the expansion of energy access to unelectrified households will also interact with the above policy outcomes. While I currently do not simulate these interactions, the existing model outcomes offer suggestions on possible pathways.

I expand these ideas in the subsequent sections of this chapter. First, I outline the potential winners and losers under different policies, and assess their expected support or opposition to respective policies. I then discuss the drivers of declining solar and wind costs across the world, and how would these dynamics interact with India's climate policies. Subsequently, I explore the institutional challenges in India's electricity distribution sector, how they may hinder realization of India's climate policy targets, and what are the synergies in addressing these challenges and facilitating climate mitigation. This is followed by a discussion of the expansion of energy access and its interaction with climate policies. Finally, I conclude by discussing the possibilities of future work.

5.1. Distribution of Impacts of India's Climate Policies

The model outcomes are indicative of the impacts of India's climate policies on different stakeholders. These impacts may suggest how political economy factors will support or restrict the design and implementation of policies. Stakeholder groups that benefit from particular policies are likely to support them, while those whose economic interests face damage are expected to raise opposition. An understanding of these political economy interactions may suggest policy adaptations to gain broad based support.

At the industry end, three outcomes are noteworthy. First, the fossil industry suffers losses under any climate policy compared to the counterfactual of no climate policy. In particular, coal production and coal based electricity see sharp declines. That India has vast coal reserves, that the coal industry is largely government owned and operated, and that it is among the largest formal employers in India[42] indicate that the industry is likely to oppose stringent climate policies. Second, while all climate policies negatively impact the coal sector, the impact of non-fossil electricity targets is slightly less strong as compared to an economy-wide climate policy, as there is no binding constraint on emissions. This results from non-fossil targets driving away coal demand from electricity to other sectors. Thus, it is expected that the coal industry will more strongly oppose an economy wide emission policy as compared to an electricity-sector specific policy. Third, the non-fossil electricity sectors, particularly solar and wind power, benefit from all climate policies. While the non-fossil electricity industry is not as large in terms of capacity as coal or thermal power, the steep growth in recent years has been accompanied by entry of large industrial players, with arguably more political clout.[43] Besides, as discussed earlier, the market and policy environment for non-fossil electricity is very favorable. These factors suggest that the support for climate policies favoring non-fossil electricity is expected to continue.

The impact on consumers entails assessing welfare losses. By the virtue of its economic efficiency, an economy-wide carbon pricing policy leads to least consumer welfare loss. Physically, this means that under an economy-wide carbon price, a consumer would have to give up the least amount of her consumption to maintain the same price levels. The model suggests near zero welfare loss on a per ton CO_2 basis under an economy-wide policy. Introducing non-fossil electricity targets along with carbon price increases the consumer welfare loss significantly, primarily because of the impact of more expensive electricity across the economy. Thus, it can be expected that all else equal, a consumer would favor economy wide carbon pricing with minimal welfare loss over sector specific policies. Further, while this is not currently modeled, economists have argued in favor of recycling carbon pricing revenues to compensate consumers for the welfare loss (Metcalf 2007; Jenkins & Karplus 2016). This may help build more consumer support for carbon pricing.

These implication are summarized in **Table 9** where different colors represent the direction and magnitude of the impact of climate policies on different stakeholders. The impacts are relative to the reference case of no climate policy. It is notable that imposition of non-fossil electricity capacity targets favors the non-fossil industry at the expense of consumer welfare. One possible solution to gain across-the-

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[42] As on Mar 31, 2016, Coal India Limited – India's state owned coal mining company – employed 333,097 personnel (Coal India Limited 2016).
[43] See, for example, LiveMint (2017a)

board support for policies could involve compensatory revenue transfer to losing stakeholders, particularly to the coal and fossil electricity industries, and to consumers (Jenkins & Karplus 2016).

***Table 9**: Impact of India's climate policies on key stakeholders*

Stakeholder		**Economy-wide carbon pricing**	**Economy-wide carbon pricing + Non-fossil electricity target**
Industry	Coal	🟧	🟨
	Fossil Electricity	🟨	🟧
	Non-Fossil Electricity	🟢	🟩
Consumer		🟨	🟧

🟧	🟨	🟢	🟩
Strongly negative	Moderately negative	Moderately positive	Strongly positive

5.2. Declining Costs of Solar and Wind Power: Path towards Stronger Decarbonizing Policies

The declining costs of solar and wind power have been briefly discussed earlier, along with modeling of their impacts on policy outcomes. **Figure 26** (IRENA 2016) outlines historical decline and future projection of global weighted average installed cost of utility scale solar PV plants. Evidently, all cost components have seen cost reductions and the trend is expected to continue in the future. **Figure 27** (IRENA 2016) plots the LCOE of onshore wind power from 1983-2025, illustrating trends and projections similar to that for solar power. In general, by 2025, the global weighted average LCOE of solar PV, onshore wind, and offshore wind are expected to drop by 59%, 25%, and 35% respectively (IRENA 2016).

Recent works highlighting the drivers behind falling costs may shed light on their interactions with climate policies. Kavlak et al. (2016) analyze the causes of cost decline of solar PV modules in 1980-2012, and classify the drivers under low and high level mechanisms. They illustrate that while R&D was the key high level mechanism for cost reduction in 1980-2001, economies of scale have become a more significant cause of cost reduction since 2001 (**Figure 28**). This is an important finding as it provides evidence for the synergies between policy support for renewables and possibilities of stronger decarbonization pathways as renewable costs decline. Policy support for renewable electricity may drive investment and encourage scale economies (for example: in PV manufacturing), which, in turn, drive down costs, and may provide possibilities for not only increasing renewable mandates but also adopting climate policies covering a wider economic base.

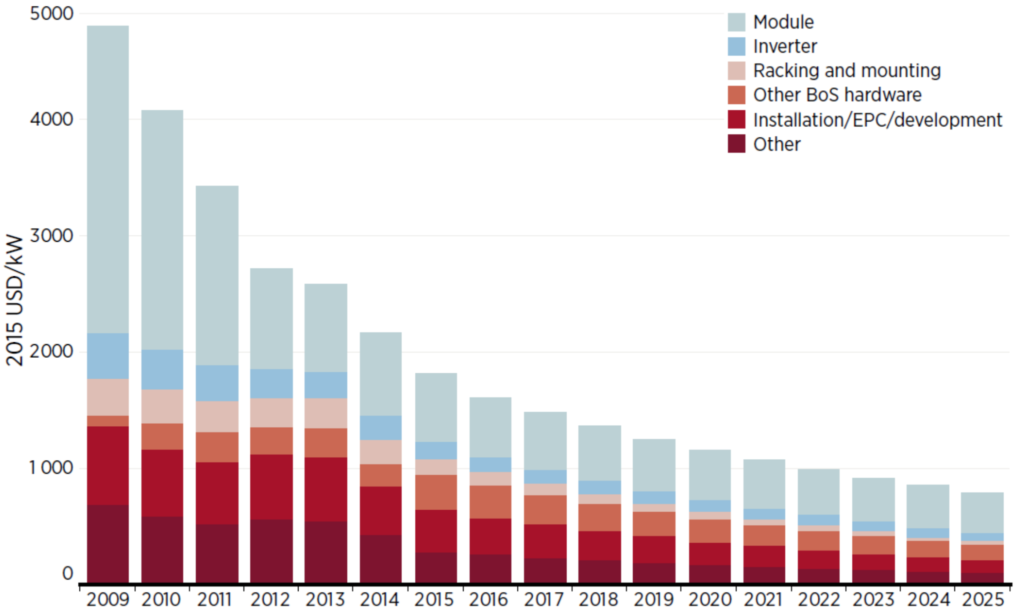

Figure 26*: Global weighted average utility-scale solar PV total installed costs, 2009-25, IRENA (2016)*

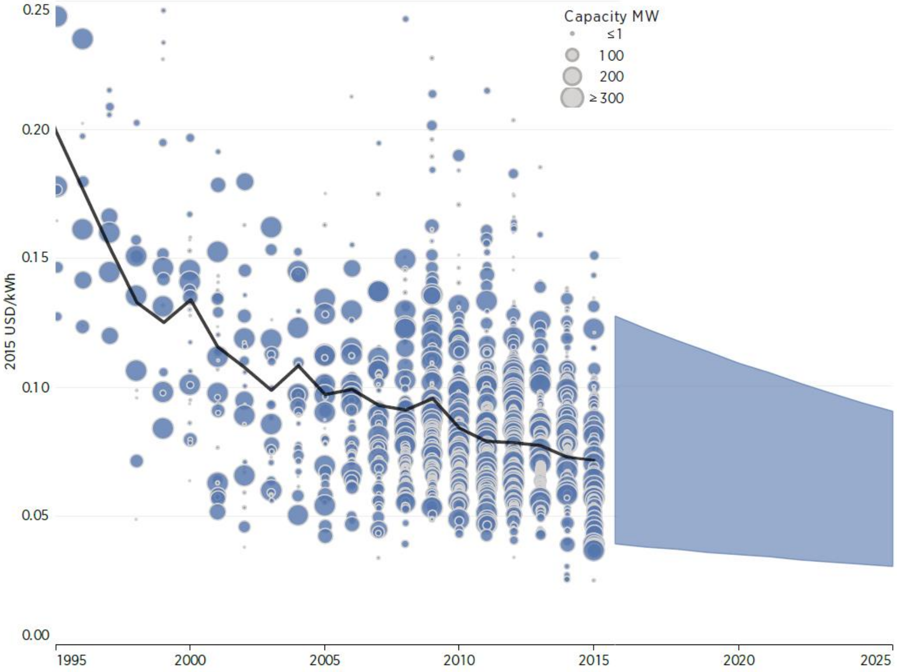

Figure 27*: Levelised cost of electricity of onshore wind, 1983-2025, IRENA (2016)*

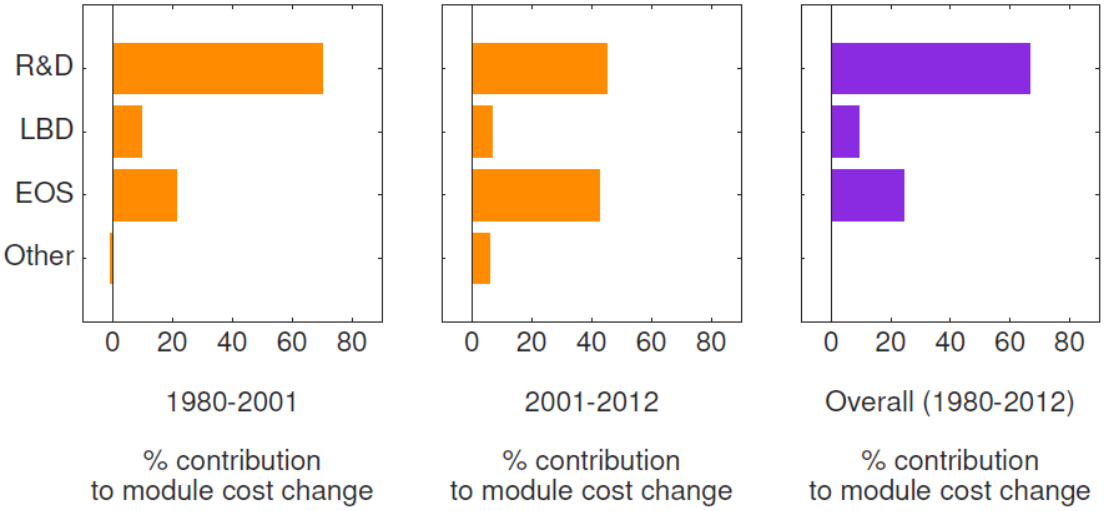

***Figure 28**: Percentage contribution of the high-level mechanisms to PV module cost decline; R&D: Research and development, LBD: Learning by doing, EOS: Economies of scale, Other: other mechanisms such as spillovers (Kavlak et al. 2016)*

The results in this work provide evidence for the constructive interactions between declining renewable costs and India's climate policies, and indicate the possibility of stronger decarbonization pathways. Notable implications are:

(i) At lower costs, inclusion of wind and solar power in the electricity mix will drive down electricity costs, and therefore not have a negative impact on consumption. This could enable achieving India's dual policy objectives of sustaining electricity growth while limiting GHG emissions.

(ii) Availability of cheaper electricity will contain consumer welfare loss, likely helping gain support for implementation of more aggressive climate targets.

(iii) Declining wind and solar costs interact in a complex manner with the fossil electricity industry. Under non-fossil targets (with or without economy-wide policies), lower electricity price due to cheaper wind and solar power will drive up overall electricity demand, pulling with it the share of fossil electricity as well. In the absence of economy-wide emission constraints, this may increase total emissions. Consequently, cheaper wind and solar power will necessitate a higher carbon price to regulate CO_2 emissions from fossil electricity, likely resulting in opposition from affected industry groups. Thus, while cheaper wind and solar may help gain consumer support for stronger climate policies, the fossil electricity industry is likely to oppose any stronger action. This may be addressed by including appropriate revenue transfer measures.

It should be noted that technology constraints such as grid intermittency challenges may eventually constrain the extent of reduction in wind and solar power costs, affecting the policy synergies. Davidson et al. (2016) model the possible incorporation of wind energy into China's electricity mix, and estimate that without increasing operational flexibility of China's coal-heavy electricity mix, only 10% of the total estimated physical potential of wind resources will be realized. The coal dominated Indian electricity sector may face similar challenges, restricting addition of intermittent wind and solar power in the grid.

5.3. Institutional Challenges with India's Electricity Distribution Sector

The distribution sector in India's electricity system poses several institutional challenges to implementation of climate policies, particularly to policies that pertain to the electricity sector. The poor financial health of state DISCOMs has required repeated bailouts from central and state governments,[44] but in 2015, the outstanding DISCOM debt again stood at $66 billion (GoI 2015b). Several operational features of the DISCOM sector perpetuate these financial crises, and are also likely to jeopardize climate mitigation policies if not timely addressed. The following institutional challenges bear mention in this context:

(i) **High AT&C Losses**: The aggregate transmission and commercial losses of electricity in India amounted to 22.07% in 2013-14 (CEA 2014), implying that utilities did not get paid for more than one-fifth of the power that they purchased and supplied. Factors causing these losses include: poor distribution infrastructure, unmetered agricultural electricity, theft, inaccurate billing, poor targeting of cross subsidies, and non-payment of bills. The losses have declined considerably over the years, falling from as high as 38% in 2003, but are still substantial.

(ii) **Underpricing of tariffs**: Over the years, the average billed tariff across most of the country has seen a decline as compared to average cost. Pargal & Banerjee (2014) note that in 2003, the states were on an aggregate charging an average billed tariff that was well above cost recovery, and the losses were mainly in distribution. However, in 2011, the states were on an aggregate charging below cost recovery. They further note that an increasing trend of underpricing may make the positive trend in declining distribution losses less effective. Maithani & Gupta (2015) indicate that underpricing is done to keep tariffs below cost for large sections of the population, and particularly to subsidize electricity to small scale rural consumers.

(iii) **Unmetered agricultural demand and cross subsidies**: The electricity supplied to agricultural consumers is primarily unmetered and the consumption is calculated from engineering estimates of power requirement of water pumps. While the share of agriculture in total electricity consumption was 23 percent in 2011, estimates suggest that the revenues were only 7 percent of the total (Pargal & Banerjee 2014). The lost revenue is cross subsidized by overcharging industrial and commercial consumers. However, with the delicensing of captive generation, and with

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[44] Two successive debt restructuring schemes in 2001 and 2012 offered effective bailout packages amounting to $7.4 billion and $18.7 billion respectively (Pargal & Banerjee 2014).

availability of solar power at tariffs lower than regular utility based commercial tariffs,[45] commercial enterprises may move away from the grid, rendering the cross subsidies unsustainable.

These challenges not only decrease the efficiency of the electricity sector, but also threaten the implementation of climate policies that drive mitigation through the sector. For instance, high AT&C losses compound the financial implication of low capacity factors of solar and wind power, making them less lucrative for utilities. Further, underpricing of tariffs makes it financially unviable for utilities to add expensive solar and wind power to their purchase mix. Unmetered agricultural demand and loss of commercial consumers with high WTP further constrains the purchasing capability of utilities. Utilities require operational efficiency and financial viability to help realize gains from any climate policy – be it the economy-wide carbon pricing regime or non-fossil capacity targets. My results show that the impacts of both of these policies are driven by increase in non-fossil electricity. However, in its current state, the model does not account for the presence of institutional barriers that may deter inclusion of non-fossil electricity in the mix. The magnitude of the impact of policies may thus be far lower in the presence of these barriers.

These challenges are recognized by policymakers in India. The operational improvements prescribed in UDAY, the latest scheme for financial turnaround of DISCOMs, attempt to address them. Along with short term debt restructuring, the scheme aims long term operational improvements. Certain salient features include (Ministry of Power 2015):

(i) Quarterly tariff increase
(ii) Improving billing efficiency through metering and tracking of losses
(iii) Augmenting electricity infrastructure and introducing smart metering technologies
(iv) Demand side management to improve efficiency
(v) Ensuring states' compliance with renewable purchase obligations (RPOs)

Implementation of these performance improvement measures will be important for achieving the objectives of India's climate policies.

5.4. Increasing Energy Access along with GHG Mitigation Policies: Conflicts and Synergies

In section 2.4.5, I discussed the gap in electricity access in India and highlighted its importance for policymakers. Expanding electricity access to the currently unelectrified 45.5 million rural households[46] is

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[45] See, for example, LiveMint (2017a)

[46] Source: REC (2017), accessed on May 9, 2017

a policy priority, as well as a complex challenge, when considered along with India's climate mitigation policies. While I have not yet included expansion of energy access in the model, a theoretical discussion of likely interactions can be developed from the existing modeling outcomes.

Increase in energy access can be modeled as an exogenous increase in electricity demand beyond the demand driven by endogenous economic growth. This exogenous increase would represent both providing electricity to currently unelectrified households as well as increasing the availability of electricity to electrified rural households. Importantly, this demand would serve rural households with lower disposable income who would be less inclined to pay for expensive electricity. The addition in electricity mix should thus not come at a higher price. In view of the modeling outcomes, and assuming that expanding energy access is a priority, the following observations can be made:

(i) While all climate policies lead to increase in electricity prices, the increase is lower in an economy-wide policy, compared to a non-fossil target policy. Adding more non-fossil electricity in the mix, while their costs are still high, will make electricity more expensive and may conflict with the objective of expanding energy access. All else equal, an economy-wide emissions policy will be the least conflicting with expanding energy access.

(ii) The above may not hold true if non-fossil electricity costs see sharp declines. As seen in section 4.2, lower wind and solar costs drive up electricity demand in non-fossil and combined policy scenarios. Policy synergies that decrease renewable costs will thus help achieve the dual objectives of expanding access and limiting emissions.

(iii) Until the required drop in non-fossil electricity costs is observed, subsidies can be employed either on the supply side to keep non-fossil electricity costs low, or on the demand side to keep prices low. However, these subsidies would arguably lead to higher welfare losses.

A side note beyond the modeling outcomes is pertinent. Recognizing the multiple challenges with utilities that make grid expansion challenging, off-grid systems may be employed to expand access. Indeed, policymakers recognize this opportunity, and have included support measures for rural off-grid system developers (Kumar & Chaterjee 2012). While this would arguably dissociate electricity access expansion from the DISCOM challenges, higher cost of off-grid electricity would nevertheless require subsidy support, adding to welfare loss.

To summarize, until the marginal cost of non-fossil power does not compare with the marginal cost of thermal power (accounting for costs of last mile connectivity), achieving the dual policy objectives of expanding energy access and mitigating GHG emissions would require subsidy support.

5.5. Future Work

The existing model provides opportunities for several future improvements. To begin with, as discussed in the previous section, the expansion of electricity access can be modeled as an exogenous demand increase in electricity. While I have qualitatively discussed possible outcomes of expanding access while pursuing climate policies, enhancing the model will provide quantitative insights on the extent of these impacts. It will also facilitate evaluation of required subsidies and their welfare impact.

The current version of the model solves statically in two states – 2011 and 2030. The model can be made recursive dynamic to study the pathways of policy impacts from the present to 2030. This may also allow for assessing whether intermediate policy objectives (such as the renewable targets for 2022) will be achieved under proposed policies.

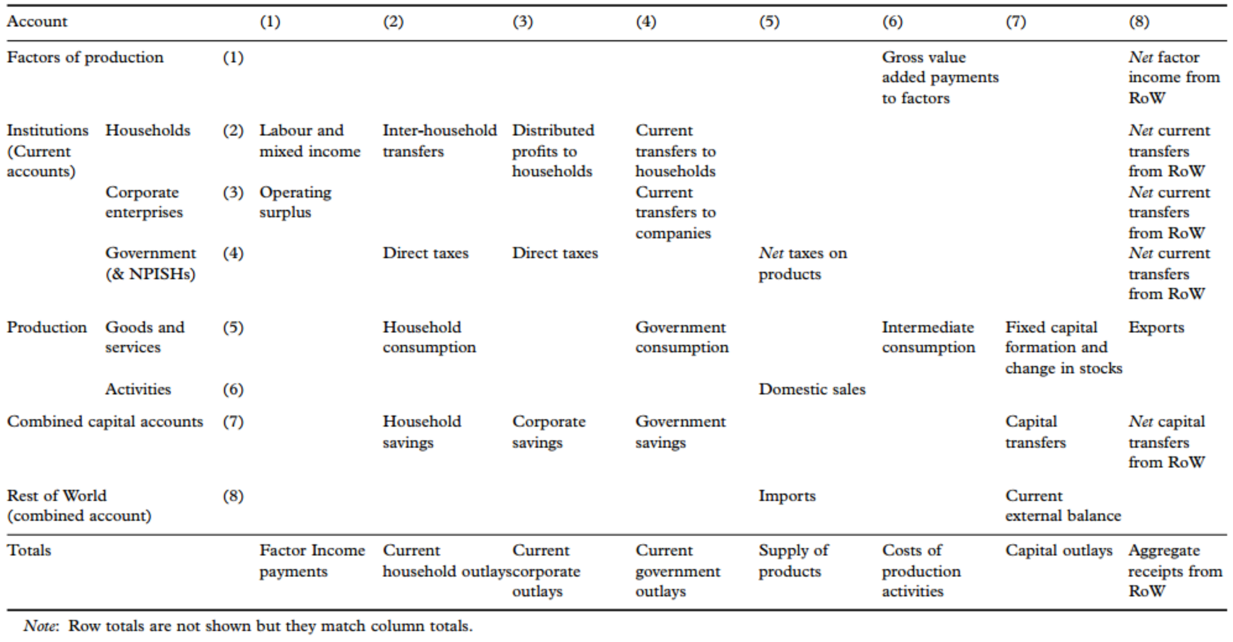
Recognizing the importance of wind and solar technologies in achieving India's climate policy objectives, a third improvement could include enhancing the representation of wind and solar power in the model. For instance, solar power could be split into utility scale and rooftop. Wind power could be disaggregated into on shore and off shore – to account for future offshore wind power addition in India.

Further, with one representative household, the model currently does not capture income and expenditure heterogeneity among households in India. Incorporating household heterogeneity in the model can provide valuable insights into the impact of climate policies across diverse income groups. It will also facilitate more accurate analysis of the impact of compensatory revenue transfer schemes.

Finally, recognizing the air pollution challenges faced by India, the economic model can be combined with an atmospheric model to assess the air quality co-benefits of climate policies.

This thesis serves as a strong foundation for expanding the model along the above mentioned pathways.

Appendix A: Illustrative Social Accounting Matrix (SAM)



Account			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Factors of production		(1)						Gross value added payments to factors		*Net* factor income from RoW
Institutions (Current accounts)	Households	(2)	Labour and mixed income	Inter-household transfers	Distributed profits to households	Current transfers to households				*Net* current transfers from RoW
	Corporate enterprises	(3)	Operating surplus			Current transfers to companies				*Net* current transfers from RoW
	Government (& NPISHs)	(4)		Direct taxes	Direct taxes		*Net* taxes on products			*Net* current transfers from RoW
Production	Goods and services	(5)		Household consumption		Government consumption		Intermediate consumption	Fixed capital formation and change in stocks	Exports
	Activities	(6)					Domestic sales			
Combined capital accounts		(7)		Household savings	Corporate savings	Government savings			Capital transfers	*Net* capital transfers from RoW
Rest of World (combined account)		(8)					Imports		Current external balance	
Totals			Factor Income payments	Current household outlays	Current corporate outlays	Current government outlays	Supply of products	Costs of production activities	Capital outlays	Aggregate receipts from RoW

Note: Row totals are not shown but they match column totals.

Source: Round (2003)

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