Policy Analysis of Renewable Electricity Development in India: From A Transition Modelling Perspective

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ABSTRACT: *India has started the transformation of its electricity sector towards renewable sources intertwined with the privatisation of the electricity market since 1990s. The government has targeted 60 GW wind and 100 GW solar installed capacities by 2022 and* designed *a range of policies to realise the targets. However, government interventions and target settings may end up with failures. Transitions towards renewables are multidimensional and involve complexities, nonlinearity and contingencies, but policy making processes tends to simplify them. Complying with the specific features of transitions, we apply a 'transition model', developed with the system dynamics approach and underpinned with the transition theories, to investigate the past and the future of the electricity sector's transition in India from 1990 to 2030. The simulation results show how the privatisation of the market in 1990s has led to increase in renewables in the past 25 years. Six future scenarios are also developed, and the transition pathways are simulated for each scenario. It is found that: 1. coal will be the dominant source of electricity in every scenario, 2. wind will have the highest share among renewables and 3. solar will need government support to realise its ambitious 100 GW target.*

Keywords: System dynamics approach, Sustainability transitions, Transition modelling, Renewable energy, Simulation, India.

1 Introduction

The Indian electricity generation sector is being transformed rapidly from fossil resources towards renewable sources along with changes in its structure from fully centrally-monopolistic to partially-liberalised market. This multi-dimensional transformation is an example of a 'societal transition which aims to serve societal needs' such as energy equity, energy security and greenhouse gas (GHG) emissions reduction (Moallemi *et al.*, 2015b). The transition has become one of the top priorities of the government to realise as it can satisfy the country's growing electricity demand, and at the same time can reduce its escalating GHG emissions. The government has set national targets and proposed supporting policies to facilitate the transition and to realise the intended targets. These targets and policies can succeed (Dulal *et al.*, 2013), but they often fail or are very expensive according to the previous experiences of government interventions in other countries (Robinson, 2015; Tahmassebi, 1992). To reduce the risk of failure, any direct or indirect interventions should be performed having considered their impacts on the current dynamics of the transition and also the plausible pathways of the electricity sector in the future.

The understanding of the dynamics should be in connection with the historical development of the sector and also based on the prospect of driving forces in the future (Fouquet, 2010; Rühl *et al.*, 2012; Zhao, Chang, and Chen, 2016). Considering the non-linearity and the complexity of interactions as well as the presence of uncertainties and contingencies, a simulation model is required to acquire a better understanding. The models are diverse in terms of their formulation, underlying conceptual foundation and ontological basis. However, not every model would suit for the understanding of the transition dynamics as long-term, co-evolutionary, multi-dimensional and path-dependent processes. The model should be, as it is called in the recent literature (Holtz *et al.*, 2015; Moallemi *et al.*, 2015a), a 'transition model'. This is a model which incorporates the profound, pervasive and polycentric (multi-actor, multi-scale, etc.) transformation of a societal system, such as an electricity sector, in an intergenerational timescale (Köhler *et al.*, Working paper).

Accordingly, this paper aims to explore the transition pathways of the India's electricity sector in terms of installed capacities, generations, etc. with a transition model. These pathways are assumed as the accumulation of changes in historical transitions started from 1990 and are explored in the face of plausible future scenarios in 2030 horizon. In particular, we are interested to answer how have some major driving forces, such as market privatisation, influenced the transition and shaped the current state of renewables? What would the future for renewables and conventional resources' shares look like across different scenarios? Under what policy arrangements/scenarios will the desired vision for renewables be achieved?

To answer these questions, model simulation is run from 1990 to 2030 and its results are discussed in interaction with the descriptive explanation of the transition in narratives. The interactions between narratives and simulation results allow for the inclusion of the effects of soft and external factors that are not normally captured in the model-based policy analysis but are qualitatively explained in narratives. The interactions also allow seeing the side effects of policy interventions which are hidden in the narrative-based description of policy impacts but are apparent in the long-run simulation of non-linear and causal relations. With this regard, Section 2 explains the method and steps taken. The results from the simulation runs and discussion are presented in Section 3. Section 4 concludes the findings of the research.

2 Method

This policy analysis exercise was conducted in three phases. In Phase 1, a transition model was developed firstly. It is a system dynamics model with a stocks and flows structure developed in

Vensim Professional 6.3. The model is also underpinned by the conceptual frameworks in sustainability transitions field (de Haan and Rotmans, 2011; Frantzeskaki, 2011; Geels, 2002; Yücel, 2010) to better address the specific features of transitions. Then, the transition model was set up with data collected from the India's electricity sector (Moallemi *et al.*, 2016). The model's parameters were optimised with the historical data to better match with reality. Model simulations were run in Phases 2 and 3. In Phase 2, the historical transition of electricity sector from 1990 to 2015 was reproduced (Subsections 3.1 and 3.2). This helped to understand whether the model imitates the real behaviour of the electricity sector or not. It also revealed insights about the past changes. In Phase 3, the model simulation was run for a longer time period, till 2030 (Subsection 3.3). It laid out a basis for our discussion about the future transition pathways, in terms of installed capacities, GHG emissions, etc. in different plausible scenarios.

Before proceeding to the simulation runs, the overview of the transition model (which is the basis of the research) as well as the model implementation's setup is explained as follow.

2.1 Overview of the transition model's architecture

The model was developed based on the group of emerging conceptual frameworks in the sustainability transitions field which describe the transformation of societal systems (de Haan and Rotmans, 2011; Geels, 2002). It allowed us to develop a model customised for the long-term, path-dependent and multi-dimensional nature of transitions and not a SD model of a generic change process. It also assisted in conceptualising the mechanisms of dynamics in the model, defining the appropriate boundary of the system, generating a dynamic hypothesis and developing the main structure of the model. Accordingly, the model conceptualised the electricity sector as a 'societal system', composed of several generation options as 'competing constellations' and functioning normatively to satisfy some 'societal needs' such as demand-supply balance and energy security (de Haan and Rotmans, 2011; Geels, 2002). It was defined that constellations are empowered by 'actors', e.g. generators and distributors, and 'actors' decisions', e.g. investment decision (Yücel, 2010). The model also separated between internal and external mechanisms in transitions using the concept of 'destabilisation and formation driving forces' from Frantzeskaki (2011). Based on this conceptualisation and according to the qualitative insights of the India's electricity sector, a narrative of the historical transition was developed. The transition narrative can complement the simulation results in policy analysis (will be discussed in Section 3.2). This narrative along with the conceptualisations in the sustainability transitions forms the dynamic hypothesis and the causal loop diagram (see Figure 1) for SD model development.

The model's main structure in Figure 1 is composed of nine components. The Pricing Component computes tariffs for the trade of electricity between generators, distributors and end-users and also the costs and benefits of electricity generation and distribution. The output of the Pricing impacts how investors invest in different sources. The Investment Component investigates the dynamics of investors' decisions and how they invest in renewable compared to conventional sources. Investors' decision is defined as a function of the attractiveness of different sources and is interlinked with the decision of generators and distributors. The Capacity Component simulates the growth in installed capacities in reaction the incoming investments. It also formalises technology progress and changes in resource efficiency of different sources throughout the time. Based on the installed capacities and also plant load factors, the Generation Component determines the generation of electricity from new and old capacities and per each individual source.

The amount of electricity generated from each component determines the satisfaction of societal needs, i.e. energy access, energy security and sustainability. The Demand-Supply Balance Component specifies the growth of electricity demand for each consumer group and based on that, it calculates the gap in access to energy. The Energy Security Component models how much fossil fuel is required for conventional power plants and what portion of that should be imported from overseas. And the Environment Component specifies the amount of GHG emitted from the generation of electricity. The present states in each of these three components are compared with the desired targets set by the government and then expressed as the satisfaction of societal needs. The satisfaction of societal needs signals for the continuity and the intensity of policy mechanisms, such as Feed-in Tariff (FIT), in the Policy Component. Based on the level of government interventions and the share of public investment, the Financial Burden Component analyses total government expenditures.

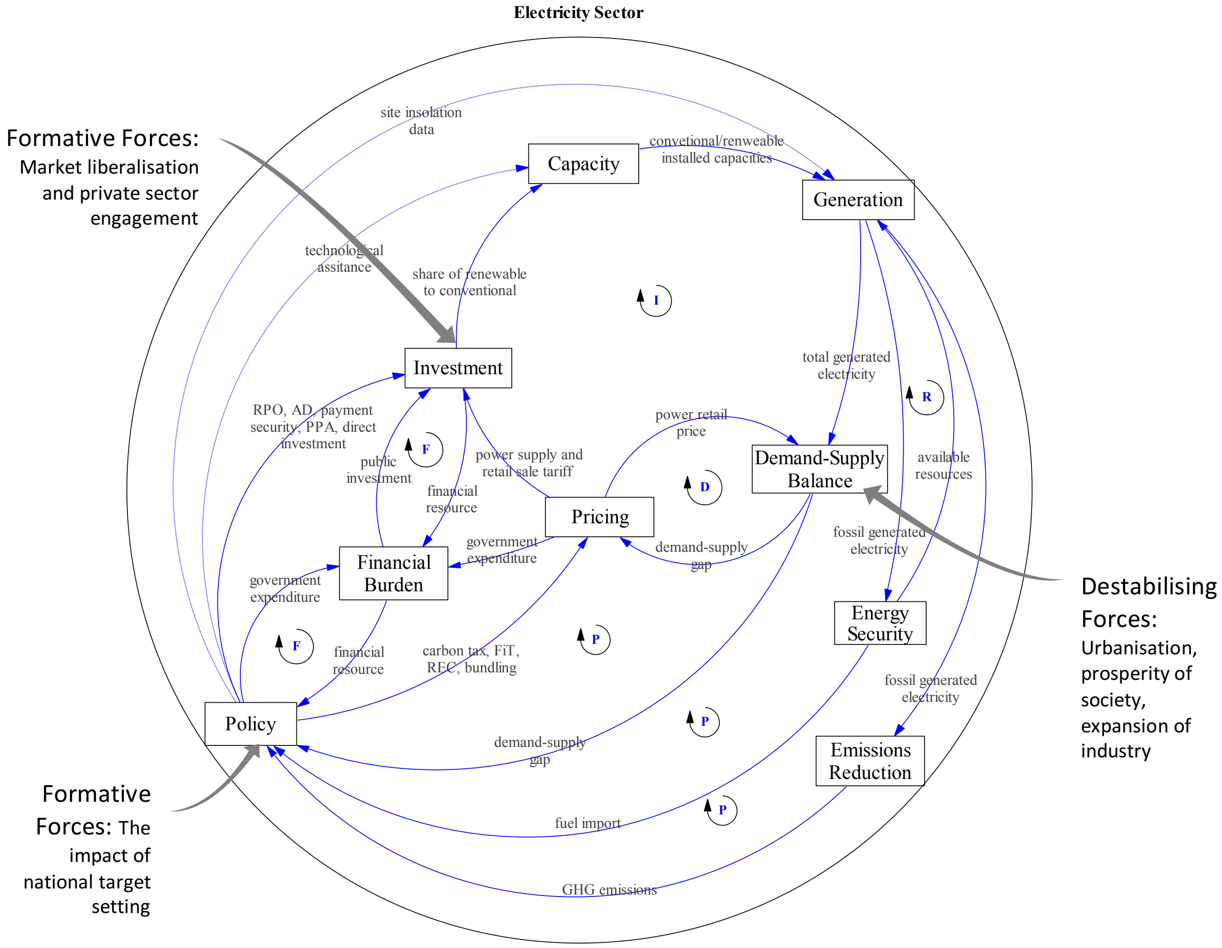

Figure 1. Causal loop diagram representing the interactions between different societal components in electricity sector based on the conceptualisations of sustainability transitions field

The endogenous dynamics of transition needs to be completed by external destabilising and formative driving forces. The impacts of the forces cannot be generated through the internal dynamics and they should be imposed from external of the system. These forces were already identified in the qualitative narrative of transition. Market privatisation and the prosperity of society are two examples which influence investment and demand for electricity.

2.2 Model implementation

The model's main components are implemented in Vensim. They are represented by stocks and flows variables, and the relations between them are defined by relevant equations. They are not discussed here as the focus of this paper is on the policy analysis based on simulation runs. However, the simplified version of the stock and flow diagrams for Investment Component and Policy Component are presented in Figure 2 and Figure 3 to give an idea of the underlying model's structure.

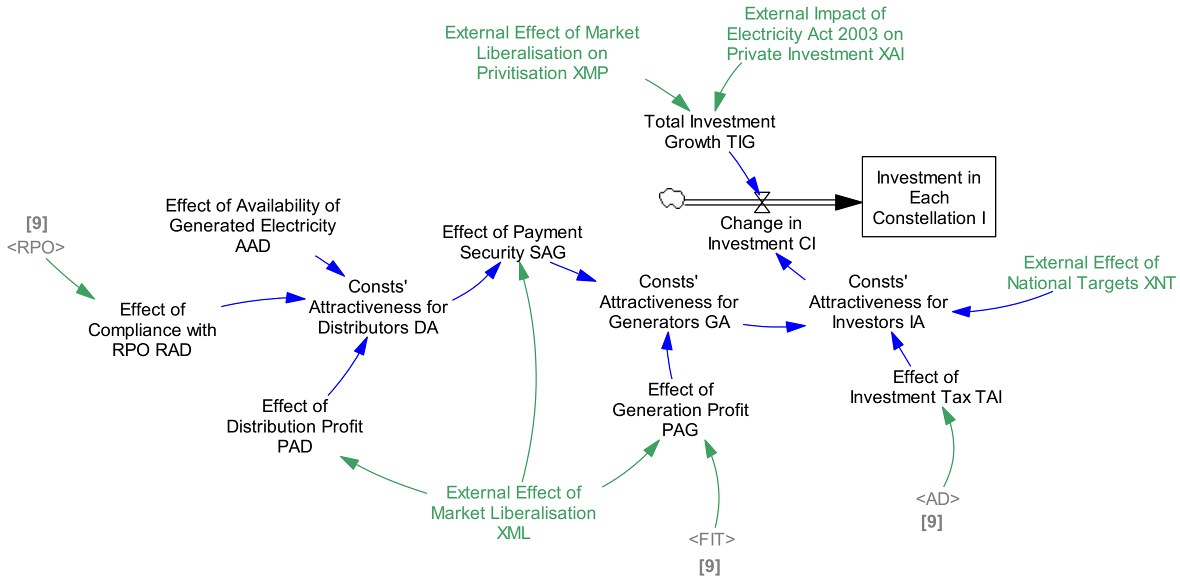

Figure 2. The simplified stock and flow diagram for Investment Component

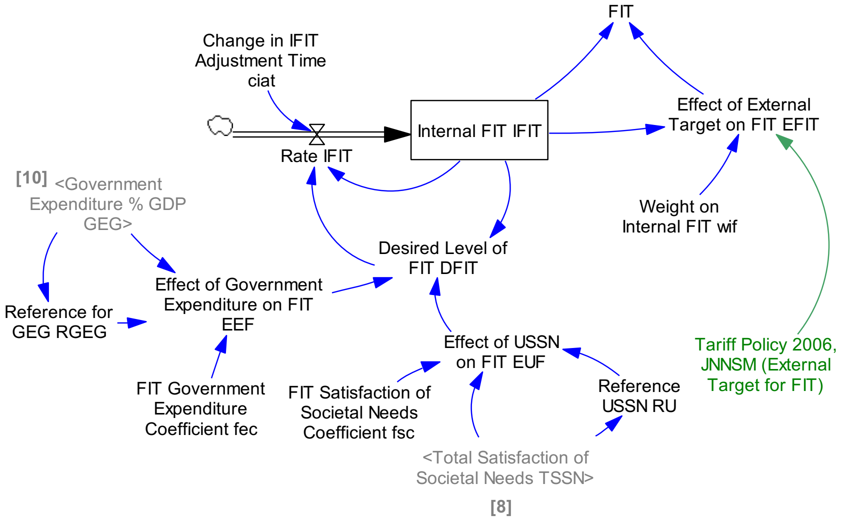

Figure 3. The simplified stock and flow diagram for Feed-in Tariff setting as an exemplar of policy mechanisms in Policy Component

The model is set up to investigate the interactions of coal, gas, wind and on-grid solar photovoltaic, and four model's subscripts are created for them in Vensim accordingly. The dynamics of other conventional sources including hydro and nuclear and also other renewables such as small hydro are assumed only exogenously and by time series inputs. Hydro and nuclear powers are not included as their competition with renewables has not been significant in the past 25 years in India. Other renewables are marginal compared to wind and solar as well. Wind and solar have had the highest capacity of on-grid renewable electricity and the highest annual rate of growth among renewables respectively. They will be the most influential in the course of transition.

The model described is fed with the data from the Indian electricity sector (see Appendix 1). They are used either as model's (exogenous) constants and time series required for simulation runs (such as growth of GDP in the computation of electricity demand) or the documented data for model validation/behaviour reproduction (such as historical tend of installed capacities). This range of data also includes historical (1990 to 2015) and future/estimated values (2015 to 2030). For historical values, most of the data are collected through archival research and mainly from the series of the annual reports published by Ministry of Power (MoP, 2015), Planning Commission (GoI, 2015), Central Electricity Authority (CEA, 2015), national policy documents legislated by Government of India (GoI, 2006; MNRE, 2010; MoP, 2003) and international organisation's special reports on India. The missing historical data have been interpolated based on the available data. For future values, most of data are the trends forecasted in the International Futures (IFs) model database (UDenver, 2015). For those variables whose value is not available in IFs database, the exponential or linear trends of historical data are used.

A time step of a quarter of a year was selected for model simulations. However before that, the model should be calibrated to generate behaviours matched with reality. Since the model is composed of nine components, each with several parameters, a partial model calibration was conducted (Sterman 2000 p. 866). Accordingly, each component was isolated from the rest of the model, the shadow variables were replaced with documented data, and then the values of the component's parametric assumptions were optimised.

3 Results and discussion

3.1 Reproduction of historical transition (1990 to 2015)

In this section the model's results are compared against the actual behaviour of the transition between 1990 and 2015. The comparison reveals to what extent the simulated results follow the same patterns and turning points with the documented behaviour, and if there is a difference, how it can be justified. With this regard, the documented and simulated behaviours of three key output variables were compared. The Normalised Root Mean Square Errors (NRMSE) were calculated as a measure for the magnitude of possible diversions between these two values.

Figure 4 shows documented (bold line) vs. simulated (dash line) electricity demand for agriculture, commercial, industrial and domestic sectors with NRMSEs equal to 21%, 6%, 5% and 4% respectively. The higher NRMSE for agriculture sector can be explained by the fact that electricity in agricultural sector is highly subsidised and is under the control of social (unions) and political decisions. So the exact value of agricultural demand and its changes cannot be completely captured by the model. However, its general trend is still represented similarly as the model considers the demand's response to the economic growth and changes in the price of electricity.

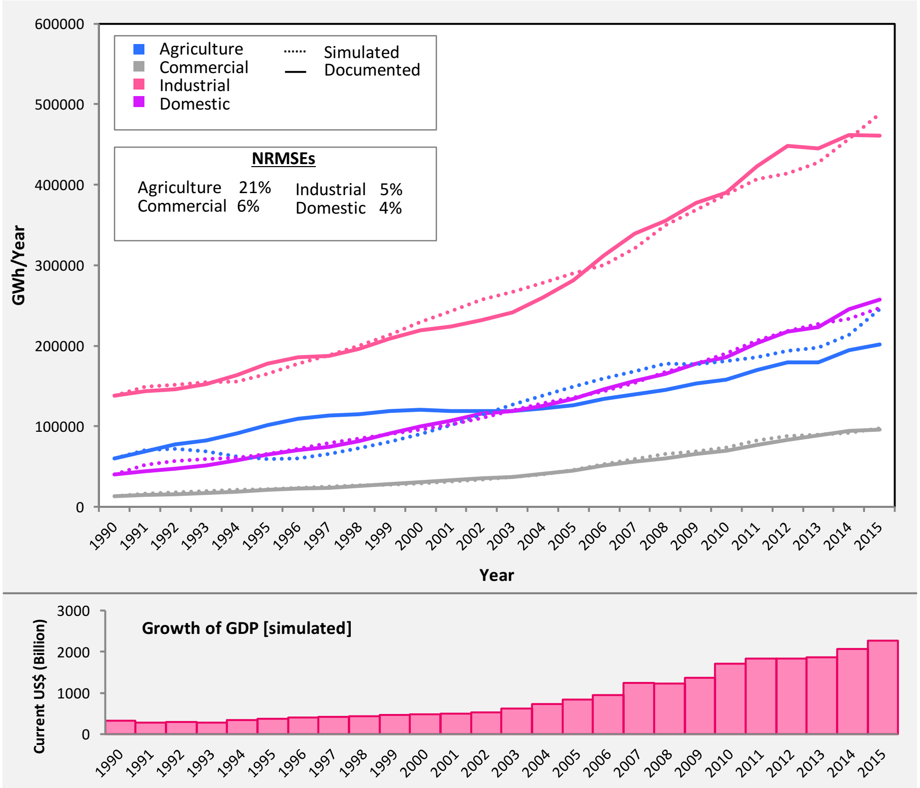

Figure 4. The simulated vs. documented growth of demand per sector in response to the simulated growth of GDP

Another output variable is the tariff under which distributors sell electricity to end-users, i.e. tariff for retail sale of electricity in each sector (see Figure 5). The price of electricity, in general, goes up in response to inflation rate, turbulence in demand-supply balance and gradual increase in the cost per unit of distribution companies. This pattern is observed in the diagram. NRMSEs are 15%, 7%, 8%, 9% for agriculture, commercial, industrial and domestic sectors respectively, which are acceptable in general. The higher diversion for agricultural sector can be justified with the same reason for the one that was mentioned for the diversion of its demand from documented data.

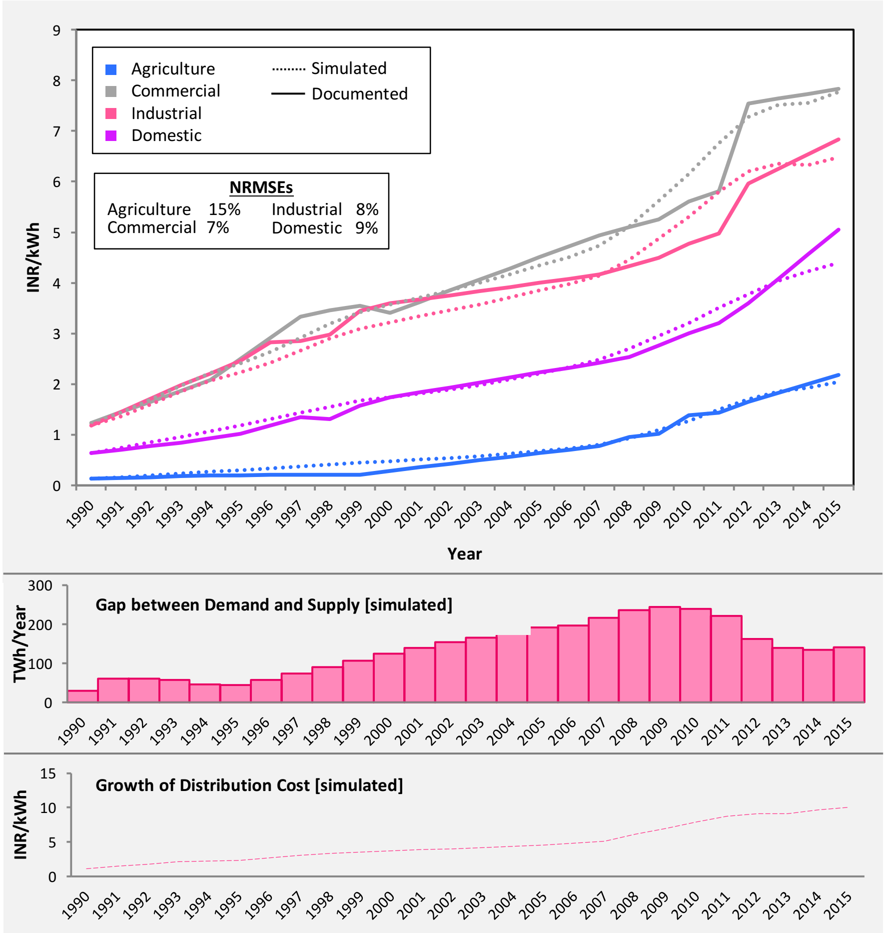

Figure 5. The simulated vs. documented tariff for sale of electricity per sector in response to simulated changes in distribution costs and demand-supply balance

The documented and simulated behaviours of the third output variable, installed capacity per source, are represented in Figure 6. Changes in the installed capacity for wind and solar speed up as a response to policy initiatives; wind's response to the legislation of Electricity Act in 2003 and solar's response to National Solar Missions in 2010. NRMSEs for coal, gas, wind and solar are 6%, 10%, 27% and 44% respectively. The NRMSEs for wind and solar are large. One reason for that is the unstable policy condition around renewables and the other is informal bureaucratic bindings, such as land acquisitions delays. They are not well presented in the model and can lead to diversions from the documented behaviours. However, even with a large error, the trend is still the same, and therefore the model's behaviour is acceptable.

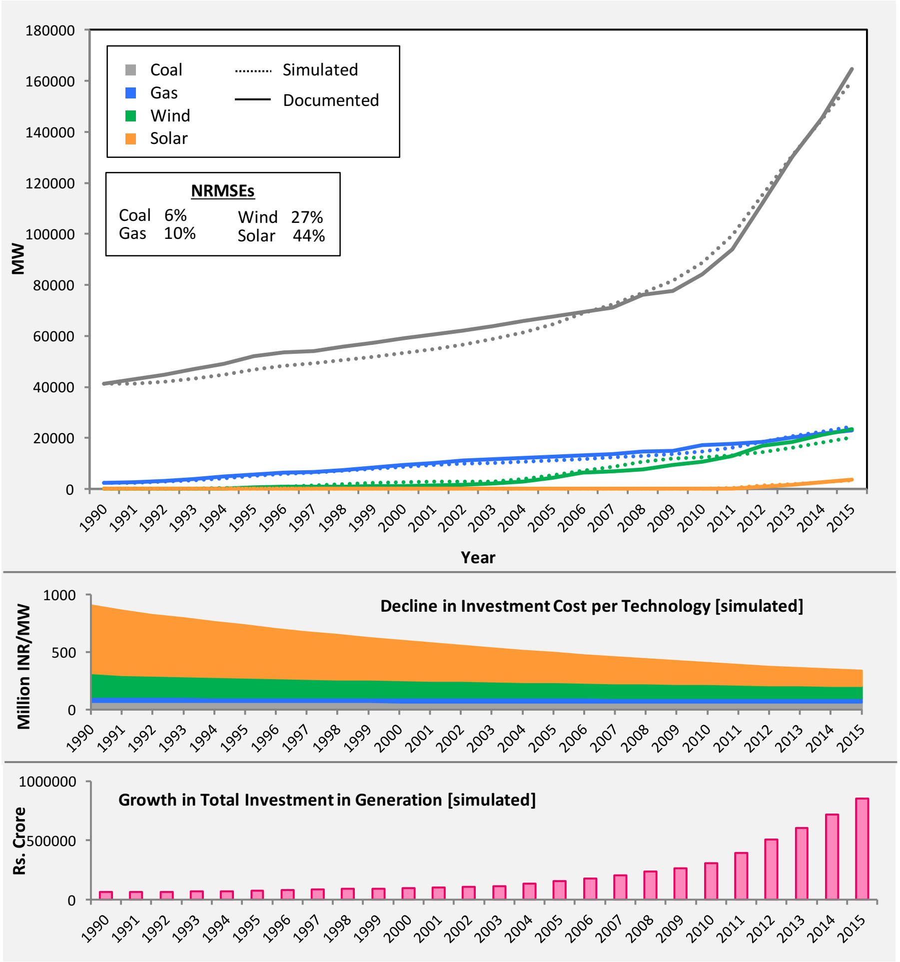

Figure 6. The simulated vs. documented growth of installed capacity per source in response to simulated decline in investment cost and growth in total investment

3.2 Interaction of transition model and narrative: market privatisation and the rise of renewables

Starting from the early 1990s and intensified by the Electricity Act in 2003, the gradual reform from a government-control towards a regulated competitive market boosted investments in the electricity sector. It also introduced market policy instruments, such as FIT to stimulate generation. Moallemi *et al.* (2015a) discussed how this market privatisation impacted the development of renewables in a qualitative narrative. However, it can be investigated quantitatively with model simulations now. This is a benefit of the transition model in complementing the qualitative story of change in the narrative. With this regards, model simulations are run in two conditions: one in the presence of market privatisation (as it happened in the past) and the other in a hypothetical situation with no market forces. The results are compared and analysed in the following and the role of market on emergence renewables is highlighted.

The primary and direct impacts of market privatisation are disinvestment, private sector's engagement and the flow of foreign investments. Figure 7 shows that the share of private investment has been increasing but still insignificant before mid-2000s. However, with the Electricity Act 2003, private investments take off and grow to almost 62% of public investment in 2015. These huge investments are used to increase total installed capacity with an aim to remedy power shortage and to improve grid access in the country (see Figure 6).

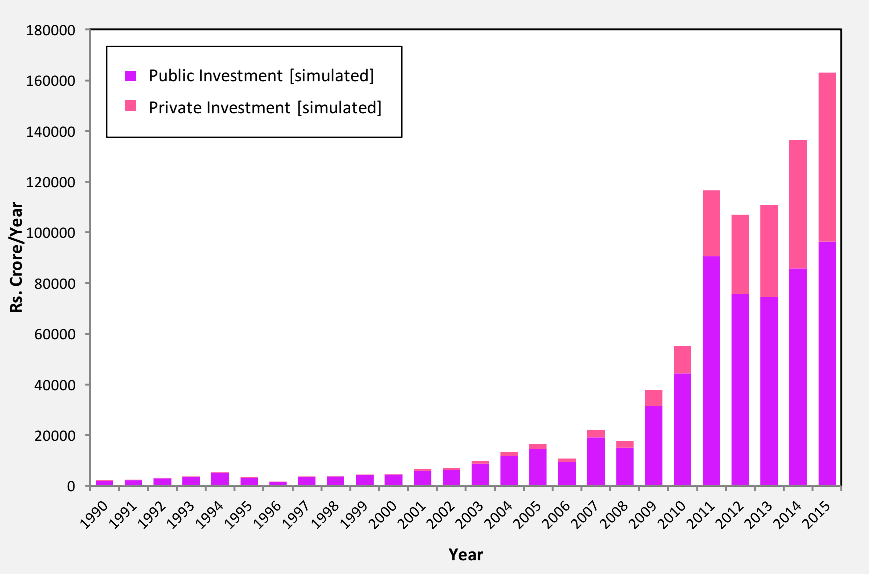

Figure 7. The simulated growth of public vs private investments in power generation sector

Due to the government subsidies on fossil fuels, the lower investment cost of conventional (see Figure 6) as well as their higher load factor compared to renewables, most of the increased investments were directed towards conventional sources in 1990s. However, the enactment of Electricity Act 2003 and the introduction of market-based policy instruments for renewables, such as FIT, changed the distribution of investments among sources. Market policies influenced the properties of renewable sources, such as the generation unit benefit of wind and solar, and made them attractive options for the investment of semi-rational and self-interested private actors. Figure 8 depicts how FITs which were introduced in 2008 for wind and in 2010 for solar have raised the generators' benefit. It is obvious from the figure how cutting FIT for wind in 2012 and delays in the grant of FIT for solar resulted in a sudden drop and a gradual decrease in the wind and solar benefits respectively. Figure 8 also shows the impacts of change in the unit benefit of wind and solar generation and their subsequent effects on total wind and solar investments. The impact of wind FIT cut in 2012 is not obvious on total investment since its trend depends on a variety of other factors (such as the growth in total investment, tax benefits, etc.).

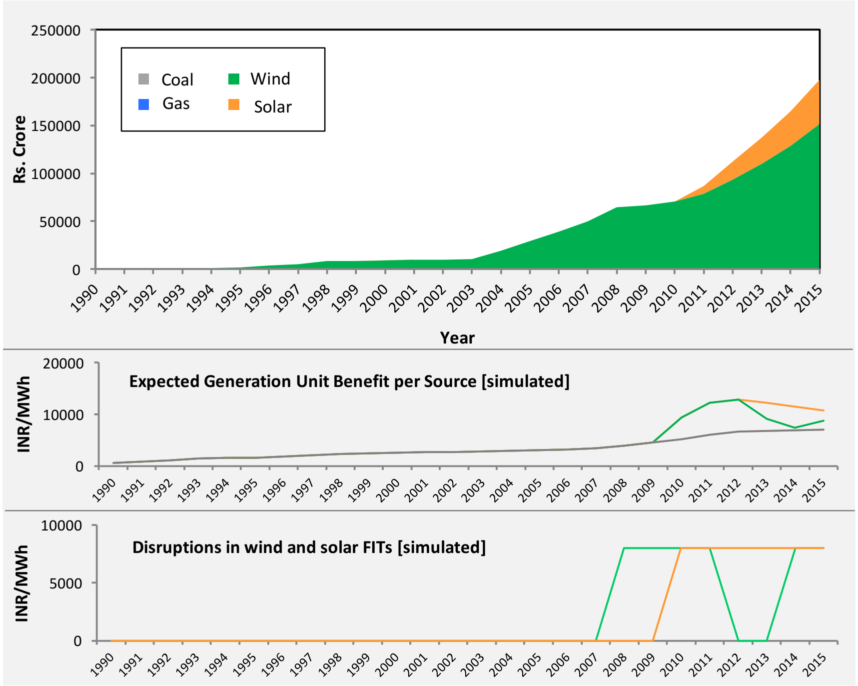

Figure 8. The simulated total investment in wind and solar in response to simulated changes in generation unit benefits of respective sources and actual instabilities in wind and solar FITs

In addition to increase in total investment and FIT, market privatisation has also had an indirect impact on actors' decision. It raised the sensitivity of investors, generators and distributors to the profit and the payment security in power trade, which ended up with favouring profitable renewable businesses. This has been the result of the replacement of state actors in a monopoly with self-interested private ones whose decision is based on the cost-benefit analysis and the attractiveness of different sources in a competitive structure.

In sum, market privatisation has boosted renewables, wind and solar in particular, due to multiple impacts. This can be observed in Figure 9 by the differences in attracted investments for wind and solar in the presence of market privatisation and its absence (a hypothetical situation).

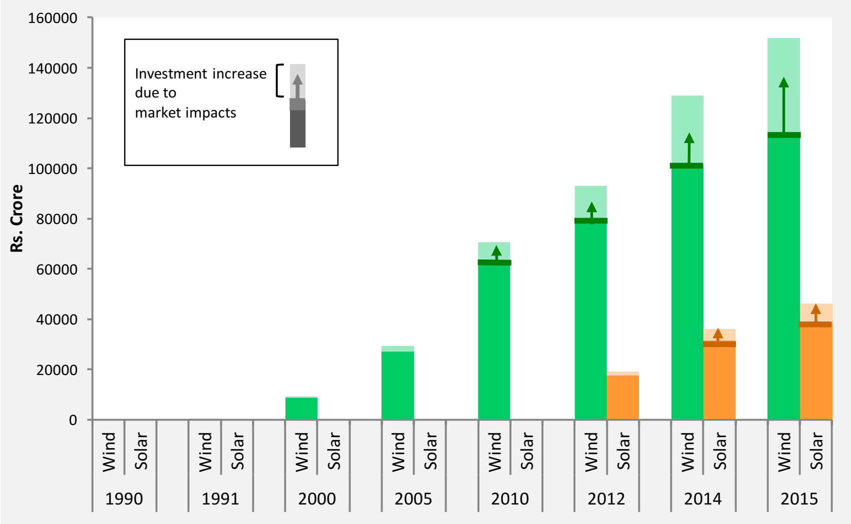

Figure 9. The simulated increase in renewable investments due to market privatisation

3.3 Transition pathways in future scenarios

Another use of a transition model is to shed light on the transformation of Indian electricity sector in the face of the uncertain future conditions. Here we discuss this process in two following Sub-sections:

3.3.1 The development of scenarios

To explore future transition pathways, scenarios are developed based on the variation of two driving forces: the structure of sector and the motivation of transition.

- *The structure of the sector:* the electricity sector can be ruled by state or market. This is similar to structural patterns that were sketched for the future of UK energy transitions (Foxon, 2013; Trutnevyte *et al.*, 2014). In a market-led future for India, the dominant role is for the free interactions of market actors (market competition) complying with existing institutions. In other words, market is the central coordinating mechanism though the government and regulatory frameworks are still in place to incentivise the interactions of the market actors. Incumbent regime actors/technologies tend to remain in dominancy due to their economic advantages compared to new alternatives. More emphasis is on FIT as the preferable policy instrument which does not mandate on actors and at the same time maximise the system's welfare. Market actors' decisions are highly sensitive to profit and payment security and therefore investment is made based on the financial return. More private investment is expected in this condition. However, investment is subject to and vulnerable to high risks, such as fossil fuel's price shocks, as there is no governmental hedging against risks. In short, a market structure works more economically efficient. It increases the total level of investment while may fail to redirect investments towards renewables and to achieve targets for emission reductions. On the other hand, in a government-led future, government actively shapes transition. The dominant role of the government is to co-ordinate actions and to meet national targets. Government removes barriers such as transmission capacities and required skills. Certain types of technologies are selected and supported through technology-push programs. Subsequently, a steeper technological progress is expected due to government's investment. The realisation of national targets is of high priority, and the attractiveness of different sources for investment is highly influenced by these targets. There is more public investment. Private sector investments are also obliged to stick to the government plans. Accordingly, the generation and distribution's decisions are more sensitive to compliance with regulations rather than to profit and payment security. In order to make sure about the achievement of the targets, government puts more emphasis on Renewable Purchase Obligation (RPO) and Accelerated Depreciation (AD) as preferable policy instruments. Government also see itself responsible for hedging actors against risks. In short, a state-controlled sector can better satisfy top-down targets but at the expense of a huge cost on the budget.

- *The motivation of the transition:* the second driving force is the motivation that electricity sector should strive for in transition. The weight of different factors in the motivation changes as transition progresses. For instance, energy transition in India has been addressing energy equity, energy security and energy sustainability in the past 25 years (Moallemi *et al.*, 2015b). This is similar to what has been referred to as 'energy policy trilemma' in the experience of UK's energy transition (Trutnevyte *et al.*, 2015). In an equity-first portray of future, keeping a balance between supply and demand and access to electricity with the same quality for everyone are first priorities of transition. With this regard, grid connection and the reduction of grid loss via improving transmission and distribution networks are important. Conventional sources also become more competitive/justified as they can generate more stable energy compared to renewables. In a security-first future, less dependency on fuel imports is prior to other motivations. Therefore, improvements on the resource efficiency of conventional power plants and more renewable power plants are expected for reducing the total amount of fuel imports. And finally, in a sustainability-first future, maintaining natural resources, creating a culture of responsibility and reducing GHG emissions become the core motivations. Similar to security-first future, renewables are more competitive and justified. Policies such as carbon price on fossil fuel consumptions and environmental premiums for the purchase of renewables are making more sense in this condition.

The characteristics mentioned for each driving force can be translated qualitatively into model's parameters and assumptions as follows:

- Equity-first: A higher impact of demand-supply balance on the satisfaction of societal needs.
- Security-first: A higher impact of energy security on the satisfaction of societal needs.
- Sustainability-first: A higher impact of emissions reduction on the satisfaction of societal needs.
- Government-led: The high impact of national targets on increasing the attractiveness of conventional/renewable sources for investors; The regulated impacts of fossil fuel price's shocks on fuel price; The high rate of public investment; Low sensitivity to profit and payment security and high sensitivity to compliance with regulations in actors' decisions; Less weight on the internal feedbacks of system's performance and more emphasis on government pre-defined targets in policy setting process.
- Market-led: The low impact of national targets on the attractiveness of different sources; The deregulated impacts of fossil fuel price's shocks on fuel price; The high rate of private investment; High sensitivity to profit and payment security and low sensitivity to compliance with regulations in actors' decisions; More emphasis on the internal feedbacks of system's performance and less reliance on government pre-defined targets in policy setting process.

Six normative scenarios emerge by crossing these two driving forces (see Table 1). Different scenarios can be distinguished from each other based on the qualitative assumptions of their driving forces. These qualitative assumptions have to be turned into the parameters' value for model simulations. To come up with the relevant numbers, some sensitivity analyses were conducted and the responses of output variables to the different ranges of variation in the value of parameters were observed. Based on the results of sensitivity analysis, the values are chosen which make a meaningful change in the output variable and are also in accordance with the qualitative assumptions of each scenario. These quantitative values are presented in Appendix 2.

Table 1. Six normative scenarios of future

	Equity-first	**Security-first**	**Sustainability-first**
Government-led	*Scenario 1*	*Scenario 2*	*Scenario 3*
Market-led	*Scenario 4*	*Scenario 5*	*Scenario 6*

3.3.2 Simulation runs and model's behaviour in the scenarios

The model is setup with each set of parameters presented in Appendix 2 and is run for 40 year time period, from 1990 to 2030. The comparison of simulation runs for different output variables across scenarios brings insights about future transition pathways. The simulated results for three different outputs are discussed as follow.

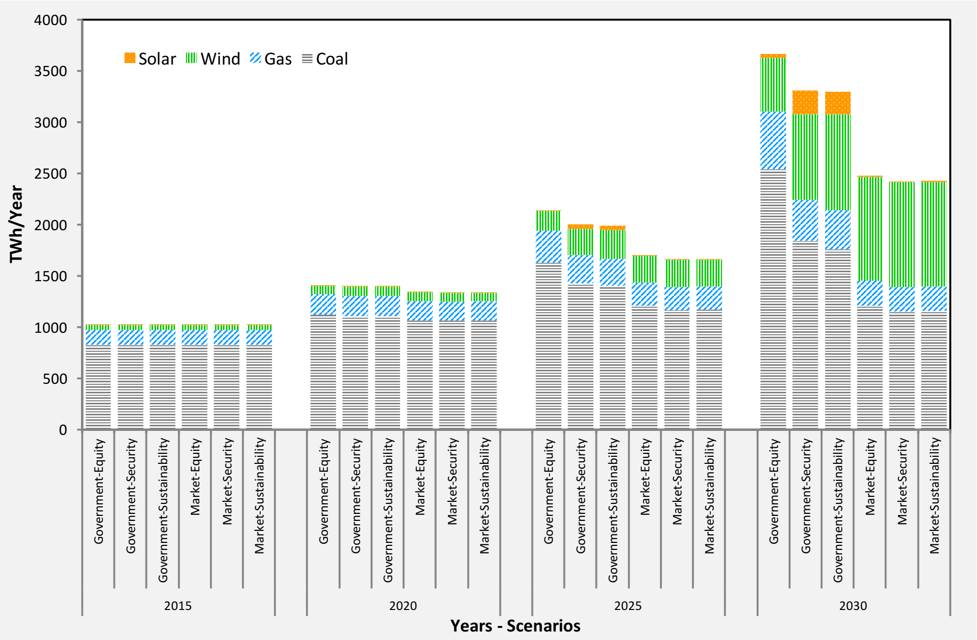

Figure 10. The simulated generated electricity from different sources under different scenarios

Figure 10 presents the simulated results of electricity generation from different sources, across six scenarios and in four milestones till 2030. As it is represented in the figure, total generation will be higher in a government-controlled structure compared to a market-led structure due to the active investment of the government and their determination to realise the power sector's targets in National Five Years Plan's targets. Total generation is also the highest in the government-equity scenario which corroborates the main assumption of the scenario, i.e. priority in improving energy access and equity. When it is a market-led structure, variation in giving priority to equity, security or sustainability does not significantly change total generation and the share of different sources as the sector operates with a market-dominated logic; a logic which is not overshadowed by the priority of societal needs.

As it is apparent from Figure 10, in the simulated state of electricity sector in 2030, coal will remain the dominant regime under any circumstance. This is mostly due to the sunk investments (inertia to as-is situation) and the technological eases in conventional systems which keep their cost of generation competitive. It is also because of the higher capacity factor of conventional power plants which generate more electricity from the same size of capacity compared to renewables. Though coal remains in its dominancy, renewables, especially wind, gain an uptake after 2025 and become a serious competitor to coal. Wind will be technologically mature and very cost-efficient in future. This results in a large share for wind in total generation, no matter what the scenario is. It is even more obvious when we look at the market-led structure, when market decides about the future pathways with cost-benefit analysis. Solar, another promising renewable, will also grow notably in the last 5 year to 2030 while will still remain at margin compared to wind. Solar appears stronger in a government-control future, with priorities given to security and sustainability. This resonates the fact that solar needs to be protected with some command-and-control policies such as solar RPO, not only against conventional, but also against its own family competitor, wind.

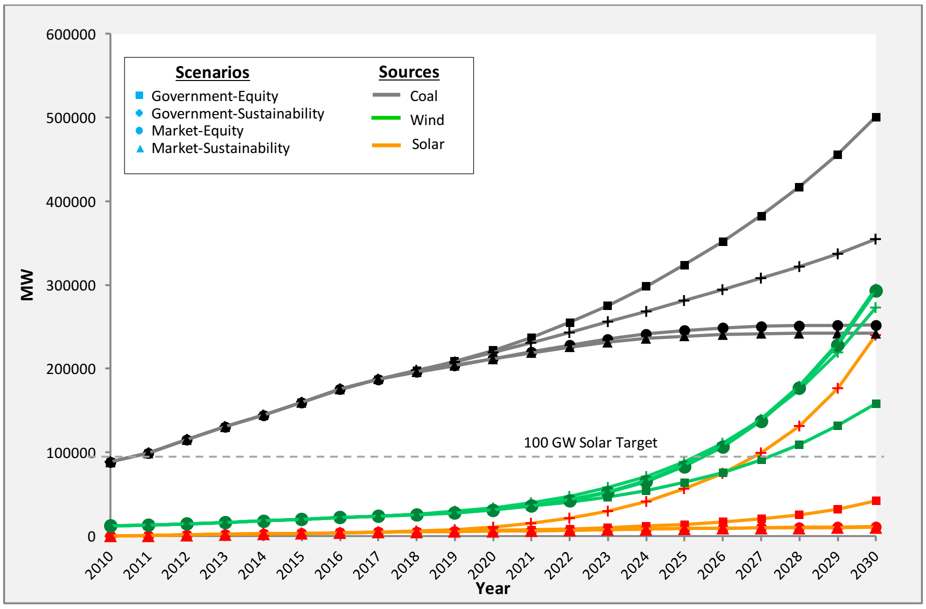

Figure 11. The simulated growth of coal, wind and solar installed capacities across different scenarios

Figure 11 shows how the growth of install capacity complements our argument on the future state of solar. It is perceived that the realisation of 100 GW solar target by 2022 is not easy to achieve, and only happens under Government-led & Sustainability-first Scenario by 2027. This means that the development of solar requires the active participation of government through public investment, national target setting for emission reductions and the coordination of actions/projects to meet those targets. In this case, the transformation of the electricity sector is being facilitated not only through renewable-empowering policies, such FIT, which favour all renewable sources, but also through solar-specific command-and-control policies, such as RPO, which secure a specific share for solar against its competitors. This achievement however would certainly come at the cost, a reduction in total generation (due to the sustainability motive) and public financial burden (due to the government expenditure).

It can be also concluded from Figure 11 that at which conditions the established conventional regime starts to break down. The conventional regime's destabilisation is an integral part of transition to a sustainable future. The trend of installed capacities shows that coal's growth flattens under market-led scenarios, no matter whether the motivation of transition is equity or sustainability. This behaviour makes sense considering the preference of the market actors to wind over coal in long run due to its profitability. The destabilisation of coal in the market-led scenarios results in the steepest decline in the GHG emission intensity (CO_2-e per GDP) compared to the government-led scenarios (see Figure 12) although the total GHG emissions will be increasing under any condition in future (see Figure 13). Apart from its environmental benefits, the destabilisation of coal in market-led scenarios causes a lower total generation and a higher deficit in energy access (see Figure 10).

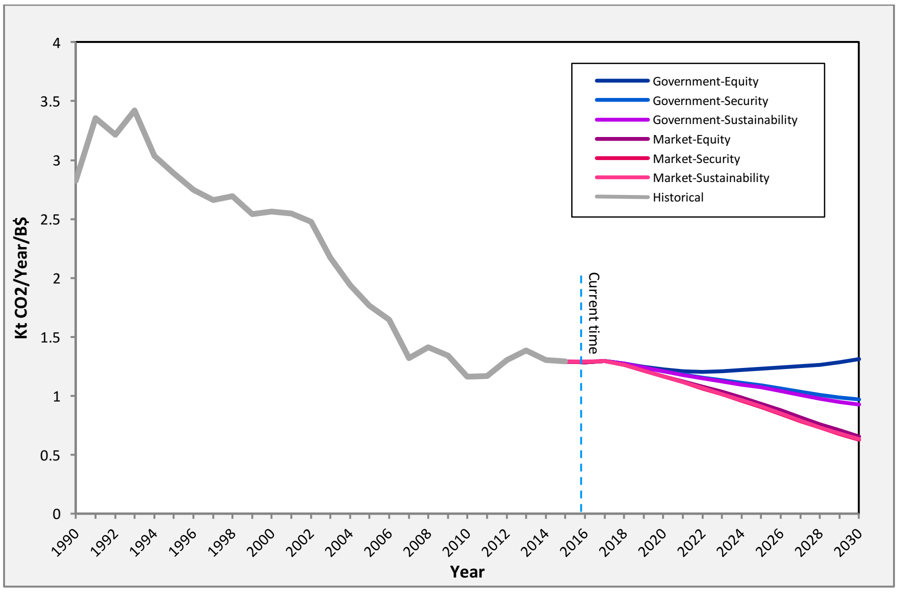

Figure 12. The simulated GHG emission intensity (CO_2-e per GDP) under different scenarios

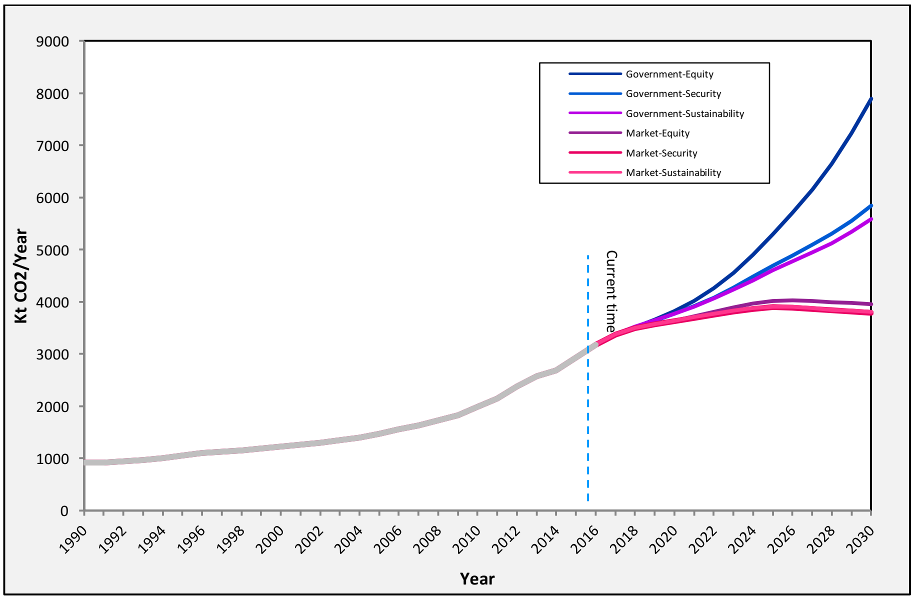

Figure 13. The simulated GHG emissions (total) under different scenarios

3.4 Limitations of the model

The transition model, developed for this paper, has some limitations which may be addressed in the later versions. One is that the model does not include the infrastructural feasibilities and their impacts on renewable exploitations. Wind and solar can theoretically increase very fast based on the growing investments and falling technology price. However, the potential wind and solar energy availability of the country as well as the network of transmission and distribution grids would limit these exponential growths. This cap can change the future state of renewables in terms of total installed capacity. Another limitation is the incomplete formalisation of bureaucratic and construction delays in the model. A foremost example of these delays is related to land acquisition for the construction of wind farm and solar power plants. It can sometimes lead to a month up to few years delays in the start of the project, even if the required investment and technology for construction is available. Addressing these two issues can improve the simulation results and make the subsequent policy insights more accurate.

4 Conclusions

The simulation of electricity sector's transition, presented in this paper, was the outcome of integration between classic system dynamics modelling and transition theories. This type of dual quantitative-qualitative approach to study long-term systems' transformation is called transition modelling. Taking this approach results in a more comprehensive inclusion of the drivers of change which are not normally captured with a quantitative technique. It subsequently provides a more realistic portray of the change and also generates more realistic results.

The model simulated Indian transition in three parts. First, it replicated the historical transition from 1990 to 2015 and assessed the goodness of fit to historical data with root mean square errors. Second, it was discussed how the simulation results can complement the qualitative understanding of historical transition. It was explored with the example of market privatisation and the rise of renewables. Third, the model projected future transition pathways till 2030. Six distinct scenarios were drawn, and the behaviour of key output variables including generation, installed capacity and the GHG emission intensity were investigated across different scenarios. The projection of future pathways brought insights on the future state of renewable and the actions required for achieving the targets.

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Appendix 1

The input and output variables for each model's component

	Constants	Parameters	Time Series Data	Shadow variables	External forces	Output variables
Pricing	– Initial values for wholesale and retail tariff – Fixed O&M costs – Average lifetime of generation capacities – Heat content of sources – Initial investment costs	– Sensitivity factors – Adjustment times	– Inflation rate – Fuel price	– LCOE – Demand-Supply Balance – Enforceable FIT and REC – Capacity factors – Heat rates of capacities – Efficiency of capacities – Demand per sector – Generated electricity per source – Learning multiplier	– Effect of environmental premiums on distribution cost – Fossil fuel price shock – Carbon tax for sources	– Distribution unit cost and benefit – Generation unit cost and benefit – Wholesale and retail electricity tariffs – Investment cost per source
Investment	– Average lifetime of generation capacities – Tax on assets – Fixed O&M costs – Interest rate	– Sensitivity factors – Adjustment times – Perception delays – Reference levels	– Share of public to private investment – Public investment	– Government expenditure – Investment cost per source – Enforceable AD and RPO – Capacity factors – Generation unit cost and benefit – Distribution unit cost and benefit – Generated electricity	– Impact of Electricity Act 2003 and Market Liberalisation on private investment – Effect of national vision and targets on attractiveness different sources for investors	– Total investment – Investment growth per source
Capacity	– Initial installed capacities per source	– New capacity acquisition delay – Adjustment times – Perception delays – Endogenous and exogenous learning index	– Initial resource efficiency	– Investment cost – Investment growth		– New and old installed capacity per source – Efficiency of new and old installed capacities per source – Learning multiplier per source

Generation	– Grid loss	– Perception delays – Capacity factors’ coefficients	– Generated electricity from other renewable and conventional sources	– Efficiency of capacities – Installed capacities per source – Available fossil fuel – In-used fossil fuels per source	– Impact of Wind Rush	– Generated electricity per source – Net (total) generated electricity
Demand-Supply Balance	– Initial demand – Initial target for demand-supply balance	– Reference level of GDP – Sensitivity of demand to GDP – Price elasticity of demand – Perception delays – Adjustment times	– GDP	– Net generated electricity – Retail electricity tariff	– The impact of urbanisation and prosperity of society – Effect of government targets for demand-supply balance	– Actual and forecasted demand – Discrepancy between desired and current demand-supply balance
Energy security	– Heat content of sources	– Adjustment times	– Total energy import	– Generated electricity from old and new capacities – Efficiency of new and old capacities	– Price shocks and constraint on energy import – Effect of government target for share of fuel import	– In-used fossil fuels per source – Domestic and imported fossil fuels – Available fossil fuel – Discrepancy between desired and current fuel import
Environment	– Emission intensity of sources	– Adjustment times		– Generated electricity from old and new capacities – Efficiency of new and old capacities	– Effect of climate change negotiation and concerns for GHG emissions	– GHG emissions – Discrepancy between desired and current emissions state

Satisfaction of societal needs		– Sensitivity factors – Perception delays	– Discrepancy between desired and current states of demand-supply balance, emissions and fuel imports	– Oil price shocks and the rise of energy security – The impact of climate change negotiations – The rise of energy equity, energy convenience and grid connection	– Satisfaction of societal needs
Policy	– Initial level of policy mechanisms	– Sensitivity factors – Adjustment times – Weights for internally and externally defined targets		– Effect of Tariff Policy 2006, JNNSM, National Electricity Policy 2005 and Electricity Act 2003 on governmental targets for policy mechanisms	– Enforceable level of FIT, AD, RPO and REC
Financial burden			– Government expenditure – Discrepancy between desired and current states of demand-supply balance, emissions and fuel imports		– Government expenditure on generation sector

Appendix 2

Set of parameters' value for each scenario

Parameters (dimensionless)	**Base case**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Sensitivity of SSN to Demand-Supply Balance SSDB (future ec)	.02	.08	.05	.001	.08	.05	.001
Sensitivity of SSN to GHG Emissions SSGM (future er)	.03	.01	.01	.07	.01	.01	.07
Sensitivity of SSN to Fuel Import SSFI (future ps)	.04	.01	.09	.01	.01	.09	.01
External: Effect of National Vision and Targets Setting VT	(.06, .028, .073, .174)	(.09, .037, .053, .01)	(.03, .024, .083, .4)	(.03, .024, .093, .4)	(.03, .024, .053, .01)	(.03, .024, .053, .01)	(.03, .024, .053, .01)
External: Fossil Fuel Price Shock FPS ([coal], [gas])	. 1, .07	(.01, .02)	(.15, .15)	(.2, .18)	(.2, .18)	(.29, .22)	(.29, .22)
External: Effect of Market Liberalisation on Public and Private Investments MLI	.2	.01	.01	.01	.8	.8	.8
Sensitivity of Actors to Profit and Payment Security (mlg, mls, mld)	(.01, .27, .34)	(-0.05, -0.02, -0.05)	(-0.05, -0.02, -0.05)	(-0.05, -0.02, -0.05)	(.03, .4, .55)	(.03, .4, .55)	(.03, .4, .55)
Weight on Internal FIT wif	.03	.01	.01	.01	.05	.05	.05
Weight of Internal RPO wir	.03	.01	.01	.01	.05	.05	.05
Weight on Internal AD wia	.05	.01	.01	.01	.09	.09	.09