Assessing the evolution of India's power sector to 2050 under different CO_2 emissions rights allocation schemes

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ABSTRACT

This paper assesses the evolution of India's power sector to 2050 and identifies crucial low carbon technologies to meet its NDC and long-term climate change mitigation targets under various carbon emission rights allocation schemes using a multi-region global energy systems model TIAM-UCL where India is modelled as a separate region. Six scenarios were developed – reference case, NDC, global 2°C and three scenarios where CO_2 emissions of all model regions converged in 2050 based on criteria of GDP/capita, emissions intensity of GDP and per capita emissions. The analysis shows that emission rights allocation schemes influence the total energy system development costs, long-term electricity generation requirements, and share of renewables especially solar PV generation to meet the 2°C target. The model runs also show that solar-PV is the single most important generation technology for decarbonisation of India's power sector. Limiting the share of solar-PV generation can lead to 20% reduction in total electricity generation and increase system costs substantially for 2050. Further, the results also indicate that India may have 200 – 215 GW of stranded coal generation assets in 2050 in the low carbon scenarios. Our analysis suggest that India is one of those countries which are at the development stage and also highly risked with the lock-in in carbon emitting infrastructure especially coal-based generations unless action taken in the near-term.

Key words: Burden sharing; India's NDC; Stranded assets; TIAM-UCL

1. Introduction

India is one of the signatories of the Paris agreement with a National Determined Contributions (NDC) target of reducing its GHG intensity to GDP by 35% in 2030 compared to that in 2005. It is an important player in any global climate agreement because of the size of its economy and growing emissions (Balasubramanian, 2015) as it is one of the largest and fast-growing CO_2 emitting countries in the world. However, similar to the other developing and emerging markets, its per capita electricity consumptions and emission are relatively low compared to that of the developed countries. In 2013, India had 18% of the world population but only 5.7% share of global energy demand (IEA, 2015). India's annual national electricity consumption per capita was about 600 kWh which is much less compared to nearly 13,000 kWh in the U.S. (Sreenivas, 2014). Given the projections for strong economic growth (Smialek, 2015) and its large unmet demand for energy, emissions from India could grow rapidly in the coming decades due to expected expansion of its energy system, especially the electricity generation sector which is projected to increase up to 8 times in 2050 compared to the 2010 generation (Gambhir, et al., 2013). Therefore, India has to heavily invest in its electricity generation sector to meet the growing demand for electricity. On the other hand, India also should reduce its future emission from the energy system to contribute to the global effort on limiting temperature rise well below 2°C by 2100, expressed in the Paris agreement (UNFCCC, 2015).

There are discussions (Grubb, 1990; Rose, 1990; Azar, 2000; Bode 2004, Baer et al., 2008; Hohne et al., 2013, Waisman, et al., 2019) on how the mitigation burden should be shared across the globe due to differences in per capita emissions as well as CO_2 intensity (CO_2/GDP). The latest study (Waisman, et al., 2019) proposes an approach that is bottom-up, country-driven, policy-relevant and consistent with a global mitigation goal. Extensive work is also being done looking into low carbon pathways for India and studies have highlighted the important role of the power sector in overall decarbonisation (Shukla and Chaturvedi, 2013; Gambhir, et al., 2013; Shukla et al., 2015; Anandarajah and Gambhir, 2014; Liu et al., 2015a). However, less attention has been paid to how the progression of India's energy system varies under different carbon emissions allocation schemes. Thus, this paper focuses on how does India's power sector evolve till 2050 under different emissions rights allocation scheme. This paper identifies important trends and future developments in the Indian power sector under the different allocations and evaluates role of key generation technologies. The scenarios are built around NDC's and analysis also focusses on lock-in investment and stranded assets (coal generation technologies) under different scenarios.

The remainder of this paper is set out as follows: Section 2 reviews relevant literature on CO_2 allocation schemes, low carbon futures for India, and role of CCS for India. Section 3 describes the TIAM-UCL model and data and assumptions and defines the scenarios modelled. Section

4 discusses the results of the model runs and their implications while Section 5 concludes on key findings

2. Literature Review

2.1 Carbon Emissions Rights Allocation Schemes

The allocation of emissions rights between different countries involves complex and often conflicting value judgements from ethical and political point of view (Baer et al., 2008; Bührs, 2010; Hohne et al., 2013). This is because the initial allocation is subject to perceptions of fairness and equality as it can lead to extra costs or generate revenues where allowances can be traded (Leimbach et al., 2010). Zhou and Wang (2016) identify eight criteria (e.g. egalitarianism, equity, efficiency) commonly used in literature that lead to the large number of allocation rules or schemes. A defining feature of these schemes is that they allocate emissions for the long-term future, for example till 2100, leading to two main benefits (Bode, 2004). First, it creates certainty for investments, particularly for installations with long lifetime such as power plants. Second, it deters short term non-compliance because there is significantly reduced scope to re-negotiate national targets for the next commitment period. The latest study (Waisman, et al., 2019) proposes an approach that is bottom-up, country-driven, policy-relevant and consistent with a global mitigation goal.

An early proponent in emission allocation is Grubb (1990) who argued that allocating emission permits based on national population, i.e. equal per capita principle, is the only real solid basis for allocation. The added benefit of equal per capita principle is that it is based on strong moral reasoning – "the atmosphere is a global common whose use and preservation are essential to human well-being" (Baer, 2002). Equal per capita allocation schemes have been widely studied by academics, in both methodological and application aspects (Rose, 1990; Azar, 2000; Bode, 2004). The strict application of equal annual per capita allowances suffers from two major criticisms. First, some countries would find it near impossible to comply because of high current emission levels, such as USA, Canada and Australia. Second, it does not consider the fact that high-income countries are responsible for a majority of the historical emissions. In response, two major derivatives arise from the principle of equal per capita emissions – contraction & convergence (C&C) and equal cumulative per capita emissions (commonly known as historical responsibility).

The C&C approach was articulated by Meyer (2000) with the rationale that global CO_2 emissions need to be cut substantially with the aim to gradually equalize per capita emissions in different countries. This gradual equalization is the main difference in this scheme as compared to allocating equal per capita emissions from starting year. The regional economic impacts of adopting C&C approach were modelled by Persson et al., (2006) and Knopf et al., (2012). It was also reported that the existence of international emissions trading increases the political feasibility of C&C approach because it raises the economic welfare of major opponents to emissions restrictions (Böhringer & Welsch, 2004). The C&C approach was extended forward by Höhne et al. (2006) as Common but Differentiated Convergence (CDC). This requires all countries' per capita emissions to reach the same level ('common convergence') but actions of developing countries are delayed and conditional on developed countries acting ('differentiated'). The main difference here compared to the C&C approach is that developing countries only start converging when their per capita emissions reach a certain percentage above the global average. Hof et al., (2010) found that the difference in regional costs under C&C and CDC are significant in the short term but move in a similar direction in the long term.

The application of historical responsibility, also known as equal cumulative emission per capita, is the second derivative of the equal per capita principle. Here, the absorptive capacity of the atmosphere is allocated equally to all people, not just from the present year but from much earlier, such as 1850. Hohne et al. (2103) argue that this approach seeks to combine equality (per capita) with the principle of responsibility (accounting for cumulative historical emissions). This feature has found appeal in literature and the use of historical responsibility has been advocated by La Rovere et al. (2002), Nabel at al. (2011) and Pan et al. (2014).

An extension of the principle of historical responsibility is to discount historical emissions, justified on the basis of four reasons (Posner & Weisbach, 2010). First, emissions have decreasing marginal warming potential despite their long lifetimes. Second, people in the past did not have complete knowledge of the effects of emissions and thus legally and ethically cannot be liable for their actions. Third, scientific advancement has made it easier for developing countries today to deploy low carbon technologies. Finally, pragmatic and political considerations dictate that historical responsibility may only be palatable if discounting is used. Liu et al., (2015b) applied an annual discount rate of 1.5% to historical emissions and found that this led to a 38% reduction in Annex I countries' responsibility for the period 1900 – 2050.

The problem of climate change can be framed as a matter of resource sharing (per capita equal access to atmosphere commons) or as burden sharing. In the burden-sharing framework, the costs of emissions reductions (deployment of low carbon technologies and reducing resource consumption) must be shared equally. Accepting this principle of equal sacrifice but also bearing in mind the declining marginal utility of income leads to the conclusion that rich countries must make greater sacrifice than poorer countries (Baer, 2002). Thus, emission rights can be allocated inversely proportional to each country's GDP/capita. The use of GDP/capita as an indicator for emissions allocation can be justified on the basis of vertical equity (Rose (1990) and also on the basis of differences in ability to pay for mitigation (Winkler et al., 2002). The use of this ability to pay principle can also be traced back to Article 3 of the UNFCCC text that mentions "common but differentiated responsibilities and respective capabilities" (UN, 1992). In addition, use of GDP/capita will also account for the 'right to development' of developing countries as they will have more emissions allocations to secure their basic needs (Hohne et al., 2013).

Emissions intensity of GDP is the ratio of emissions produced for every unit of GDP. The use of this indicator seeks to reward or compensate more carbon efficient countries for their emission reduction efforts (Rowlands, 1997). Hence, allowances are allocated to countries inversely proportional to emission intensity. In order to make the use of this indicator realistic, Miketa and Schrattenholzer (2006) introduced a gradual global convergence in emission intensities of different countries. The use of emission intensity will likely place a greater burden on developing countries that do not have a services-based economy. It can also be argued that the reduction in emissions intensity of developed countries does not represent real decoupling of emissions and economic development but rather a shift in emissions intensive manufacturing to developing nations (Davis & Caldeira, 2010; Wiedmann et al., 2015). It would thus be fairer to use consumption-based accounting of emissions rather than territorial emissions if schemes based on emissions intensity of GDP were to be used.

2.2 India Low Carbon Studies

There are number of papers and reports published focussing on India's low carbon pathways (PC, 2014; Shukla and Chaturvedi, 2013; Shukla et al., 2015; Anandarajah and Gambhir, 2014; Liu et al., 2015a; Kumar et al. 2018; Rue du Can et al., 2019). India's Planning Commission (PC, 2014) formed an expert group to suggest low carbon pathways consistent with inclusive growth till 2030. A multi-sectoral, dynamic optimization model was used to simulate a baseline scenario and a low carbon scenario (LCS) both of which have in common inclusive growth policies. Shukla and Chaturvedi (2013) used a top-down integrated assessment model (IAM) GCAM (Global Change Assessment Model) to simulate a business-as-usual scenario and two low carbon scenarios, while Anandarajah and Gambhir (2014) used a bottom of IAM (TIAM-

UCL) to develop low carbon scenarios, both studies consistent with global 2°C target. Shukla and Chaturvedi (2013) report that in the short run demand-side policies (e.g. energy efficiency) and technology push policies (e.g. subsidies or high feed-in tariff for renewables) are found to have greater influence on altering the long-term pathway compared with exclusive reliance on the carbon price. Shukla et al., (2015) also found similar results when they studied the conventional stabilization and sustainable approach scenarios by combining a global Computable General Equilibrium (CGE) model with bottom-up technology rich ANSWER-MARKAL as part of the global Deep Decarbonisation Pathways (DDP) Project. Anandarajah and Gambhir (2014) examined the role of renewables in India's 2050 climate mitigation targets using TIAM-UCL global energy systems model. The authors conclude that renewable energy can play an important role to meet the CO_2 reduction target. About 41% of the reduction (compared to Reference Scenario emissions) is met by renewables in 2050. Another 16% is met by fitting CCS to biomass power plants. Therefore, the net contribution of renewables (including sinks via biomass with CCS) to meet the target is 57%. Liu et al., (2015a) conducted a model inter-comparison between five modelling teams looking into decarbonizing India's power sector till 2050 under different scenarios. In all scenarios, models decarbonized by increasing the efficiency of coal-fired generation, additional gas-fired generation, and greater penetration of low-carbon energy such as renewables, nuclear, and CCS. Kumar et al., (2018) reviewed India's low carbon scenarios using a meta-analysis and found that policy scenarios suggest that it is possible to achieve a reduction in energy intensity by 70% with emission intensity declining by more than 90% by 2050.

2.3 Role of CCS technology

Many studies have demonstrated that the deployment of CCS technologies plays an important role in reducing global and regional CO_2 emissions in the long run (van Vuuren et al., 2013; Krey et al., 2014; van Vliet et al., 2014; IEA 2016). Specific studies (Garg and Shukla, 2009; Viebahn et al., 2014)) for india suggest that there are potential for CCS to play a role in India. It has been estimated that capturing emissions from the 20 largest point sources could save up to 12.4 $GtCO_2$ cumulatively over the period 2010-2030 representing 27% of all India emissions over that period (Garg and Shukla, 2009). Viebahn et al., (2014) assessed the prospects for CCS in India and indicated a wide range of possible storage capacities in India from 47 to 572 Gt of CO_2. However, the Planning Commission (PC, 2014) categorized this technology as unviable even with social discount rates and monetized mitigation benefits. Shukla and Dhar (2016) recognise that CCS deployment in modelling output is misleading due to uncertainty of

CCS capacity and costs in India. Shukla and Chaturvedi (2013) state that “the greater and early focus on pushing renewable energy technologies can be a better risk hedging strategy in the case of stringent stabilization targets rather than end-of-pipe mitigation technologies such as CCS”.

2.4 Summary

The literature review finds out that there are cons and pros with different emission allocation and burden sharing schemes. India’s huge pending demand for energy between now and 2050 constitutes a unique opportunity for the Indian government, the private sector, and the international community to demonstrate how low carbon technologies can contribute to economic development and strengthen developing economies’ mid-century low carbon strategies (Rue du Can et al., 2019). Further, less attention has been paid to how the progression of India’s energy (electricity) system varies under different carbon emissions allocation schemes. It is widely agreed in the literature that CCS is not a preferred technology for India as it has not been commercialised yet. However, heavy fossil fuel dependent country like India, which has done relatively little to prepare for the deployment of CCS (Havercroft and Consoli, 2018), may need CCS in order to reduce its mitigation cost. Therefore, we have included CCS in this paper to capture emissions from coal- and gas- based powerplants.

3. Methodology, data, assumptions and scenarios definition

3.1 TIAM-UCL

This paper uses a multi-region global energy system model called TIAM (TIMES Integrated Assessment Model)-UCL (Anandarajah et al., 2011), where India is modelled as a separate region with its own energy system represented and can trade energy commodities such as coal, oil, gas, biomass (solid and liquid) and oil products with other regions. The model is built based on the TIMES modelling framework (LouLou and Labriet, 2007). For each region, base year energy service demand is exogenous and future projections are driven by estimates of GDP, population, household size and sectoral outputs.

TIAM-UCL performs scenario-based simulations to minimize total discounted energy system cost over the modelling horizon by determining a cost-optimal level of deployment of energy end-use and energy conversion technologies and resources to meet the energy service demands. This is done by linear optimization subject to constraints imposed (e.g. resource availability, emission constraint, trade constraint etc.). Since this study focuses on the power sector in India, the electricity processes modelled in TIAM-UCL are discussed further below. A full detailed description of the model structure, sectors and modules can be found in the Model Documentation (Anandarajah et al., 2011, Anandarajah and Gambhir, 2014).

TIAM-UCL represents changes in sectoral demand profile and electricity supply across six time slices based on three seasons (winter, summer and intermediate) and two diurnal periods (day and night). The base year data is calibrated from IEA Extended Energy Balances of OECD and non-OECD countries. These have not been altered for this paper, primarily due to the short timeframe. However, for India the electricity generation was calibrated for 2010 from India's Central Statistics Office (CSO, 2015). New electricity generation technologies in the model are categorized into technology groups – coal, gas, dual coal/gas, oil, nuclear, hydro, biomass, geothermal, solar-PV, solar thermal, wind and wave. The technology groups further divide into generation processes that include data on costs (investment, fixed O&M, variable O&M), construction time, plant lifetime, availability factor and conversion efficiency. The model also allows for imposition of additional constraints on a particular technology such as start year, resource availability (e.g. wind potential), maximum generation and share of generation.

TIAM-UCL allows for the introduction of several CCS technologies for the power sector. So, for this research CCS is introduced in the developing regions (including India) in 2040 and the developed regions in 2035. This staggered introduction is based on the finding from two studies. The economic "barrier for CCS is clearly higher in India than in other emerging economies, such as China, or even industrialised countries, as Indian plant investment costs tend to be higher due to complex ambient conditions and low feedstock quality" (Viebahn et al., 2014). Furthermore, the IEA (2015) noted India's continued dependence on increased global support for CCS technology. Major assumptions such as GDP and population growth have been presented in Appendix I.

3.2 Scenarios Definitions

Since the motivation of this paper is to assess the evolution of India's power sector under different CO_2 emissions allocations schemes, six different scenarios were developed under different emissions allocation schemes. This section describes how the scenarios are setup – their rationale and assumptions.

The first scenario is a reference scenario (REF). This will show the least-cost mix of energy technologies India would deploy without any specific policy constraints or preferences, as well as no emission constraints. Each of the five scenarios that follow has REF fixed till 2015.

The second scenario is NDC, which implements two key pledges in India's submission, extrapolated for 2040 and 2050 to enable comparison with other scenarios. The pledges of other countries have also been implemented from their submissions to the UNFCCC (2016).

Table 1: India's targets for NDC scenario

Target year	Emissions intensity of GDP	Non-fossil installed electricity capacity
2030	35% lower than 2005	40%
2040	50% lower than 2005	45%
2050	65% lower than 2005	50%

The third scenario is 2°C, which keeps global temperature rise to within 2°C from pre-industrial level. In this scenario, a global emission constraint has been applied and the model identifies the least cost CO_2 mitigation pathway that meet the global 2°C target. There is no specific constraint for India's emissions.

The fourth scenario: Per Capita Convergence (PCC). CO_2 emissions of all regions converge to 1.3 tonne/person in 2050.

The Fifth scenario: Emissions Intensity Convergence (EIC). CO_2 emission per unit of GDP off all regions converges to 80 tonne/million US$ in 2050.

The sixth scenario: Ability to Pay (ATP). Regions are allocated CO_2 emission allowances in the inverse of GDP/capita, i.e. poorer regions are allowed to emit more CO_2.

Each of these three scenarios fixes maximum global CO_2 emissions for 2030, 2040 and 2050 based on the RCP2.6 (Representative Concentration Pathway), also known as RCP3PD (Meinshausen et al., 2011). This pathway was chosen primarily to reflect the well below 2°C ambition expressed in the Paris agreement (UNFCCC, 2015). The three scenarios also had limited emissions trading, primarily to force all regions to make changes to their energy mix. Each region could sell up to 30% of its allowances, consistent with the assumption used by Leimbach (2003). The resulting CO_2 emission allocations for India in the 5 scenarios are shown in Figure 1. EIC has the lowest allocation and NDC the highest. ATP and PCC are nearly the same in 2050 but follow different trajectories, with ATP seeing steeper decline from 2030 – 2040. All four low carbon scenarios were built on NDC scenario.

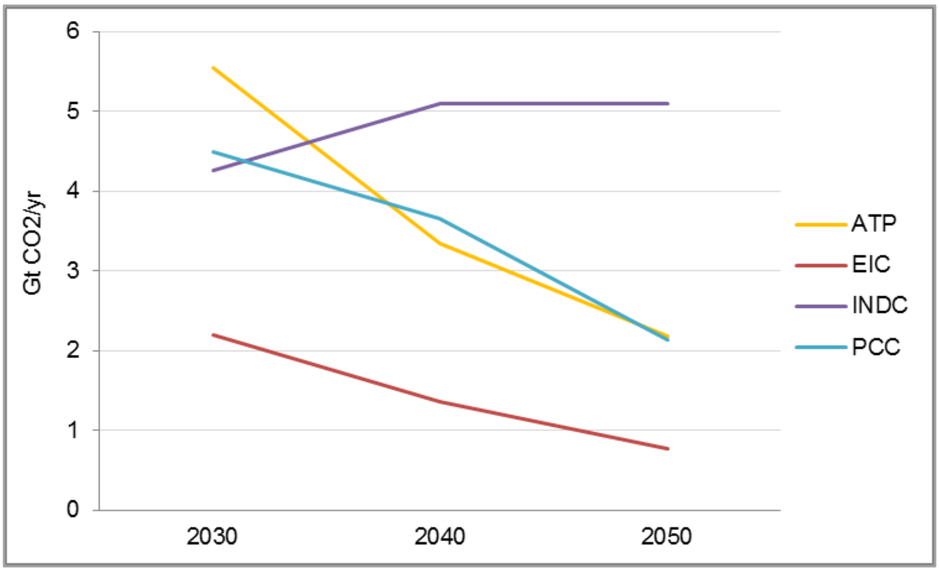

Figure 1: CO_2 emission allocation for India under different scenarios

4. Results and Discussions

This section discusses the results of the modelling runs in TIAM-UCL to understand the evolution of India's power sector to 2050. Furthermore, sensitivity analysis is performed to understand the impact of limiting solar PV capacity on energy system, GDP growth rate, and impacts of early availability of CCS. TIAM-UCL is a multi-region global model, but only results for India has been presented in this paper

4.1 Electricity generation, fuel mix and CO_2 intensity in 2050

The level of electricity generation in 2050 exhibits variation between the different scenarios, as shown in Figure 2. It also shows the contribution of electricity to final energy use. Electricity generation increases three to five-fold over the next 35 years depending on emission rights allocation scheme. In the same time period, electricity's importance rises because its share in final energy use grows by a multiple of two to four. It can be seen that the amount of electricity generated (left y-axis) and its contribution to final energy (right y-axis) are directly correlated to stringency of emissions reductions, i.e. EIC > ATP, PCC > REF, NDC. This trend is observed because the electricity sector can make the greatest contribution to emissions reductions. For those scenarios with lower % of electricity in final energy use (REF, NDC), end-use sectors such as industry and transport rely on coal and oil for their energy requirements.

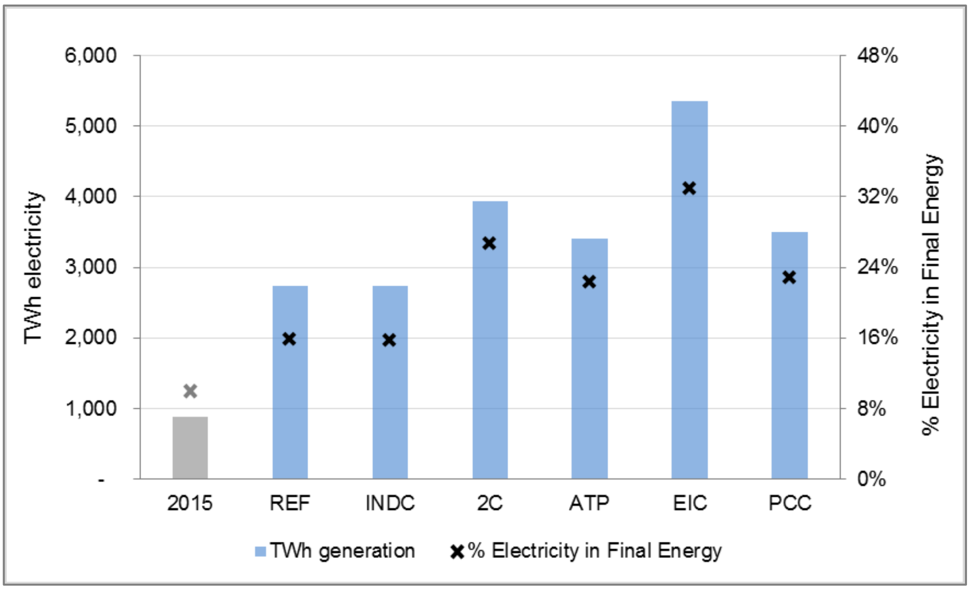

Figure 2: Electricity generation in 2050

Figure 3 shows the electricity generation mix in 2050 and percentage share of renewable generation under all six different scenarios together with the corresponding numbers for 2015. Coal continues to dominate electricity generation in REF with over 60% share in 2050, followed by solar-PV and hydro. REF and NDC give similar results, with NDC having a slightly lower share of coal which is replaced predominantly by solar-PV and then gas. The similarity between these two scenarios can be explained by the fact that the emissions intensity target in NDC does not place a significant constraint on emissions because of the strong growth in GDP. Further, India's 2030 NDC target also includes a 40% share of non-fossil fuel based technologies that can presumably include wind, solar, hydro and nuclear. In all the four low carbon scenarios (2C, ATP, EIC and PCC), share of coal generation in 2050 is well below 3%, which may result in stranded assets (see Section 4.5). The share of renewables in electricity generation correlates loosely with the stringency of emissions reductions (Figure 1). The EIC has the lowest allocation of emission (highest level of burden) for India and hence the largest level of renewables deployment. On the other hand, REF and NDC have much higher emissions allocation (lower burden) for India and subsequently the lower share of renewables. Solar-PV constitutes over 50% of the electricity generation in all four low carbon scenarios. Coal is nearly zero here because of the stringent emission constraints. Despite the emissions constraints, the model does not build any CCS, even though the technology was made available for India from 2040. This is because of the existence of legacy plants and constraints on the speed and build rate of CCS plants. ATP has the highest share of solar-PV (2/3rd) which has the knock-on effect requiring greater installation of gas capacity to act as a back-up for peak-load.

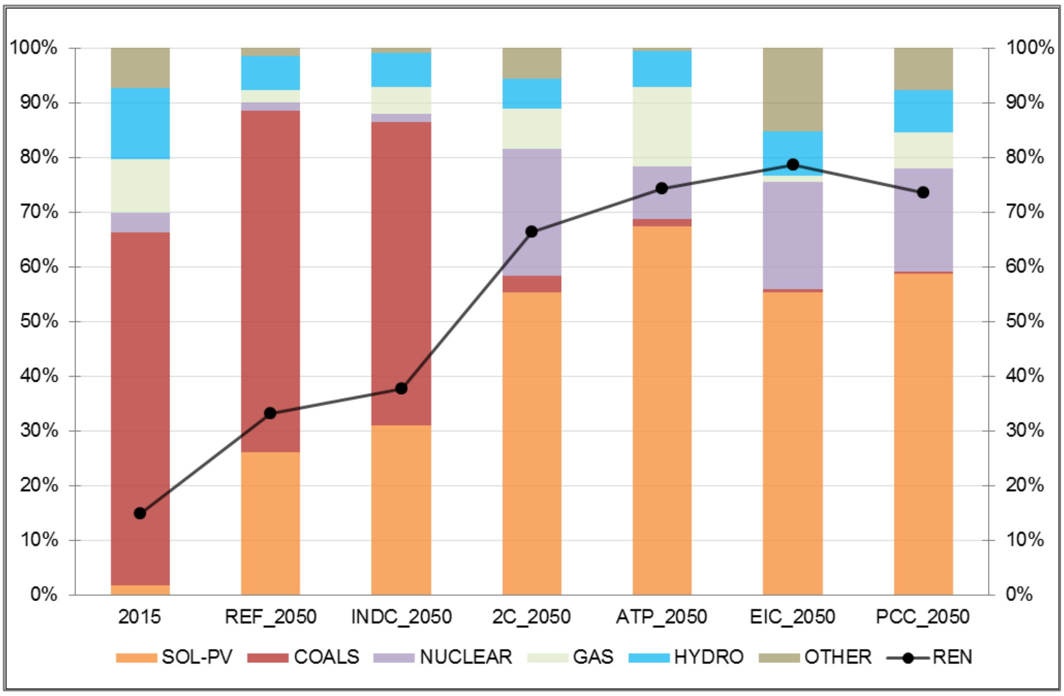

Figure 3: Share of fuels for electricity generation in 2050

The CO_2 intensity of electricity generation rapidly decreases in 2050 in all four low carbon scenarios and it is close to zero in EIC (Figure 4) where we observe a highest share of Solar PV generation. The intensity decreases under REF and NDC scenarios as well. The declines in CO_2 intensity in REF is explained by the diffusion of low-cost Solar PV.

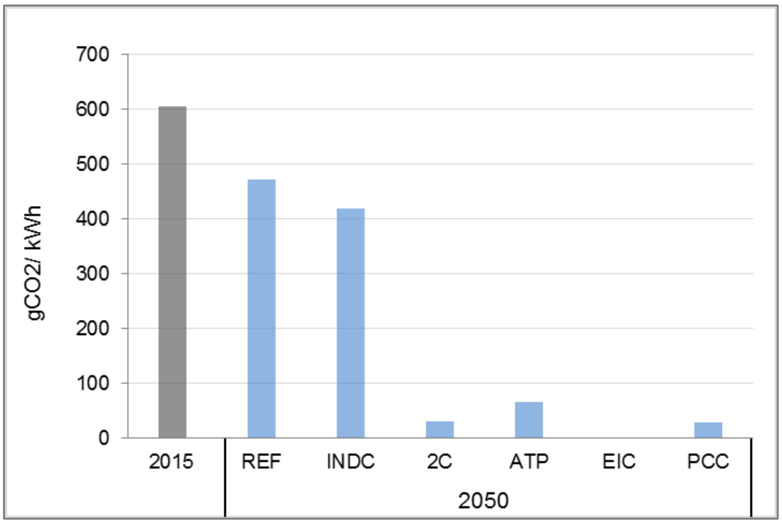

Figure 4: Carbon intensity of electricity generation

4.2 Cost comparison of scenarios

Figure 5 shows the regional total discounted energy system costs relative to REF for India. It is observed that NDC pathway does not impose any significant cost burden nor savings compared to REF. This is explained by the near similarity of 2050 total electricity generation (Figure 2) and generation mix (Figure 3) in NDC and REF scenarios. The total discounted energy system cost is about 5% more in 2C, PCC and ATP scenarios compared to that in REF. The EIC has the highest total system cost, 15% more compared to that in REF, due to the highest burden sharing scheme (most stringent mitigation pathway for India– Figure 1) that leads to near net-zero CO_2 intensity of electricity generation in 2050 (Figure 4).

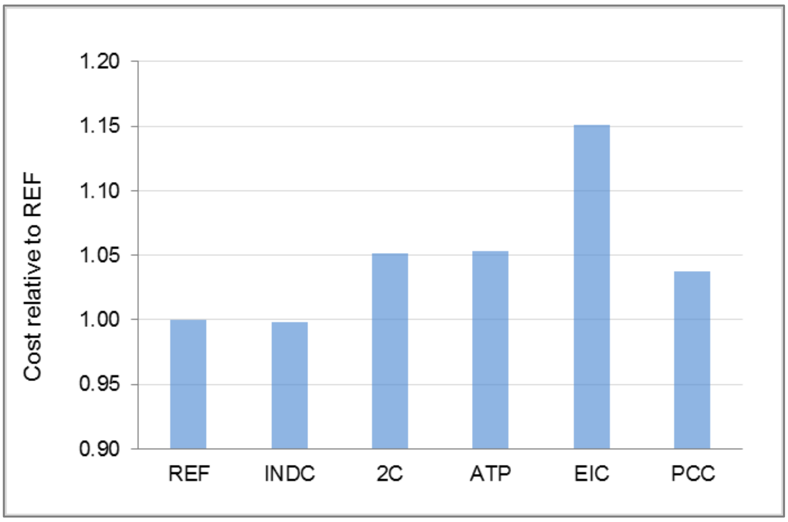

Figure 5: Total discounted system costs relative to REF

The difficulty in pursuing EIC from the cost perspective can be illustrated more clearly in Figure 6 which shows the annualized system cost (additional to REF scenario) as a percentage of GDP in 2040, 2045 and 2050. The components of annualized system cost in TIAM-UCL are investment costs, fixed operating and maintenance costs, variable operating and maintenance costs and costs associated with endogenous trade. With the exception of EIC, all other pathways modelled have an additional cost of less than 1.7% of that year's GDP. This means that cost as a share of GDP cannot be used as a strong argument to not pursue one of these low carbon futures. However, EIC has high additional costs that shoot beyond 31% in 2050.

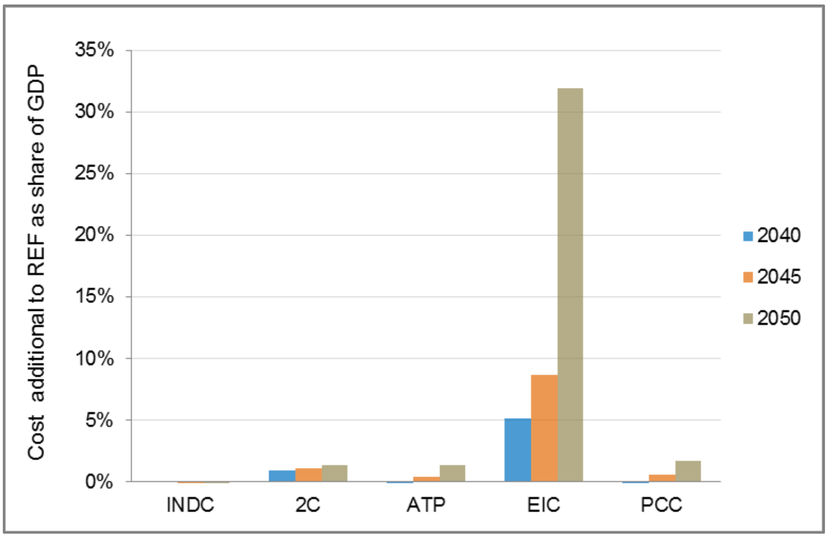

Figure 6: Additional energy system cost relative to REF as share of GDP

4.3 Role of solar-PV

The model output for installed solar-PV capacity for 2030 and 2050 is shown in Figure 7. This has been calculated on the basis of assumed capacity factor of 25% in 2030 and 30% in 2050. In 2030 (top panel in Figure 7), solar-PV deployment is highest in 2°C and EIC, crossing 160GW. The strong growth of solar-PV capacity continues to 2050 with around 800 GW installed in each of 2°C, ATP and PCC representing a four to six-fold increase in 20 years. EIC is the most carbon constrained scenario and hence it seen even larger (1100 GW) of deployment. It has been estimated that India's solar power potential is 750 GW (MNRE, 2014). However, the report only considers 3% of wasteland area, less than 20% of current rooftop area and makes no provision for technology advancements. Other estimates (Engelmeier 2014; NITI Aayog 2015) suggest that India could install 1000GW of solar-PV. In order to account for the possibility that such high deployment may not be feasible, sensitivity analysis has been performed in Section 4.5.

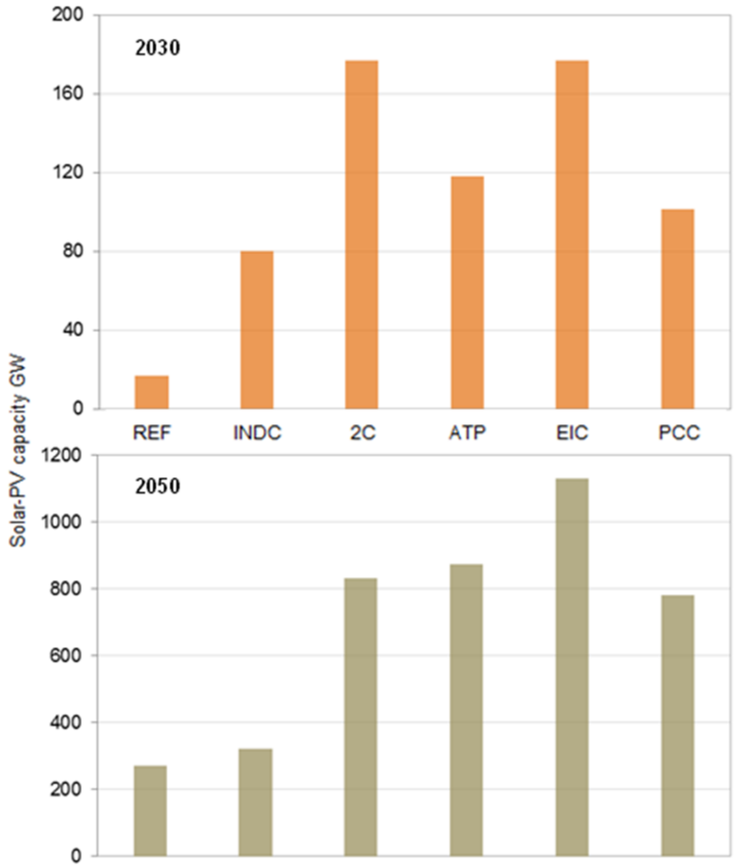

Figure 7: Installed solar-PV capacity in 2030 and 2050

4.4 Estimating stranded coal generation assets

In this section, the evolution of coal generation is explored. Figure 8 shows the installed capacity requirement calculated using a capacity factor of 70%. This is higher than the 60% achieved in India from 2008-2012 (EIA, 2016). However, the higher number is in line with the assumption made by Grover and Chandra (2006) to account for technological improvements and greater emphasis on operational excellence.

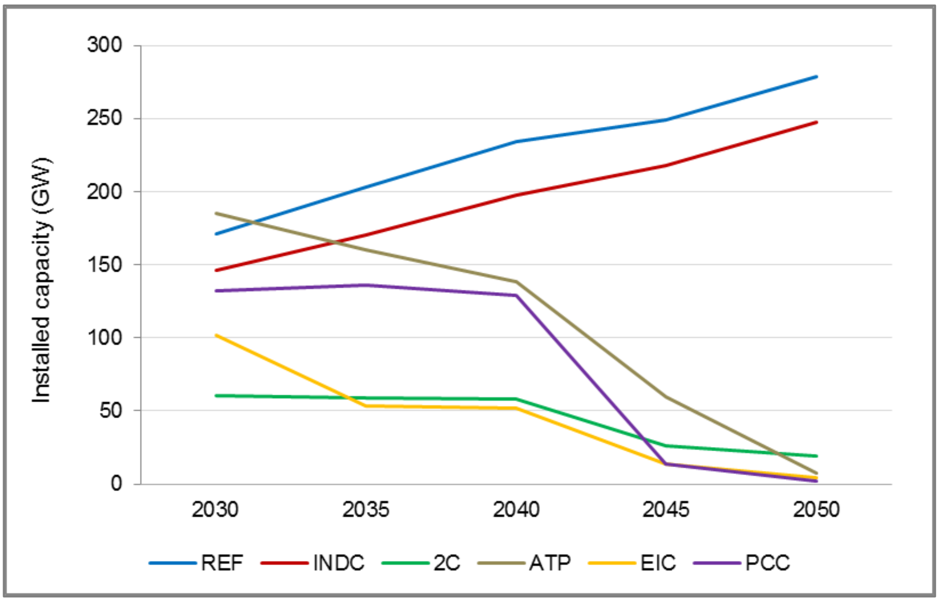

Figure 8: Coal installed capacity requirement from 2030-2050

A quick assessment can be made of the stranded assets resulting from existing and proposed coal power plants. According to official figures, as of April 2016, India's installed coal capacity was 186 GW (CEA, 2016) of which 95 GW was added in 2007 or later (CEA, 2015). It is assumed that 70% of this 95 GW will be in operation in 2050. The total coal power capacity under construction and development, excluding projects that have only been proposed or announced, is estimated to be 230 GW (CoalSwarm, 2016). A conservative estimate suggests that at least 50% of this new capacity will be eventually commissioned and continue operation beyond 2050. These two assumptions indicate an installed capacity of 220 GW in 2050. Combining this with the model results shown in Figure 8, the additional coal capacity required for 2050 coal generation is calculated. It is clear, that the four low carbon scenarios will have between 200 – 215GW of stranded coal generation assets in 2050, even if no new coal power plants were developed in India henceforth. The volume of stranded assets is larger than the present installed coal capacity of 186 GW.

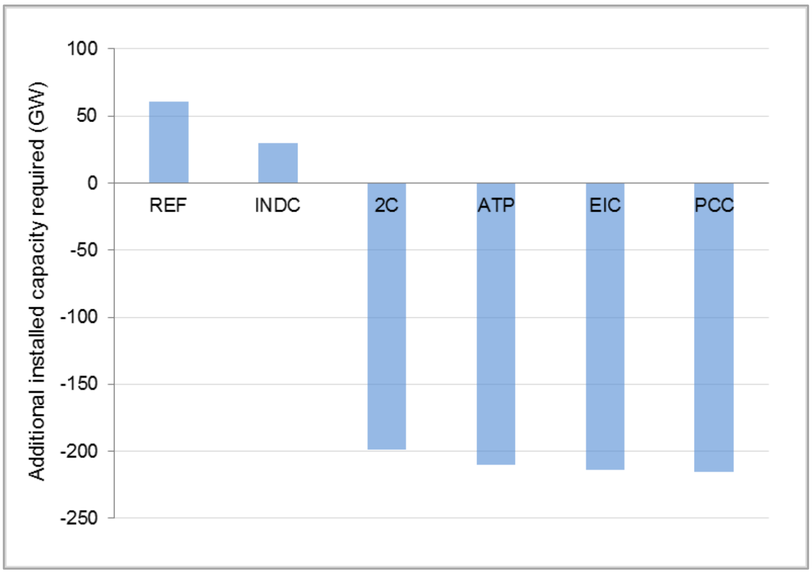

Figure 9: Additional installed coal capacity required for 2050 generation

4.5 Sensitivity analysis

The parameter values and assumptions in any modelling exercise are subject to change and error. Sensitivity analysis seeks to investigate how these potential changes and errors impact the conclusions drawn from the model (Pannell 1997). Sensitivity analysis were performed by changing values important driver (GDP growth) and also of two important parameters for India – start date of CCS, and limiting the share of solar-PV capacity for generation.

Early introduction of CCS

The model introduced CCS for India from 2040. Figure 10 shows how much CCS contributes to electricity generation in different scenarios if it was introduced for India in 2030. As expected, the uptake is greatest in EIC because this scenario has the smallest emission allocation. CCS share is about 7% in PCC but zero in ATP even though they have the same emission allowance for 2050. This is because ATP has a much larger allowance during 2030-2040 and hence there is less pressure on the power sector to reduce its emissions.

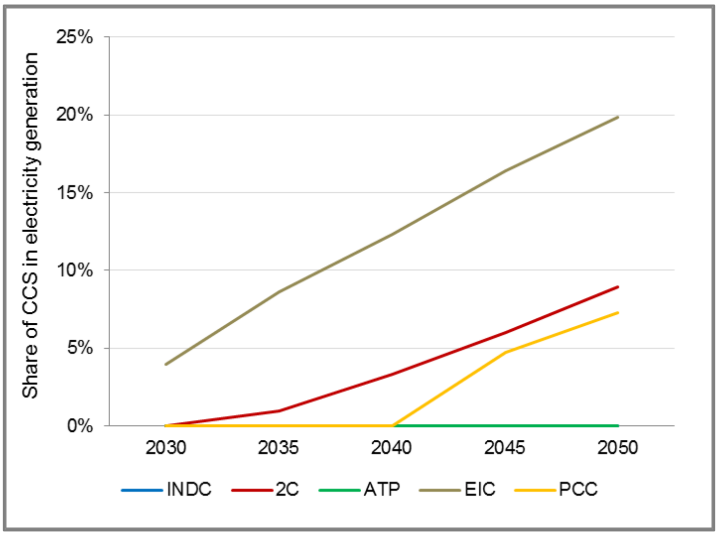

Figure 10: Share of CCS in electricity generation if available from 2030

Given these findings, the rest of this section focuses on the EIC scenario only, since this is the one where CCS plays a significant role in electricity generation. Figure 11 compares the annualized system cost of REF, EIC with CCS in 2040 and EIC with CCS in 2030. Till 2040, there is only a small difference in costs between the three scenarios shown. However, in the last decade (2040-2050, the cost of EIC becomes significantly higher if CCS was not introduced early. In 2050, the early introduction of CCS, more than halves the cost of pursuing EIC pathway. The very high cost of EIC_CCS_2040 is driven by two main reasons. First, the model is forced to invest in more expensive solar thermal and wind to provide 15% of electricity generated in 2050 (see category others in Figure 6). Second, India has to buy emissions permits from other regions in order to satisfy the stringent emissions constraint.

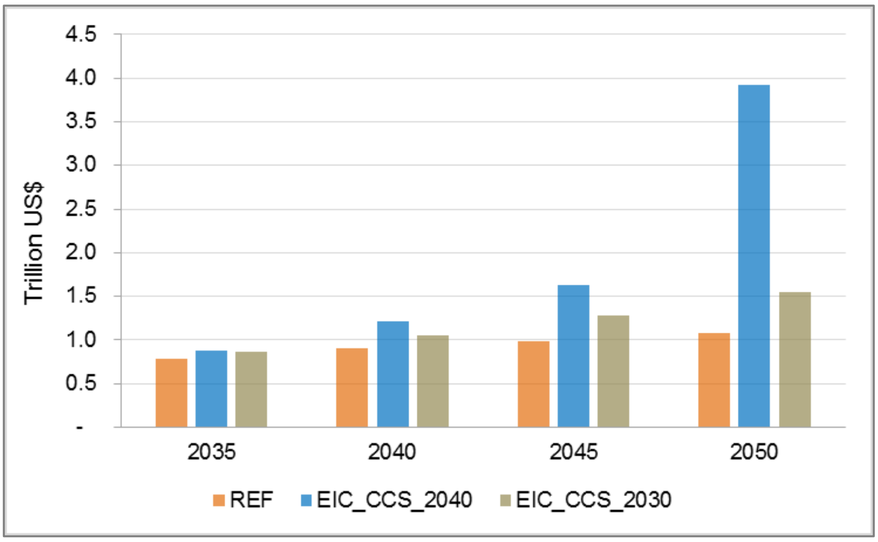

Figure 11: Annualized system cost with early CCS for EIC scenarios

Limit on Solar-PV capacity

The results from Figure 3 show that the share of solar-PV in generation is more than 50% for the four low carbon scenarios. Such a high level of deployment of a single technology may not be feasible for the following reasons. First, there will be technical challenges in developing and implementing new grid management practices, load balancing mechanisms and electricity market rules (Sims et al. 2011). Second, the intermittent nature of solar-PV necessitates investment in grid expansion, energy storage, fast response backup generators and demand-side management infrastructure (Clarke et al. 2012). Third, the large uptake of any new technology will require development of appropriate skilled labour and soft infrastructure. Thus, two cases are explored below – 40% limit and 25% limit on electricity generation from solar-PV in 2050.

Figure 12 shows drops in total electricity generation in 2050 compared to the scenarios with no upper limit on share of solar-PV generation. Total electricity generation falls by more than 20% in 2050 when solar-PV is limited to 25% of the total electricity generated. This will have important implications on investments in electricity transmission and distribution. The reduction in electricity generation is explained by lower electricity demand as a results of switching to alternative fuels and more efficient technologies in end-use sectors. This effect (reduction in total generation) is much smaller in EIC as the most stringent emissions constraint forces the model to continue generating electricity to decarbonise end-use sectors by means of electrification but from more expensive low carbon electricity generation technologies such as wind and biomass.

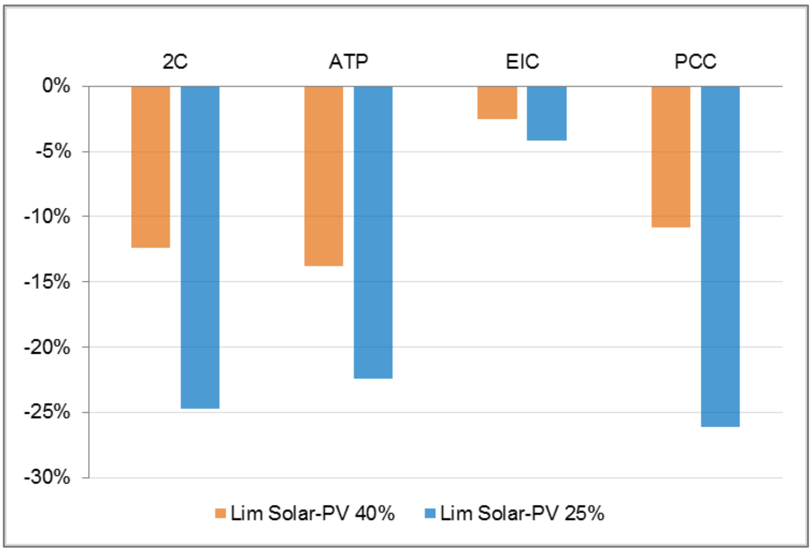

Figure 12: Change in 2050 electricity generation with limits on solar-PV

The changes described above may also increase the overall system costs. This can be shown by determining the additional cost for the scenarios that limit the share of solar-PV generation on total electricity generation. Figure 13 shows the % increase in annualized system costs under 40% limit (top panel) and 25% limit (bottom panel).

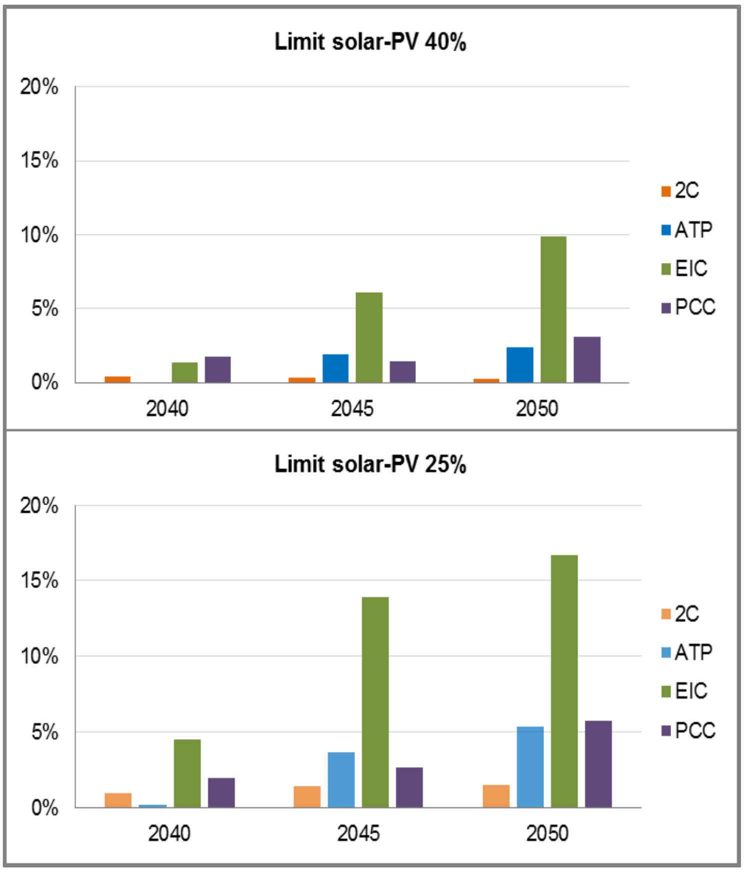

Figure 13: Increase in system costs relative to scenarios with no limit for solar-PV

In the 40% limit scenarios (top panel), EIC becomes 5% and 10% more expensive in 2045 and 2050 respectively. The other three scenarios (2C, ATP and PCC), show a marginal increase in annualized system cost. However, this effect becomes more pronounced when a tighter limit of 25% is placed. Now EIC is about 17% more expensive in 2050. ATP and PCC too become 5% more expensive in 2050 with the 25% limit.

Alternate GDP assumptions

The rate of future growth is an important driver for the scale of the energy system in IAMs (Liu et al., 2015). In order to perform sensitivity analysis on GDP assumption, the future annual GDP growth rate was lowered by 1% and increased by 1% to create two new cases. Figure 14 shows how the compounding effect of this seemingly small change in annual growth rates can cause GDP in 2050 to differ by a factor greater than 2.2. Higher GDP will lead to higher energy consumption and electricity generation. The 2050 electricity generation (bars left y-axis) and the share of electricity in final energy consumption (circles right y-axis) are shown in Figure 15.

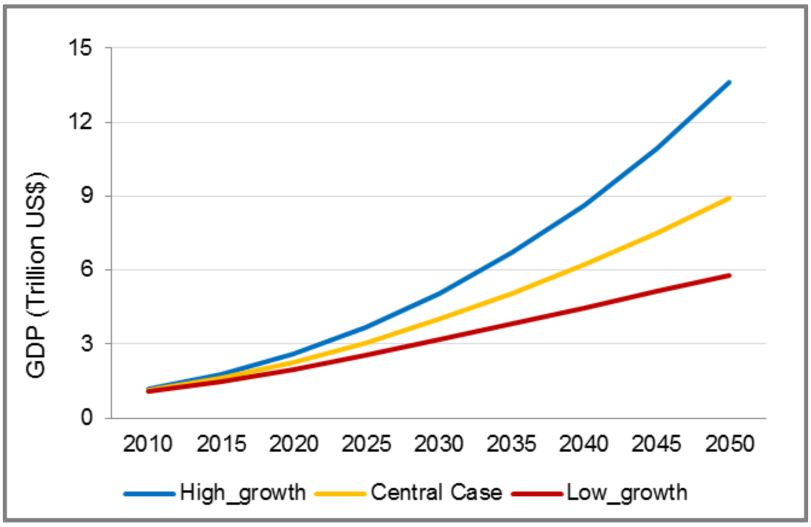

Figure 14: India's GDP under different growth assumptions

As expected, the electricity generation is 1.5-2 times higher for cases of high GDP compared to low GDP. But it is also seen that electricity comprises a lower % of final energy use when GDP is lower. This is because when GDP is lower (i.e. lower energy demand), the emissions constraint can now be met by using oil and coal in transport and industry sectors respectively, which is cheaper than using electricity.

The share of technologies for electricity generation does not change substantially from central case even under the different assumptions of future GDP growth. In all cases, solar-PV still dominates in 2050, followed by nuclear, gas and hydro. Moreover, the total discounted system cost of each scenario relative to reference case remains the same as in Figure 5. This means that a higher or lower GDP does not make any single scenario more attractive to pursue for India purely from cost perspective. In addition, the 2050 annualized cost as percentage of GDP also shows the same trend as in Figure 6. This is because the annualized cost of following a particular emissions pathway changes roughly in the same proportion as change in GDP growth assumption.

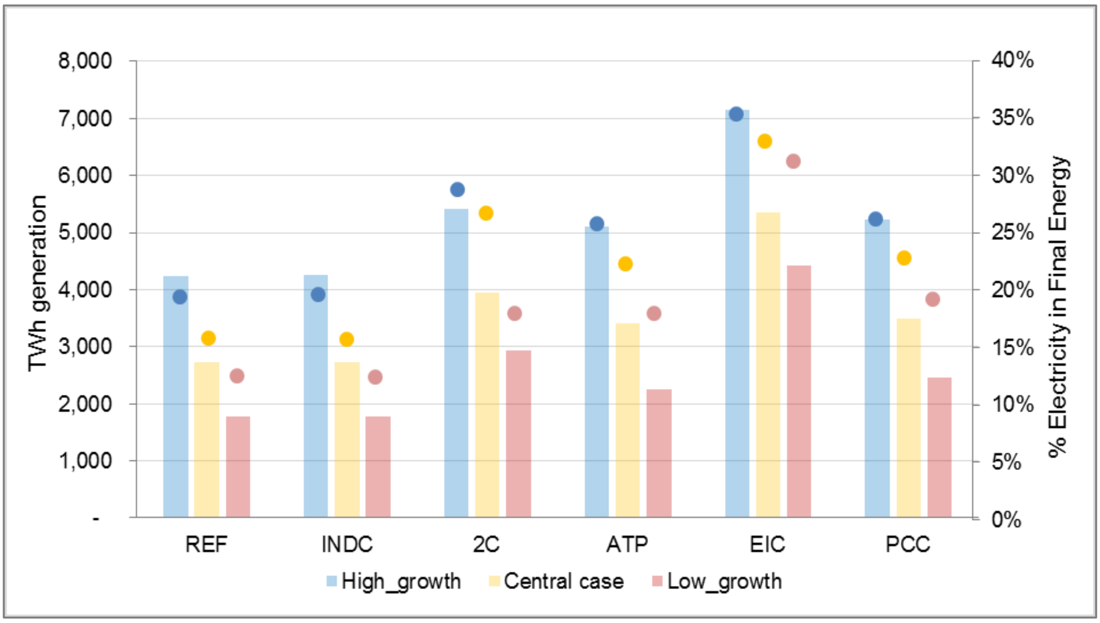

Figure 15: GDP's impact on 2050 electricity generation and share in final energy

Conclusions and Discussions

Summary of main findings

This paper fills the gap in literature by looking at various emission allocation rights schemes for India and assesses the evolution of Indian power sector under those allocation schemes. It developed four low carbon scenarios, of which three are based on different emission allocation scheme (ATP, EIC and PCC), that are compatible with 2°C carbon budget in addition to REF and NDC. It also carried out sensitivity on GDP growth rate and also with couple of crucial technologies (Solar PV and CCS).

The analysis shows that depending on emission allocation schemes, the total energy system cost, long-term electricity generation requirements, and share of renewables especially solar PV generation to meet the 2°C target varies. EIC scheme which has the highest mitigation burden for India (the most stringent CO_2 reduction target for India) can increase the total discounted energy system costs by 15% compared to that in REF. ATP and PCC schemes costs similar to the global least cost pathways that is the 2°C scenario.

Three main findings for the evolution of India's power sector to 2050 are synthesised below.

- First, solar-PV is the most important technology for decarbonisation of electricity generation. By 2050, India will require 800 – 1100GW installed capacity in the four low carbon scenarios presenting a significant challenge in scaling up from the 8GW currently. If share of solar-PV in 2050 generation is limited to 25%, total electricity generation in 2050 falls by more than 20% with no single technology being the clear winner. Additionally, the 2050 annualized system costs can increase by 2 – 17% relative to scenarios with no upper limit on share of solar-PV generation. These findings justify the current policy focus on promotion of solar-PV and point to the need for even greater emphasis on storage technologies which can help to balance the system.
- Second, coal's share of electricity generation in 2050 falls below 3% in the four low carbon scenarios. Here, a conservative estimate suggests that this will result in 200 – 215GW of stranded coal generation assets in 2050. The scale of potential stranded assets is greater than the current installed coal generation capacity of 186 GW. Stranded assets are thus a real threat to the financial health of the power sector and may weaken the government's push for power sector decarbonisation.
- Third, it was shown that early introduction of CCS technologies for the power sector in India can significantly reduce the cost of overall emissions reductions. In the most emissions constrained scenario, annualized system cost in 2050 can be less than halved if CCS is introduced in 2030 as opposed to introduction in 2040. Here, about 20% of the electricity generation in 2050 comes from CCS technologies.

Challenges for India's Energy System transformation

Besides technological challenges (storage technology, materials and grid balancing), the major challenge in India is governance and finance. The IEA's (2015) central scenario notes that by 2040, India requires a cumulative investment of $2.8 trillion in energy supply, three-quarters of which goes to the power sector, and the remaining to improve energy efficiency. This calls for effective coordination between multiple institutions and levels of government and overhaul of the energy regulatory framework. There are concerns that these decarbonisation policies could lead to significant coal generation capacity lying idle or operating at very low capacity factor in the subsequent decades because of the long lifetime of such installations. This phenomenon has been termed as stranded generation assets (IEA, 2014).

India has taken a number of policy measures towards the decarbonisation of the power sector. Currently, the government levies a coal tax of ₹400 per ton (equivalent to a carbon tax of about US$4/t$CO_2$). The Ministry of Finance (2015) also estimates that the implicit carbon tax from the excise duty on petrol and diesel is US$140 and US$64/tCO_2 respectively. In addition, there are targets for grid connected renewable generation capacity by 2022 – 100GW solar, 60GW wind, 10GW biomass and 5GW small hydropower (MNRE, 2015). The recent IPCC report on Global warming of 1.5°C, Summary for policy makers (IPCC, 2018) highlights that the challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long-term. These may increase uneven distributional impacts between countries at different stages of development. Unfortunately, our analysis suggest that India is one of those countries which are at the development stage and also highly risked with the lock-in in carbon emitting infrastructure especially coal-based generations unless action taken in the near-term.

Limitations

As with all modelling exercises, it is important to take note of the limitations of this study, among others three of which are noted below. First, due to limited resources available for this study, we have updated only the most relevant data sets for India. This may affect the accuracy of the results but the effect is mitigated since this is a long-term study. Second, TIAM-UCL as used for this work did not include energy storage technologies, which are very likely to play an important role in the power sector which has increasing share of intermittent renewable generation. Third, IAMs do not include meaningful structural representations of behavioural, social, political, and institutional factors (Clarke et al. 2012) that are important in shaping the future of the energy system.

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