The impact of policy decisions on the Indian electricity system in 2040 -a model-based analysis.

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***Abstract*—Based on a power system model, this paper studies how different policy decision evolves the future Indian electricity system of the year 2040. As of 2017, fossil fuels provided 80% of the electricity generation in India and there is a critical concern of increasing emissions in the future with a steady increase in demand. To overcome this concern, the Indian Government promotes the greening of the electricity system by setting renewable energy addition targets and other favourable policies. This paper mainly focuses on the long-term goal set in the draft national energy policy 2017, aiming 36% renewable energy in the power generation mix in 2040.**

I. Introduction

Increasing carbon emissions are a growing concern all over the world since it is criticised as the main reason for global warming. In the context of India, the power sector has contributed more than half of India's carbon emissions in 2015 [1] since 80% of electricity in India is generated from fossil fuels. With the electricity requirement projected to grow three times more than the current demand in the next two decades [2] emissions from the power sector could become a critical concern for India.

As of 2016-17, electricity consumption in the country was 1160 TWh. India has a total installed generation capacity of 330 GW, of which 66% is produced by fossil fuels, namely 192 GW of coal, 25 GW of natural gas and 0.8 GW of diesel. In total, these account for 80% of the electricity generation thus becoming the biggest electricity source in the country. Large hydropower generates 10% of the total electricity generation with an installed capacity of 44 GW. Renewable energy powers 18% of the total capacity with 21 GW capacity of solar, 34 GW of wind, 4.4 GW of small hydropower, and 8.8 GW of biopower but accounts only for 7% of the electricity generation, mainly because of its intermittency and low capacity factor. Nuclear power plants have a capacity of 6.7 GW and produce 3% of the electricity required [3].

NITI Aayog, the planning commission of the Indian government has released a Draft National Energy Policy in 2017. The key objectives of the national energy policy are to provide energy access at affordable prices, improved energy security and independence, greater sustainability and economic growth. The 'Draft National Energy Policy 2017' sets an ambition on the growth of RE in the country. It envisions that by 2040, RE can contribute a minimum of 29-36% of the electricity generation.

This paper examines the Indian power system in the year 2040 under different policy tools with the help of a modelling tool. First, setting a RE generation share target of 36%. Second, a RE generation share target of 29%. Third, the introduction of the carbon tax and fourth, emission restriction to achieve 2°C goal of the Paris Agreement.

A. Methodology

To achieve the objective of studying the future Indian electricity system in 2040 and RE contribution to it, a model of the Indian power system is built, and analyses are conducted. To develop the 'power system model,' a detailed understanding of the status quo and plans for the power sector is required. At first, the status quo power system of the year 2017 is built. It is done by surveying the current power system; capacities, operational and financial parameters of power plants like minimum load, fuel costs, investment cost so on. Then the model is expanded to simulate the future power system until 2040 using the data obtained by intensive literature survey from the national electricity plan, national energy policy, and targets set forward by the Government for future capacity additions. When specific data about the future projections on India is not available, it is then assumed from a study conducted about other countries of similar characteristics.

Once the model is developed, the simulation of the power system is carried out. During the simulation, the model will decide on the future investments in capacity additions based on the input data and simulates the operation of the Indian power on an hourly basis. The detailed working of the model is explained later. From the results of the simulation, the main characteristics of the power system like the generation mix, capacity additions, emissions from the power system, cost of electricity and compliance with climate goals are analysed. Then a new policy or target requirement is added to the reference scenario to investigate how such a change would affect the power system.

B. Scenario

Scenarios are a description of events that could happen in the future. In this study, scenarios would represent different futures of Indian electricity system under a different level of climate goals. This study has four scenarios. The main scenario is the 'Stated policy scenario' which is also the reference case. Three more scenarios are also studied; the 'carbon price scenario', and 'the 2 C scenario'.

Stated policy scenario is based on the stated plans and policies of the Indian government. The main inputs to this scenario are taken from the 'National Electricity Plan 2018' by [4] and 'Draft National Energy Policy' by [5]. This scenario tries to capture the future of Indian power system as envisioned by the Indian government.

Main elements of this scenario are as follows: The expected contribution of RE in the generation mix of 2040. NITI Aayog envisions that 36% of the electricity generation in 2040 would be powered by RE [5]. Planned state-wise RE capacity additions for the 2022 target added as exogenous capacity[1][4]. Transmission capacity between the grid zones added as exogenous capacity till 2022 [6]. Hydro plant capacities to be commissioned until 2024 is also added as exogenous capacity. Electricity demand growth is based on the latest 19^{th} electric power survey report by the Government [2]. The short term offshore wind target of 5 GW by 2022 and a medium-term target of 30GW by 2030 [7]. Under the 'Stated Policy Scenario', sensitivity analyses are carried out to study the implication of setting a RE generation target of 29% which is the lower end of the RE contribution envisaged by draft national energy policy and implication of not setting a minimum RE generation target, allowing the market forces to determine the RE growth in the country.

Carbon price scenario: Currently, in India, there are indirect ways to tax carbon by removing the subsidies on diesel and petrol and with the introduction of cess on coal. At present, the coal cess is Rs 400 (5.72 $ 2016) per metric tonne of coal [8] which is equivalent to 4 $ per ton CO_2 eq [9]. The average health cost arising due to the usage of coal in the power sector is 27.26 $ [9]. While the cess imposed by the government is five times smaller. Thus, there is a scope of introducing carbon tax for the power sector.

This scenario assumes an introduction of a carbon price of 17 $ per tonne CO_2 by the year 2025 and increasing to 35 $ per tonne CO_2 by 2040. Since India did not have any stated carbon pricing, this price is based on the carbon price proposed in China as in world energy outlook [1]. As China is the first large economy within the developing countries implementing a carbon market [10] it is relevant to analyse how a similar carbon tax value could affect the Indian power system in the future.

Price for CO_2 incentivises the use of RE since there is a penalty or price to pay for every tonne of CO_2 emitted. This would deter the use of fossil fuels as the CO_2 price would increase the cost of power from fossil fuels.

2 °C scenario: This scenario underlies the assumption that Indian electricity system would follow a trajectory that would lead to a reduction of global temperature well below 2°C. This is in accord with the Paris agreement and would put a limit on the carbon dioxide emissions from the Indian electricity system.

Inputs for this scenario are taken from 'Sustainable development scenario' of WEO 2017. In 2016, the CO_2 emissions arising due to power generation was 1089 Mt whereas the 2 °C scenario envisions that emissions would be limited to 564 Mt by 2040. The above CO_2 limit for 2040 is the limit, the power generation in India should reach to restrict the rising global temperature well below 2 °C from pre-industrial level by 2100 [1].

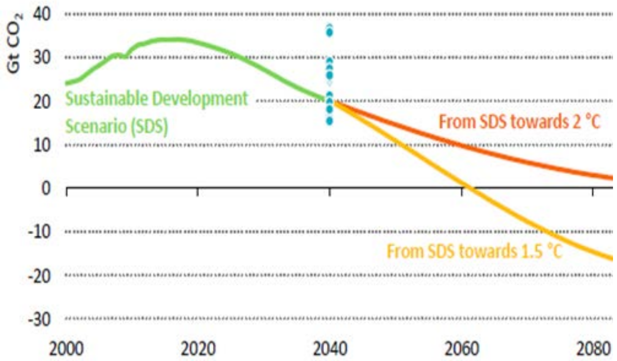

Figure 1 Projection of Worldwide CO2 Emissions to keep temperature rise below 2C [1].

The target might appear to be ambitious, to limit the emission to 50% of the current level in 2040 even though meeting more substantial electricity demand. However, it would give the policymakers an option to choose.

C. Modelling tool

BALMOREL modelling tool is used to build the Indian power system model and to study the future scenarios. The BALMOREL is a techno-economical partial equilibrium model that is used for the analyses of electricity, district heating and electricity market. It simulates the power system based on the principle of least-cost dispatch and least-cost investment [11].

In the least-cost investment mode, the model can make cost-effective investments, refurbishment and decommission of generation, storage and transmission capacities. While in the dispatch optimisation mode, the model makes use of the installed capacities in the most cost-effective way to meet the electricity or heat demand. Thus, it can find a least-cost solution for investment and dispatch within the electricity market. (ibid)

The model can run simulations on both time-aggregated and hourly basis, with very detailed geographical and technical parameters. The geographical coverage includes countries as the first layer, then regions within the country where electricity demand and transmission capacities are defined. The third layer has areas defined within each region to represent variability

[1] Exogenous Capacity refers to the plant capacities which are already existing or planned additions/ retirements. They are given as input into the model.

in generation resources within the region. The detailed characteristics of the fuels and power plants such as emission, costs, performance can also be defined in the model. (ibid)

It solves the equation of supplying the electricity demand in a particular region for every hour with the generation from plants within the region, by storing the surplus power, by discharging the stored power from storages and finally importing or exporting power to other regions via transmission links.

Even though the model tries to reflect the actual development of future scenarios, there are some limitations in the model that needs to be considered.

The model processes only the given inputs. Thus, the quality of the results depends on the quality of the input. Since nobody can predict the future perfectly, there is an uncertainty associated with inputs given to the model.

The model has some simplifications compared to real life scenarios. It assumes a perfect foresight. This means that based on the input data on demand profile and generation profile of power plants, it knows beforehand what will be demand and possible generation at every particular hour. Based on this foresight it determines the optimum capacity and dispatch. Whereas, in real cases, such a foresight on the availability of power plants, wind power, hydropower and solar power production profile is not available [11].

Also, the model assumes perfect competition and perfect dispatch based on the merit order. This means that the power generator are price takers, and nobody can influence the market. The order of power dispatch is based on order of generator with the cheapest marginal cost of generation. (ibid)

The model does not consider detailed technical issues for transmission links, such as voltage level, angle stability. It only investigates the available capacity for transmission. In real life, transmission of electricity also depends on the above parameters which cannot be modelled in BALMOREL [12].

D. Assumptions/ Input data

1) Modelling Parameters

Model Nomenclature	
Regions	Five regions are represented in the model representing each grid zones
Base Year	2017.
Study Year	2040
Simulated years	2017,2025,2030,2035,2040

Table 1 Modelling Parameters used in the model

In the model, India is divided into 5 regions representing the grid zones: the northern region, the western region, the eastern region, the north-eastern region and the southern region. The electricity demand, the demand variation and transmission capacities are defined at this level.

The year 2017 is chosen as the base year so as to have the comparison with the latest development in the power sector. The year 2040 is the study year since one of the underlying research questions is studying the RE contribution target of the Government to have 36% RE share in the power system by 2040. The model is simulated every five years from 2025 so as to represent an actual growth in the power system. If only 2040 is simulated, the model will decide in the cheapest technologies available at that time.

2) Geographical scope

Simulations are conducted over the entire Indian electricity system. Generation, transmission and demand data have been inputted at state level representing 29 states and five union territories of India. It does not include the island territories Andaman and Lakshadweep since they are not connected to the mainland grid system.

3) Financial Data

All financial data in the model, i.e. investment cost, variable and fixed operation and maintenance (O&M) cost, fuel prices are defined in USD fixed prices with the price level for the year 2016 unless otherwise mentioned. So, changes in the price variation due to inflation are not accounted in future price projections. A fixed price-level year in dollars is used to make the currency unit constant across all the data. The conversion factor for Indian Rupees is 1 USD 2016 = 69.95 INR or I INR = 0.014 USD 2016 [13]. The weighted average cost of capital (WACC) is assumed to be 9 % based on the WACC for infrastructure projects [14].

4) Electricity Demand

The model includes the annual demand data and hourly demand met pattern for the five grid zones/ regions of India. Annual demand was calculated from the monthly executive summary released by CEA for the year 2017. Hourly demand met pattern is based on monthly load curves from a study conducted by POSOCO (2016) [15], and it will reflect seasonal variation in the annual demand.

5) Demand Projection

The annual demand for the future years is projected based on the demand growth rate provided by Electric Power Survey (EPS) conducted by Central Electricity Authority (CEA) [2].

Year	**Electricity requirement (TWh)**	**CAGR**
2017	1190	6.20%
2022	1598	5.50%
2027	2064	4.30%
2032	2536	3.80%
2037	2944	3.80%
2040	3418	

Table 2 Electricity Demand Projections 19th EPS.

6) *Demand Variation*

Along with the annual demand, the hourly variation of the demand is also included in the model to represent the variation in the electricity demand according to the time of the day. The hourly demand variation profile is based on the study conducted by POSOCO (2016) on electricity demand pattern analysis for each grid regions.

These variations are for the year 2015 but are assumed to be the same for each year until 2040. Since only a daily load curve averaged for a month was available from POSOCO (2016) [15], the same profile is used as a daily load curve for every day in that month. Even though this limits the model's ability to capture the variations in demand profile across the days in a month, nevertheless it gives a good representation of seasonal variations in hourly demand met pattern across the country.

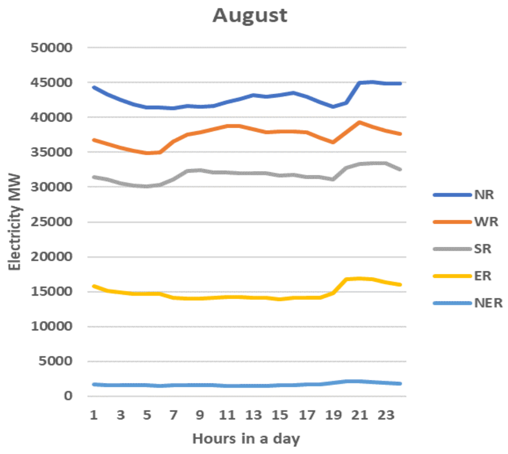

Figure 2 Average Daily load curve in August for five grid regions [15]

7) *Generation Plants*

In the model, following generation plants were added as an input for every state namely coal, diesel, gas, nuclear, solar, wind, biomass, bagasse, hydro powered by run-off river, hydro reservoir and waste to energy Latest available state wise plant capacity data has been used in the model. Also known future plant capacity additions announced by the Government, 175GW renewables by 2022 [16] and planned hydro capacity [17] are also added to the model as the exogenous capacity for each state.

8) *Transmission*

Transmission is one of the vital parts of every power system along with the power plants and the availability of fuel. A strong transmission system is required to connect the power plants with demand centres. Transmission capacity is defined only between the grid region in the model, and within a region, it is assumed that there are no transmission constraints.

The exogenous capacity of the inter-regional transmission network in 2017 and expected to increase in 2022 as per below table.

Zones	Capacity (MW) 2017	Capacity (MW) 2022
ER – NR	19,530	22,530
ER-WR	12,790	21,190
ER-SR	7,830	7,830
ER-NER	2,860	2,860
WR-NR	16,920	36,720
WR-SR	12,120	23,920
NR-NER	6,000	6,000

Table 3 Inter-regional transmission capacity [6]

Cost of transmission is another important parameter in the model which determines whether to invest in a power plant within the region or invest in transmission network to import electricity from another surplus region with the smaller marginal cost of electricity.

A report on power transmission in India suggests a cost of 5510 Rs /MW-km (109.38 $) for building transmission link. Cost of substation as suggested by IEA is 10,700 $/MW [20].

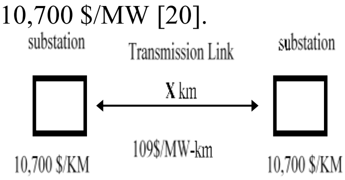

Figure 3 Schematic for Transmission investment cost calculation

E. *Limitations*

The load profile used in the model is based on a study conducted for the year 2015. It is assumed that the profile would remain the same throughout from base year to study year. In the actual profile will not be the same.

There was no study or technology catalogue available on the projected cost reductions of generation technologies like solar and wind power in India. Therefore, the price projections were based on countries which have similar cost is used.

Transmission capacities in the model are defined at the regional level and assume that within a region there are no transmission constraints. It was intended to use the inter-state transmission capacity in the model in place of inter-regional capacity as it would reflect the transmission constraints between the states. The author had contacted the officials in Power Grid, the CTU to obtain the data but they were unable to provide the required data. Hence, in the model, it is assumed that between the states within a region, there are no transmission constraints.

II. RESUTS AND ANALYSIS

A. *Stated Policy Scenario (Reference Case)*

The main policy constraint used in this scenario is to generate a minimum of 36% electricity from RE by 2040 adhering to the target of the Government. The required electricity generation in 2040 is 3660 TWh whereas in 2017 it was 1271 TWh in 2017. To meet the growing demand and requirement of having 36% RE in generation mix more power plants needs to be installed as discussed below.

1) Installed Capacity and Generation Mix.

In 2017, coal generated 972 TWh of electricity, and it is the most significant contributor to the generation mix by generating 73% of total generation. By 2040, coal remains the major contributor, but the share of coal comes down to 48.81% in 2040 due to the increased contribution from RE by 2040 to 36% as shown in Table 20.

By 2040, the installed capacity of coal has grown only by 53 GW signifying that the growth of coal is limited compared to three times increase in the electricity generation. One of the reasons for low coal growth is the low capacity utilisation of current plants which is at 54%, so there is an overcapacity of coal plants in 2017.

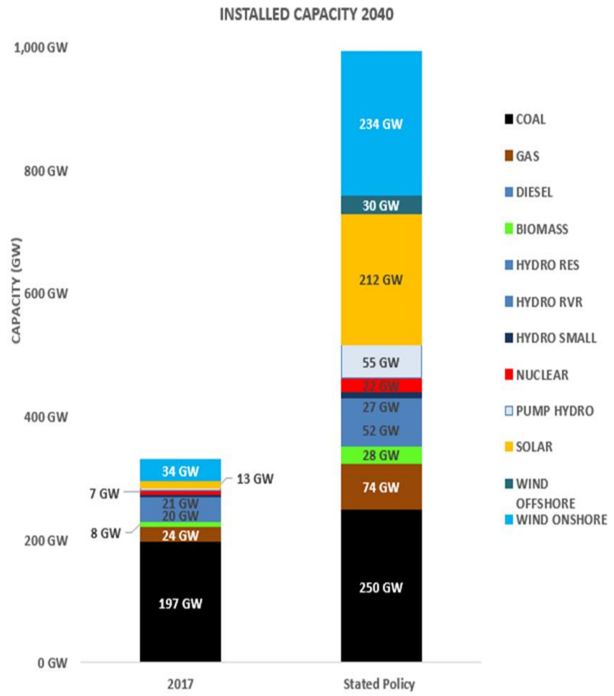

Figure 4 Installed Capacity 2040

The increased RE share in generation mix by 2040, is powered by the growth in the installed capacity of solar and onshore wind power. Solar power capacity rises to 212 GW; generating 10 % of electricity in 2040. This capacity growth in solar is a considerable increase compared to 2017, where it was only 13GW. The main reason for this growth is the minimum RE requirement used in the model as a constraint and the reducing cost of solar plants across the coming years. Similar growth can be seen in the case of wind power; the capacity increases to 234 GW by 2040 from 34 GW in 2017 producing 604 TWh equivalent to 16% of electricity generated in 2040. This significant growth is also due to the decreasing investment cost of wind power and minimum RE generation constraint used in the model. The constraint of minimum 36% RE generation could be translated in the real world as government policies that would favour the increase in the investment in RE energy sources.

A newcomer in the generation mix is the offshore wind power with 30 GW capacity by 2040. This capacity addition is because of the Government policies and target of having 30 GW offshore wind capacity by 2030 (PIB, June 19, 2018) but the capacity remains 30 GW by 2040 indicating that cost of offshore wind is still high to compete with other power sources. To boost the growth of offshore wind, the Government still needs to support it with incentives and policy.

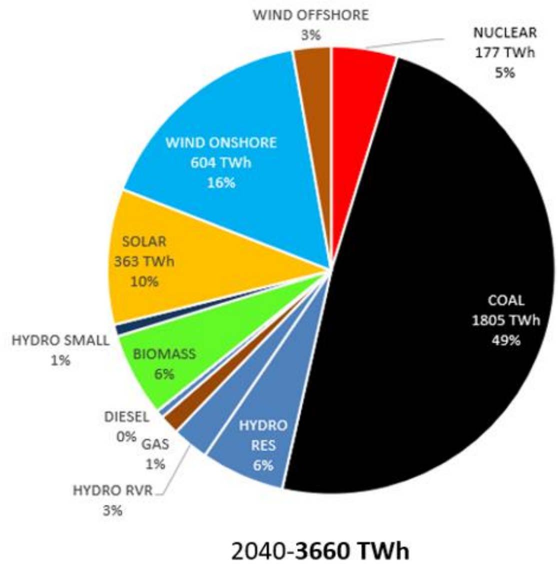

Figure 5 Generation Mix 2040

2) Flexibility.

There are four main flexible energy sources to accommodate the variability and intermittency of solar and wind power.; pump storage, hydro reservoir, gas, and coal. Pump hydro storage with 55 GW capacity plays a vital role in the system flexibility by 2040. It stores the excess power from the system during peak sun hours and excess wind power production period and then makes available this energy during peak demand times. The inherent flexibility of coal plants is also aiding in integrating solar and wind. Since coal plant can run at a minimum load of 55%, they can ramp down the production to avoid curtailment of RE.

3) Curtailment of Solar and Wind

The negligible curtailment of solar and wind power in this scenario proves the flexibility of the Indian power system to integrate renewable energy sources. The curtailed wind power is only 4.95 GWh which is only 0.001% of the available wind power. Similarly, solar power curtailed is 38.7 GWh, i.e. 0.011% of available solar power. The power curtailed is very negligible compared to the available energy from those power sources.

4) CO_2 Emissions

For In the stated policy scenario, the CO_2 emissions are increasing at an alarming rate. In 2017, power industry emitted 1034 Mt CO_2, while in 2040 the emissions shoot to 1817 Mt CO_2. This increase in emission poses a serious threat to the people in India and the world as it would lead to the increase in global warming. Even though the Government of India has a strong target of 36% RE share in a generation by 2040, the CO_2 emissions resulting from thermal plants are a critical concern. The growth in the emissions is because coal is still the primary source of power generation, producing more than 49% of electricity in 2040 equivalent to 1805 TWh while in 2017 the coal generation amounted only 970 TWh. This increase in coal generation is the reason for the increase in CO_2 emissions.

5) Sensitivity Analyses : Minimum RE generation share of 29 % by 2040

The draft national energy policy for India envisages a RE share in 2040 between 29%-36% [5],. In the above section, the power system with 36% RE share is already discussed. Now the implication of following a lower target of 29% RE share target on main results are discussed.

The most significant implication is that with the decrease in RE share, the coal generation increase to 56% share of total generation. Thus, CO_2 emissions rise further to 2036 Mt CO_2 by 2040 compared to 1817 Mt CO_2 in the Stated policy scenario. With a higher CO_2 emission than 'Stated policy scenario', an 29% target would not also be able to reach the emission intensity target of India.

6) Sensitivity Analyses : No RE share

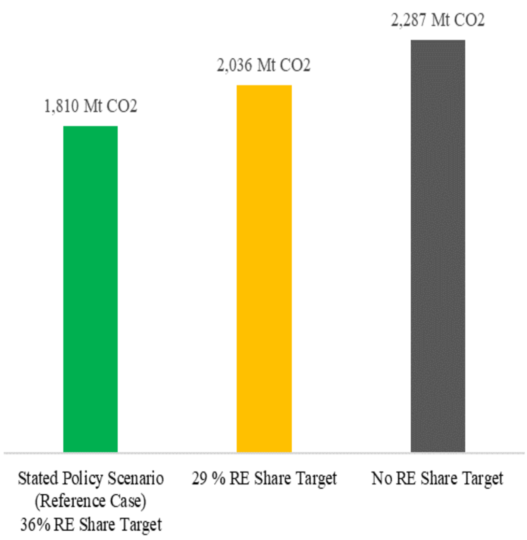

Figure 6 CO_2 Emissions under different RE contributions

To study the implication of not having a RE target and allowing the RE growth to happen by market forces, sensitivity analyses on the stated policy scenario with no RE share constraint is simulated.

Without the target on the minimum RE share in the generation mix, the RE share in 2040 is 21%. This is much lower than the targets envisaged by draft national energy policy. This would also have a serious implication on the climate goals of India as the CO_2 emissions increase to 2287 Mt CO_2.

B. Carbon Price Scenario

The 'Stated Policy Scenario', with 36% renewables in generation mix could not achieve a significant reduction in emissions compared to emissions since electricity demand is increasing rapidly. One of the policy measures that could be implemented to achieve compliance is the introduction of the carbon tax. With this tax, a price must be paid for every tonne of greenhouse gas emitted measured in per tonne CO_2 equivalent (t CO_2 e).

In the carbon price scenario, it is assumed that the carbon tax would be 17 $ per tonne CO_2 by 2025 and increase to 35 $ per tonne CO_2 by 2040 as discussed in section B.

1) Installed Capacity and Generation Mix.

It is seen that with the introduction of CO_2 price, the generation from coal is reduced to 708 TWh which is only 19% of electricity generation while in the 'Stated Policy Scenario' coal generates 1,805 TWh equivalent to 49 % of total generation. This is because, with the inclusion of CO_2 price, electricity production from coal has become less favourable since tax must be paid for every tonne of CO_2 emitted from coal plants. To complement the gap in electricity production, generation from hydropower, nuclear power, solar and wind power is boosted. The run-of-river capacity is exploited to its maximum available potential by increasing the capacity to 96 GW. Thereby, in this scenario, they contribute 10% of the total generation whereas in 'Stated Policy Scenario' they generate only 3%. The generation from hydro reservoir remains the same as the reference scenario since in both scenarios they reach the maximum potential of 52 GW.

RE technologies gain the most with the introduction of CO_2 price as it incentivises the use of RE energy. RE share in generation increases up to 48% from 36% in 'Stated Policy Scenario'. Solar power capacity increases to 340 GW and generation to 16%. Offshore wind power capacity is still the same due to high investment cost involved with offshore projects, CO_2 price introduced is not enough to incentivise it. Onshore wind continues to grow further producing 21 % of electricity, and the installed capacity of wind power reaches the maximum available potential in the country.

Another significant effect of the introduction of the carbon price is the increase in the capacity of nuclear power plants. The capacity of a nuclear power plant in this scenario is 71 GW, which is more than double the capacity of 22 GW in the 'Stated Policy scenario'. Consequently, increasing the generation from nuclear power to 15% of total generation. This signifies that the level of carbon price introduced is enough to allow more investments in nuclear power plants, which are otherwise expensive. The pump storage capacity increases to 74 GW to integrate the increased renewable energy production.

2) CO_2 Emissions

In this scenario, the CO_2 Emissions reduces to 750 Mt CO_2 which is 60% less than the emissions in the stated policy scenario showing that CO_2 price is a very powerful tool to reduce the emissions from the power system and to achieve emission targets. The emission reduction is achieved with increased generation share from RE sources of 48%.

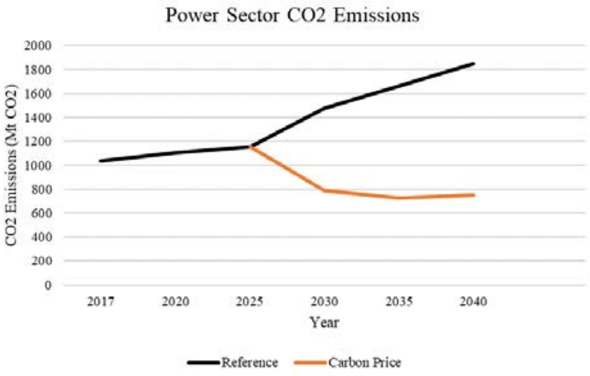

Figure 7 CO2 emissions in Carbon Price Scenario

C. The 2 C scenario

This scenario studies how the Indian power system must evolve by 2040 to meet the long-term goal of keeping the global temperature rise below 2°C by 2100.

The main constraint in this scenario is the restriction on the emission of CO_2 from the power sector set at a maximum of 564 Mt CO_2 in 2040.

1) Installed Capacity and Generation Mix.

As a result of the restriction on carbon emissions, in this scenario the generation from power plants producing CO_2, i.e. fossil fuel powered are limited.

The generation from coal plunges to 14% share in the generation mix, whereas in stated policy scenario it produced 48% of total generation. The generation from coal is replaced by non-fossil fuels: wind, solar, nuclear, and hydropower.

The generation share from renewable energy increases to 46% as there is a restriction on the CO_2 emissions. The capacity of solar increases to 286 GW, 74 GW more than the 'Stated policy scenario'. Solar is generating 490 TWh of electricity accounting for 13% of total generation. Wind power generation share increases to 22% with the installed capacity reaching its maximum potential of 304 GW.

Other RE sources, biomass and small hydro are also installed to its maximum potential available generating 6% and 2% of the total generation. The capacity and generation from wind offshore remain the same as the stated policy scenario. Even with this high restriction on carbon emission, the wind offshore has not become an attractive option. The 30 GW offshore wind installed is because of the government policy. Thus, the results signify that government support is still required in 2040 to promote offshore wind projects. In total, RE contributes 46 % of the total electricity generated and thus becomes a significant energy source in the country by 2040 under this scenario.

The next source of power that is economically viable is exploiting the hydropower potential. So, in this scenario like the carbon price scenario, all the available potential is installed increasing the total large hydro generation to 16% in the generation mix. The total capacity of hydropower including run-off river and reservoir reached its maximum potential of 148 GW.

The remaining part of generation comes from the nuclear power. The capacity of nuclear power increases to 102 GW in this scenario, while in stated policy scenario it is only 22 GW. The emission restriction has made nuclear power an attractive investment choice in this '2 C scenario' to replace coal power plants. Nuclear is producing 16% of the total generation in this scenario.

2) CO_2 Emissions

In this scenario, the carbon emissions are very low compared to the stated policy scenario and carbon price scenario as it intends to keep the carbon emissions from Indian power sector to a level that would keep the global temperature rise below 2 °C.

The emission level under this scenario peak by 2025 following a trajectory similar to world carbon emissions levels shown in Figure 1 and then reduce to a much lower level of 562 Mt CO_2 by 2040. On comparing with stated policy scenario, the emission level by 2040 in the 2 C scenario is 69% lower. To attain this level of reduction in emissions the government needs to implement strict measures on emissions, more promotion of renewable energy power projects or could use an appropriate carbon tax required to attain the emission levels. Carbon price could be used as a means to achieve the emission targets. The model results show that the carbon price required in 2040 to achieve the carbon emission target of 562 Mt by 2040 is 39 $/ Mt CO_2. It is 4 $ more than the carbon tax used in the 'Carbon price scenario'.

III. CONCLUSION

The modelling and simulation of the Indian power system have given a great understanding on the working of the Indian power system. The study was able to gather together the latest data on plant capacities, plant operation parameters, government targets on capacity additions, policies and availability of energy sources.

The results of the simulation give a view of the future Indian power system by 2040 if the government follows the target it set forwards. It is seen that the Government target of achieving 36% RE by 2040 is a technically achievable target with negligible curtailment, with pump storage and hydro reservoir being able to absorb surplus power production during peak solar and wind periods. 'Stated policy scenario' study indicates that the economically optimum capacity required to meet 36% RE share under the given constraints in 2040 as 212 GW solar, 234 GW wind, 28 GW biopower and 10 GW small hydro. A pump storage capacity of 57 GW is required to meet the flexibility requirements of increased variable generation resource. Even with higher RE share in the generation mix compared to the status quo, the carbon emissions increase to 1817 Mt CO_2 and so India is not able to reach its INDC target of reducing the emission intensity. Sensitivity analysis on the RE generation share constraint revealed that following a 29% RE share in generation mix would increase the CO_2 emission from the power sector to 2036 Mt CO_2. If a RE share target is not put forward by the Government, allowing the RE growth to take place autonomously, then the RE share in the generation mix by 2040 will be only 21% implicating much more CO_2 rise of 2287 Mt CO_2.

As a solution to this problem, to achieve the INDC target, as a policy measure carbon tax is introduced in the 'Carbon Price Scenario'. With the introduction of a price on CO_2, the price of generation from coal plant increases and generation share of coal reduces to 19% by 2040. It also incentivised to increase the capacities of wind and solar power thereby increasing the production from RE sources to 48% of total electricity production. The wind capacity reaches to its maximum potential of 304 GW and solar capacity increases to 340 GW. Thus, it is found that introducing a price on every tonne of CO_2 emitted is an excellent measure to develop a greener power system as it brings down the coal generation while incentivising the RE generation.

In both 'stated policy' and 'carbon price' scenario, pump storage is seen to play a key role in the flexibility of the power system. As an alternative scenario, 'Low pump scenario' showed us how the Indian power system could meet the RE generation target of 36%, without installing new pump storage facilities. In this scenario, coal, hydropower with storage and gas power plants smoothen surplus power and provide peak power.

The 2 C scenario showed how Indian power system of 2040 could adhere to the long-term Paris goal of keeping the temperature rise to 2 C. This calls for an immediate response from the Government to reduce the emissions from the power system. The simulation results show that the share of generation from coal plants would come down to 14% to meet the emission limit. Under the assumed cost projections of RE technologies and flexibility constraints involved, RE contributes a 46% share in the generation mix. Nuclear power is also found to be a substitute for replacing the coal generation along with RE because of its ability to run as baseload, unlike wind and solar whose power production is variable.

Cost comparison shows that scenarios with lower emissions have a higher system cost compared to stated policy scenario. This is due to the increased investment cost arising from adding more renewables and nuclear power to replace coal generation. However, on considering the health cost associated with emissions from coal power plants, the price difference between stated policy scenario and carbon price scenario comes down.

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