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Managing the Power Grid Ramping challenges critical to success of India's Renewable Energy Targets

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Abstract

Power grids operators around the world have been experiencing challenges in operating the grid with increasing penetration of Variable Generation (VG) sources like Solar PV and Wind. Variability in one form of generation must always be compensated with other forms of generation at all times to ensure grid stability. This paper focuses on the diurnal variability introduced into the Indian power grid and the consequent increase in ramping requirements due to the 175GW by 2022 renewable energy target enunciated by the Government of India. Ramping requirements were quantified for 3 potential renewable energy penetration levels on the grid by the year 2027. Nine separate solution alternatives are created using Coal, Natural Gas and Renewable & Emerging technologies as solution options to meet the identified ramping needs. Energy-mix and carbon prices are calculated for each of the solution scenarios and compared with the baseline scenario computed from the Intended Nationally determined Contribution (INDC) adopted by India in COP22. The paper concludes that the most energy cost and carbon price efficient paths for India to integrate ambitious RE capacity into India's power grid would be to convert and operate existing coal plants as peaker plants instead of as base load plants.

Keywords: Diurnal variability, Net load curve, renewable energy, generation ramping, carbon price, flexible generation

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1) Introduction

Government of India in 2015-16 launched an ambitious initiative of installing 175 GW of renewable energy on the Indian power grid by the year 2022.This target includes 100 GW of Solar energy along with 60 GW of wind energy and 15GW of Biomass power and other forms of renewable energy like small hydro etc [6,8,13,14]. The government has also enunciated its vision of taking the total Solar PV installations to 150 GW and wind to 100 GW by the year 2027. These are significant steps towards the goal of de-carbonizing the Indian power grid and achieving energy independence in India. Currently, India has a total of 305 GW of installed generation capacity as of July 2016 [1] out of which renewable energy sources (excluding large hydro) contribute about 44 GW.

Experience of power grids around the world that have been aggressively expanding the renewable energy has shown that operating the grids beyond 20% of penetration of variable sources of electricity becomes a significant challenge [2]. As the amount of Solar PV interconnected to the system increases, it has been seen that the net load curve will have a characteristic U-Shape during the day time and steep increasing demand profile during evening hours making it challenging to maintain the generation-load balance. This increases the need to have more dispatchable generation that can be quickly ramped up and down to constantly match the net load curve.

Power grid operators in India currently can choose to meet the ramping needs through conventional generation technologies like Coal, Natural Gas, Hydro, Biomass plants etc. 60% of the installed generation capacity on the Indian power grid is thermal generation using coal as fuel. These coal plants, most of which are based on sub-critical coal technologies, are designed to operate primarily as base load units and are not fully capable of quickly ramping up and down to match the needs of the new net-load curve. Using these sub-critical coal plants to meet the ramping requirements may result in a severe drop in the overall thermal efficiency of the coal plants resulting in increased carbon emissions that may off-set some of the benefit gained through installing Solar PV plants. Sub-critical coal plants may also incur additional maintenance costs due to the wear and tear created by the daily ramping cycles to which these plants will be prone to. India has 25,500 MW of natural gas plants [13] constituting about 8.5% of the total installed capacity. Given the chronic natural gas availability constraint India faces, these natural gas plants have been operating at a capacity factor of around 20% - 24% over the last 3 years. While India has high Hydro potential, the water availability during summer peak load periods may limit the availability of Hydro generation for ramping needs.

Given this context, this paper tries to explore the various solution options available to the country's policy makers and planners on how the ramping needs under high renewable energy scenarios can be met by using a combination of new and old generation technologies. A 10 year planning cycle outlook was taken during the analysis and solution development. The subsequent sections of this paper describe the concept of a net load curve, quantify the net load curve for the year 2027 and discuss the solution options available. The solution options also discover the effective carbon price for each scenario. Conclusions will be drawn based on the cost of solutions, incremental emissions generated as well as the effective carbon price incurred.

2) What is a Net Load Curve?

The power grid is a machine that needs to maintain a precise balance between the electricity demand and supply on a moment to moment basis. Loss of this balance can lead to system wide blackouts. The existing design and operation of the power grid is largely based on the premise that the demand side variability can be managed by accurately predicting the demand through advanced load forecasting tools and by using dispatchable generation to maintain the generation-load balance at all times. But with the increasing penetration of renewables, there has been a steep increase in the supply side variability as well due to variability introduced by Solar and Wind generation. The dispatchable generation on the system now needs to be flexible enough to balance out not only the demand side variability but also the supply side variability from VG resources. This may pose challenges in operating the grid since most of the thermal generation technologies that form the bulk of dispatchable generation on the grid weren't designed for flexibility.

A net load curve is the net demand on the system which needs to be served through dispatchable generation resources on the system after accounting for the supply from VG sources like Solar PV and Wind as negative loads. Net load curve can have a significantly different characteristic than the traditional load curve as the penetration of the solar PV and wind interconnected to the grid increases. For example, in California as the penetration of the solar PV resources on the grid increases, the net load curve is expected to change significantly resulting in what is widely known as the Duck Curve, shown in Figure 1 below. The net load curve on the California grid shows a distinct "U-shaped" profile during the day time hours due to the diurnal increase and decrease in the solar PV generation.

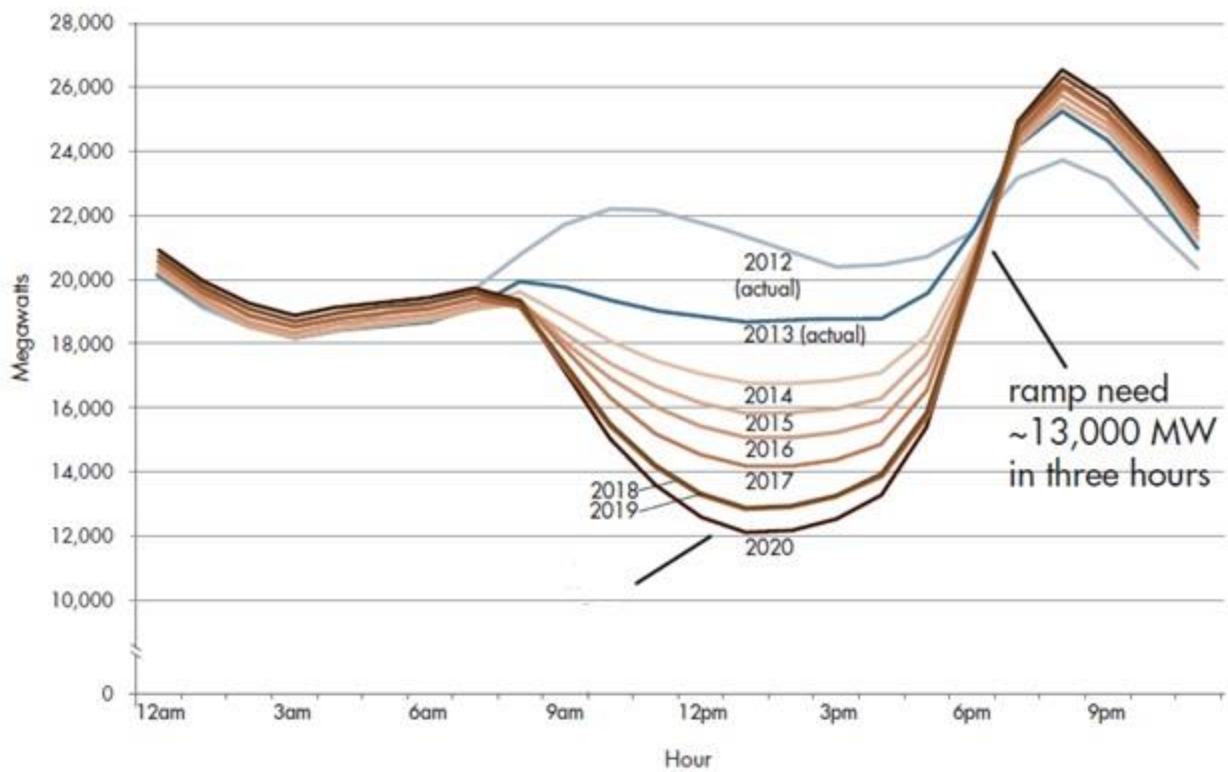

Figure 1: Net load curve on the California Grid (also called Duck Curve). Source: www.caiso.com

As the solar PV generation on the grid increases from morning hours into the noon hours, the net load on the system decreases. This necessitates an equivalent amount of other types of generation, typically thermal generation (like coal, natural gas etc.), hydro or other dispatchable resources to be ramped down. Once when the solar PV output starts to decline from noon hours into the evening hours, the net load on the system increases steeply. In most power grids, this steep increase in net load during the evening hours also coincides with the inherent increase in the load on the system at that time. This creates large ramping needs on the system which require dispatchable generation to quickly ramp their generation up to meet the steeply increasing net load curve.

3) Modeling the Net Load Curve for the Indian grid

Based on the renewable energy goals set by the Government of India it is estimated that India will have 100 - 150 GW of Solar PV generation on the grid by the year 2027 [6,8,13,14]. On a grid that is expected to have a peak load of 317 GW [13] in the year 2027, 150 GW of Solar PV can create a deep U shaped net load curve resulting in a large ramping need on the system. Modeling was done in this work to quantify the ramping need on the grid that can be expected in 2027. The forecasted peak load data for 2027, aggregated load curve of the Indian grid and the renewable energy targets enunciated by Government of India were taken from the Central Electricity Authority's (CEA) National Electricity Plan document [13].The peak load demand of 317 GW used in this analysis includes savings from the energy efficiency and demand side management. System Advisory Model (SAM) developed by National Renewable Energy Laboratory (NREL) was used to generate an average Solar PV generation profile in India [15]. Outputs from four cities geographically spread across India (Ahmedabad, Calcutta, Chennai and New Delhi) were used to average out the variations in solar insolation across India. Wind production data was obtained from two existing wind farms, one from Maharashtra and another from Rajasthan. This data was then normalized and scaled up to the proposed wind capacity of 60 GW. An assumption was made that the average power production profile of the two wind farms will be reasonably representative of the aggregate wind power production profile across India. This wind profile was compared with the wind data derived from [13] and was found to have a good match.

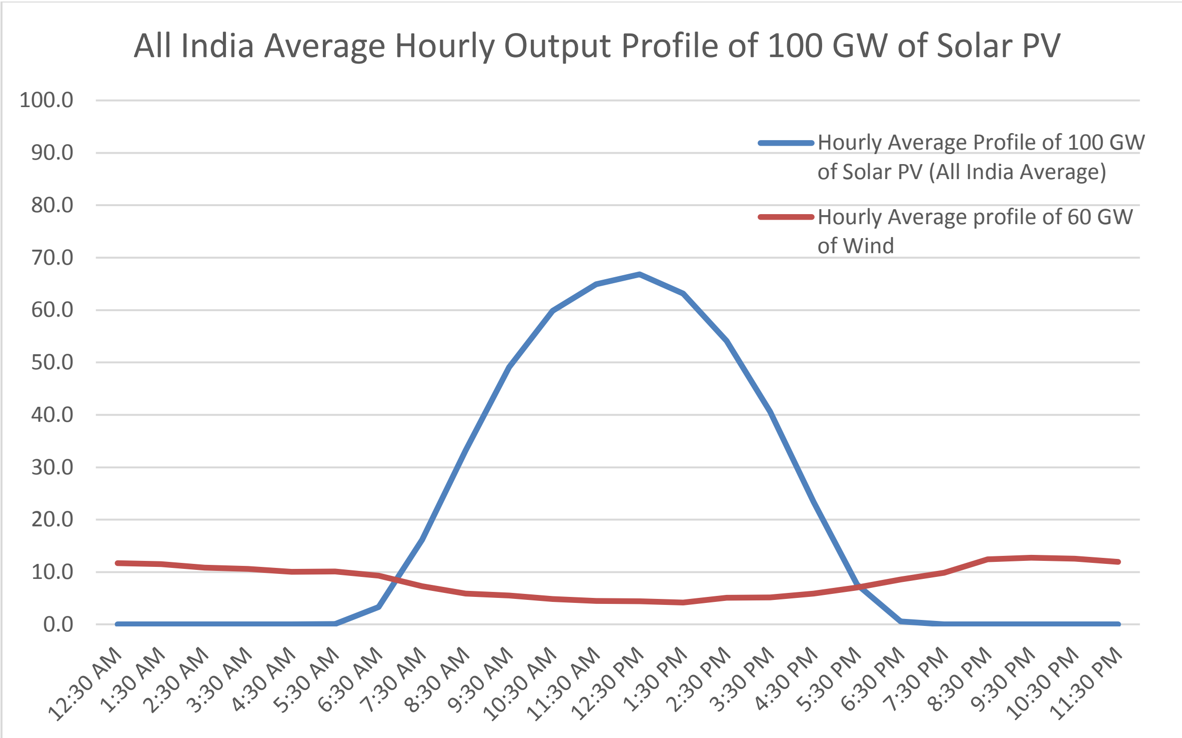

Figure 2: Expected output profile of 100 GW of Solar PV (all India aggregated level) from SAM

Net load curve of the Indian grid was calculated from the average hourly output profile of solar PV and wind generation by treating these two VG sources as negative loads. For the sake of simplicity the model assumed that the entire Indian power grid can be operated and dispatched from a single location[3] and the system does not have any transmission constraints.

The figure below shows the significant changes in net load profile of the system before and after the addition of 160 GW of VG sources. As can be seen from the plot as the solar PV generation starts to ramp up from morning hours into the noon hours (8 AM – 1 PM) the net load on the system that needs to be met from non-variable generation goes down steeply from 267 GW to 204 GW. The net load on the system increases again steeply as the solar PV generation goes down from late noon hours into evening hours (2 PM – 6 PM). In addition the load on the system goes up between 6 PM and 9 PM due to coincidental power usage by domestic, commercial and industrial customers. This creates an additional requirement to ramp-up the power generation between 6 PM and 9 PM, as shown in Figure 3 below.

[3] System dispatch and balancing in India happens from the State Load Dispatch Center (LDC) in each individual state.

For a 2027 summer peak load scenario the ramp-up requirement is found to be 101 GW between a seven hour span of 2 PM – 9 PM.

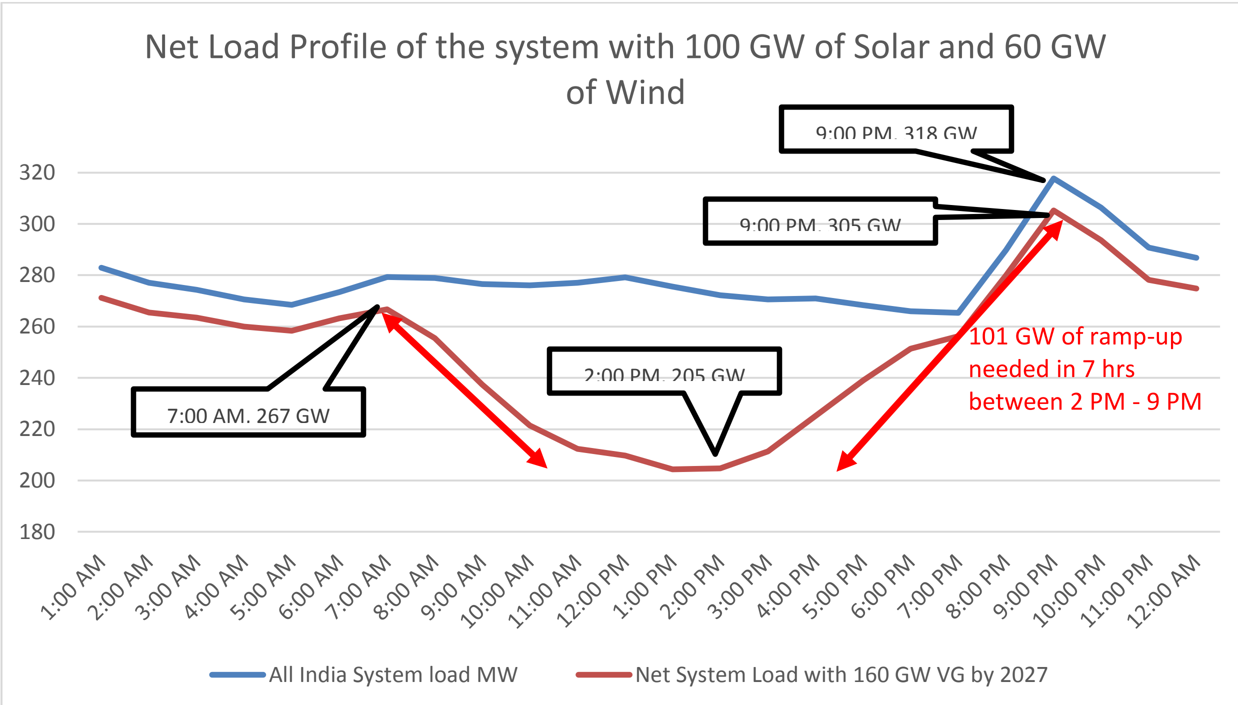

Figure 3: Impact of 100 GW of Solar PV on the net load profile of the Indian power grid

Sources: All India load curve adapted from CEA [13], Solar PV profile based on SAM Solar model created by the authors and Wind profile is based on actual wind generation projections, Net Load Profile is an estimate of the authors

In total the system can be expected to have a total ramp-down requirement of 62 GW between 8 AM – 1 PM and a total ramp-up requirement of 101 GW between 2 PM – 9 PM.

Given the current generation mix on the Indian grid where a major share of the dispatchable generation comprises of thermal plants running on coal, such huge ramping requirements may either be highly uneconomical or even technically infeasible. As can be seen from Table 1 below, 60% of all installed generation capacity in India is coal power plants.

Sector	Thermal				Nuclear	Hydro	RES	Grand Total
	Coal	Gas	Diesel	Total				
State	64196	7258	364	71817	0	29418	1977	103212
Private	72362	10581	474	83417	0	3120	48041	134578
Central	51930	7491	0	59421	5780	11651	0	76852
All India	188488	25329	838	214655	5780	44189	50018	314642

Table 1: Split of various types of generation on Indian grid (*Source: Central Electricity Authority, Status report January 2017*)

Coal power plants typically have a startup time in excess of 6 – 8 hours. Some vintage coal power plants have startup times in excess of 20 hours. While the problem of long startup time can be partly mitigated by running the coal power plants at their P_{min}[4], the ramp up rate of these plants is only around 3 MW to 4 MW per minute. Given this the grid operators will be challenged to meet the high ramp up requirements on the system. In addition running base load plants like coal power plants at their P_{min} and cycling their production several times every day increases the wear and tear in the plants and increases the maintenance costs and cycling costs [8,16].

4) Meeting the Ramping needs - Solution Space

This problem of lack of sufficient ramping capability on the system (also referred to as flexibility) may not only make the slow acting thermal units (primarily coal) economically unviable but also result in curtailment of renewable generation in order to keep the grid stable. The grid side challenges of integrating RE pose a complex multidimensional problem that needs to have multidimensional solutions. The nature of the solutions to build flexibility in the system depends on the amount of flexibility needed and in turn on the penetration of renewables on the grid.

[4] P_{min} is the least amount of MW output that a generator can generate and continue to operate stably.

In this paper we take a 10 year view of the grid and developed three different scenarios envisaging the level of penetration of renewables on the grid in this period; Low RE Penetration scenario, Intermediate RE Penetration scenario and High RE Penetration scenario. The paper uses India's INDC (Intended Nationally Determined Contributions) commitments to Paris Climate Change Agreement (2015) [17] as the baseline or the Business As Usual (BAU) scenario. For each of the RE penetration scenarios, the paper develops 3 different solutions based on three different technology alternatives to meet the ramping needs; Coal, Natural Gas and Renewable Technologies / Emerging Technologies (RT/ET)

4.1) Modeling the Scenarios

Each of the 3 scenarios and the BAU scenario have been modeled using the AIM/Enduse model for India developed by the National Institute for Environmental Studies and the Kyoto University in Japan [18]. The AIM/Enduse model is a bottom-up energy, technology and services optimisation model. It accounts for the final energy consumption and CO2 emissions in end-use sectors based on actual energy use and the way energy services are performed by energy devices. It focuses on the end-use technology selection in energy production and consumption. It calculates the future demand of energy services for several sectors, and determines the optimal set of technologies that can be used to satisfy the service demand through total cost optimisation. Based on the energy consumed by the selected set of technologies, the model estimates future energy consumption of the devices as well as the system. The model minimizes the net present value of all system costs including capital, fuel, O&M, and all other cost components.

Scenario has been defined as "a coherent, internally consistent, and plausible description of a possible future state of the world (IPCC, 1994). It is not a forecast; each scenario is one alternative image of how the future can unfold." Scenario analyses explore a plausible future by using the model to generate a set of outcomes based on the set of assumptions made. Scenario architecture provides a structure to the storyline used in the selected study. In this paper, we assumed the Intended Nationally Determined Contributions (INDC) scenario as our baseline scenario. In addition we created 3 other scenarios for how much and how fast the renewable energy penetration will be on the Indian grid.

Sector	INDC Scenario (Assumed as BAU)	Low RE Integration Scenario	Intermediate RE Integration scenario	High RE Integration scenario
Common Scenario Assumptions	• AT&C losses: Reduce to 6-8 % • Introduction of smart and micro grids • Increase production of efficient locomotives and automobiles, move towards hybrid and electric vehicles • Industries End Use Sector: Energy efficiency is improved in the designated plants in the consecutive PAT cycles. Addition of railways, refineries and distributed companies in addition to increase of designated consumers in the core energy intensive industries • Residential End Use Sector: Complete shift to LED by 2030. Push for more advanced and EE appliances, increase in solar run appliances • Agriculture End Use Sector: Shift to energy efficient solar and electric pumps; solar pumps with drip irrigation			
Renewable Energy Sector	175 GW of Renewable Energy by 2030 (excluding large hydro)	175 GW of Renewable Energy by 2027	200 GW of Renewable Energy by 2027	250 GW of Renewable Energy by 2027 Penetration of smart grids at a domestic consumer level
Coal Power Plants	Improving efficiency of	Retrofit existing Coal plants to	Retrofit existing Coal plants to	Retrofit existing Coal plants to

Sector	INDC Scenario (Assumed as BAU)	Low RE Integration Scenario	Intermediate RE Integration scenario	High RE Integration scenario
	thermal power plants	achieve Flexibility and Efficiency	achieve Flexibility and Efficiency	achieve Flexibility and Efficiency
Industry / Residential / Agriculture End Use Sectors	BAU Scenario	Same as BAU	Same as BAU	Deep EE Measures + Time of Use metering implementation

Table 2: Comparison of main assumptions across BAU scenario with Low, Intermediate and High RE penetration scenarios

Indian grid will have a total of 248 GW of installed coal capacity by the year 2022 and no new coal plants are expected to be added to the system after that [13]. Each of the three RE scenarios model the nuclear power capacity to cap out at 10 GW during the study horizon. 80% plant availability factor was assumed for all the thermal units including Coal, NG and Biomass units. India is estimated to have a total of 60 GW of installed hydro capacity with roughly 50% of it as run of the river and other smaller hydro plants that may not be able to provide any ramping capability during summer peak season. Since historical data points to a PLF of less than 50% for hydro units [13], a 45% PLF was considered in this analysis. Technologies like Off-shore wind are assumed to not have any significant presence on the grid by 2027. With this context defined, the paper tries to determine the flexibility requirement on the grid and tries to arrive at possible solution scenarios using retrofitted coal plants, Natural Gas plants and a combination of renewable and emerging technologies as solution alternatives.

The Low RE Integration scenario represents the case where India will achieve the 175 GW of renewable energy integration goal by the year 2027 instead of the proclaimed year 2022. As of 2013 India was estimated to have about 52 GW of coal capacity that is 25 years or older [21].

This number will grow to around 95 GW by 2027. The government of India has a program to renovate or replace a number of old sub-critical coal plants [19]. This scenario considers that 50 GW out of the 248 GW of coal capacity will be obsolete by 2027 and cannot be retrofitted for flexibility and efficiency upgrades. The Intermediate Scenario represents the case where India will have 200 GW of renewable energy on the grid by 2027. This case considers only 30 GW out of 248 GW of existing coal plants to be obsolete by 2027. The High RE scenario represents the case where a total of 250 GW of Solar PV and wind capacity will be installed on the grid by the year 2027. This scenario assumes that all the 248 GW will either be available for retrofits and technology upgrades or the obsolete coal capacity will be replaced with new super-critical coal capacity.

For each of the three RE penetration scenarios described above, methodology described in section 3 of the report was used to derive the net load curve. Ramping requirements were then determined from the net load curves. The net load curve for each of the three RE penetration scenario is shown below.

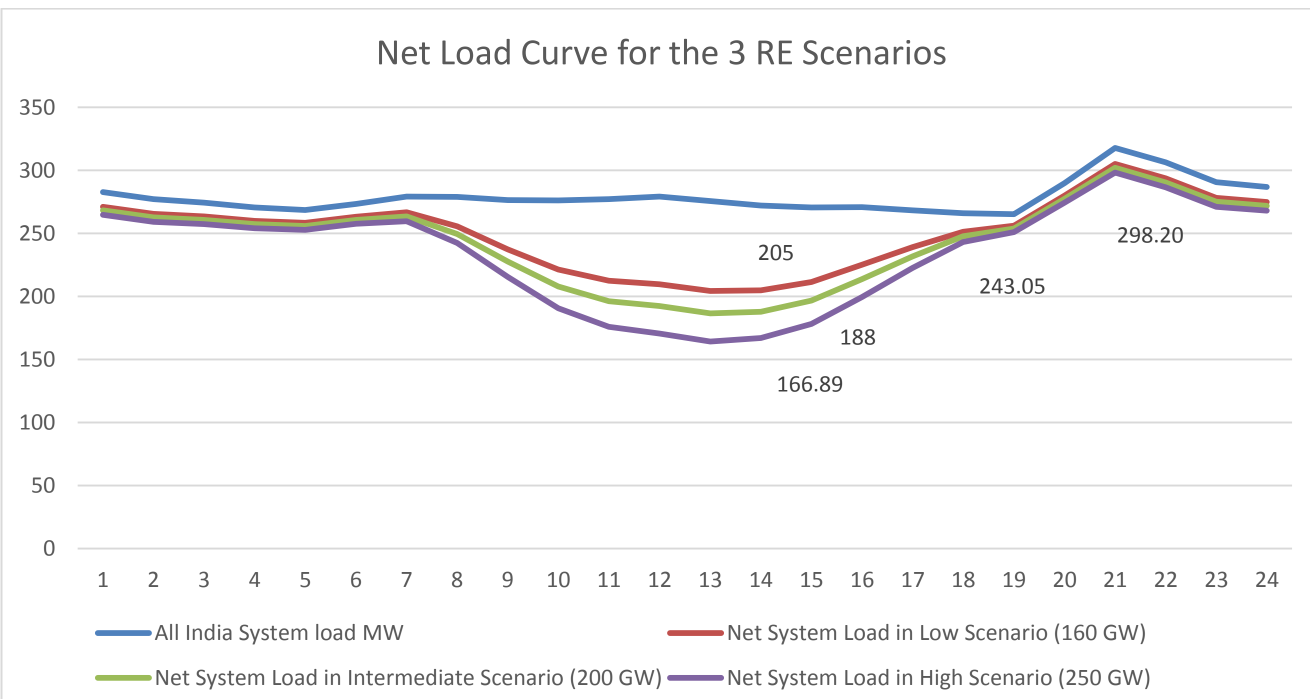

Figure 4: Net load curves for Low, Intermediate and High RE penetration scenarios

The ramp-up and ramp-down requirements for each of the three scenarios are described below.

	Ramp-down requirement (GW) (8AM-1PM)	Ramp Up Requirement (GW) (2PM-9PM)
Low RE Scenario	63	101
Intermediate RE Scenario	77	115
High RE Scenario	96	134

Table 3: Ramp up and Ramp down requirements on the Indian grid in each of the three RE penetration scenarios

Scenarios for Potential Solution paths

The solution framework to address the problem of lack of ramping can broadly be categorized into 2 types. 1) Building supply (generation) side flexibility 2) Building demand (load) side flexibility. While the paper relies mainly on supply side technologies, the High RE penetration scenario uses some demand side technologies as a part of the solution through Time of Use (TOU) and Demand Response (DR) programs. With increasing adoption of advanced metering and smart grid technologies, it is anticipated that the demand side technologies will be mature enough to provide ramping support to the grid as needed. Adopting generation technologies that are complementary to the variable energy sources, improvements in forecasting technologies, changes to the policy and regulatory frameworks and enhanced grid planning processes all form components of the comprehensive solution. While each component is complex in itself and involves an exhaustive discussion, this paper focuses primarily on the supply side (generation) technologies that will facilitate the adoption of VG sources.

The Supply side flexibility can be introduced into the system by having generation resources that are capable of quickly starting up from zero to any required output value within minutes. Such a generator should also be capable of multiple starts and stops a day and should have a dispatchable output. In this paper, three major technology streams have been considered as solution alternatives to the ramping problem. 1) Flexibility from Coal generation (Strong Coal alternative) 2) Flexibility from Natural Gas generation (Strong Gas alternative) 3) Flexibility from Renewable and Emerging Technologies (Strong RE/ET alternative). The large ramping requirement needed on the Indian grid can be addressed through any of these three supply side scenarios.

Solution Alternative A: Coal leads to meet Flexibility needs (Strong Coal alternative):

Currently over 60% of the generation capacity and 78% of actual power generated on the Indian grid comprises of thermal generation from coal [13]. While the newer coal plants that are being built on the system are based on super-critical technologies, most of the existing coal capacity constitutes sub-critical coal technologies. These sub-critical coal power plants are primarily designed for base load operation and are not suited to ramp up and down multiple times a day. Wear and tear of these plants goes up when operated in flexible mode [19, 20]. Also the thermal Efficiency of these plants goes down from 33% to 25%, resulting in relatively more carbon emissions/kWh of power produced. Given India has abundant coal reserves and that the 248 GW of capacity is sunk cost, using this capacity to meet the daily ramping requirements has been considered as one of the alternatives.

However in order to use the sub-critical Coal plants for ramping, they must be retrofitted to improve their load following and ramping capabilities. The cost of retrofits is taken as $150,000 - $225,000 / MW [19,22,23]. These investments are projected to bring the P_{min} value of the unit down to at least 55% of its name plate there by providing 45% of its nameplate rating as the flexible capacity [16, 24].

Solution Alternative B: Natural Gas leads to meet flexibility needs (Strong Gas alternative):

Natural gas plants have a very high ramp-up and ramp-down capability. These plants have lesser CO2 emissions/kWh and have higher thermal efficiencies than coal plants. Combined cycle gas turbines have a thermal efficiency of around 55% as compared to 33% thermal efficiency of sub-critical coal and 38% for super critical coal [13]. India currently has 25.5 GW of natural gas capacity which is expected to grow to about 30 GW by 2022. India however has a chronic shortage of Natural gas supply and the existing units are reported to have operated with a plant load factor as low as 23%. However given the abundancy of natural gas supply in the international market, natural gas has been considered as a feasible alternative to meet the flexibility needs. Capital expenditure of new natural gas plants has been assumed as $1,200,000 / MW.

Solution Alternative C: Renewable & Emerging Technologies lead to meet flexibility needs (Strong RT/ET alternative):

The ramping need on the system can also be met through a combination of renewable resources like Hydro and biomass as well as energy storage technologies. India has a total hydro potential of 148 GW out of which 44 GW has been installed (ref). India also has 96 GW of pumped hydro potential out of which currently only 2 GW is operational [13]. India also has about 20 GW of biomass potential with 5 GW currently installed. Biomass is generally considered to have a similar ramping capability as coal. Technology improvements and retrofits of existing biomass plants will be able to yield some improvements in the ramping capability. Technologies like offshore wind can also provide ramping capability since the production profile of offshore wind is complementary to the production profile of solar PV. However Offshore wind has been ignored in this analysis since India doesn't have even a single offshore wind farm installed and the actual generation potential, costs and technology readiness are still under evaluation [12]. Energy storage technologies have had promising developments in the past decade. In particular, costs of Battery storage are continuing to drop sharply and it is estimated that the price of battery storage will hit sub $1/watt by 2027 [14]. In this analysis storage potential both at grid and domestic level have been considered. There are several other emerging technologies like Concentrated Solar Power with storage, domestic solar PV with storage, micro grids, and smart grids etc that utilize a combination of supply side and demand side technologies to provide ramping capabilities on the grid. While each of these have not be considered separately, the paper considered all these in combination as a viable alternative.

Each of these three technology alternative paths were analyzed for each of the three levels of renewable energy penetration scenarios described earlier. Incremental capital costs, incremental fuel costs and incremental carbon emissions for each alternative as compared to the BAU scenario have been determined. It has been assumed that the thermal efficiency of old sub-critical coal plants will reduce from 33% to 25% when the units are ramped up and down in daily cycles and operated for peak load serving purposes. Other assumptions that have been used in the analysis are listed in Table 2 below.

Price of Coal / ton = $30 [a]
Price of Gas in India = $6.5 /MMBtu [b]
of years of service for capital investment = 30 Years
Gas consumption = 4.25 TJ / GWHr [c]
Emissions from Coal = 1.76 ton CO2/ton coal consumed #
Emissions from Gas units = 47.12 Tons of CO2 / TJ ##
Biomass fuel consumption = 1000 Tons / GWhr [d]
Emissions from Biomass units = 1.0 Million Ton / GWHr ##

Table 4 Assumptions used in the Analysis

Sources:

a: http://opengovernanceindia.org/xfakeuc/coal-prices-long-term-forecast-to-2025-data-and-charts. Indian power sector gets lower quality of coal and this can be taken as average price. It also includes $ 6/ton of Clean Environment Cess (Union Budget, 2016)

b: http://www.ogfj.com/articles/print/volume-13/issue-12/departments/the-final-word/gas-pricing-in-india.html Gas prices have variability. Authors have taken an average value around the 2016 prices in India.

c: Average for Indian plants for 2015-16 mainly based on [13] and personal communication with industry experts d: NCV of average feed used in some Indian biomass based gasifiers (personal communication)

Mitra et al (2004); # # IPCC 2006 GLs Energy volume chapter 1;

Details of the three solution alternatives for each of the three RE penetration scenarios are provided in Tables 5, 6 & 7 below. Each of the three solution alternatives (Strong Coal, Strong Gas and Strong RT/ET) try to determine the magnitude of ramping each type of generation technology can provide, with the goal of minimizing the total incremental cost to the system. This is achieved through minimizing the incremental new capacity that needs to be built.

CapEx for coal is the cost of retrofitting the existing coal plants with flexibility upgrades. The authors recognize that some of the existing coal capacity in India may already be capable of ramping up and down in daily cycles (for example new super critical plants), however for the sake of simplicity and keeping the results conservative, all coal plants were considered to require flexibility upgrades to meet the daily ramping cycles. CapEx for hydro generation is the cost of converting existing large hydro plant to a pumped storage facility. Preference for using other emerging technologies as an alternative has been kept low since technologies like smart grids, TOU metering, demand response systems, micro grids etc are relatively behind other generation technology options in their maturity for deployment.

Low RE Penetration scenario with 160 GW of Solar PV and Wind energy by 2027 resulted in a total ramping need of 101 GW on the system. The Strong coal alternative for this scenario resulted in 71 GW out of 101 GW of ramping need be supplied from retrofitted coal. 20 GW of ramping would be supplied from existing Natural Gas plants and 10 GW from existing hydro. 71 GW of ramp up capability from coal translates to 156 GW of retrofitted capacity for coal plants based on 80% plant load factor and a ramping capability of 45% of name plate rating of units. Strong gas alternative resulted in 25 GW of new green field natural gas capacity along with 104 GW of coal plant retrofits (providing 47 GW ramping) and 5 GW new biomass capacity. The strong RT/ET alternative, which focuses on enhanced renewable sources to meet the ramping needs without extending existing coal and gas ramping available, resulted in 10 GW of new pumped hydro conversions along with 8 GW of new biomass and 6 GW of grid connected battery storage.

Low RE Penetration Scenario	ID		Coal[5]	Gas[6]	Hydro[7]	Biomass	Battery - Grid	Battery - Retail	Other Emerging Tech	Total
BAU mix [8](GW)			248[9]	30	60	10	0	0	0	
	1	CapEx ($ Mil) / GW	225	1200	750	900	1000	1500	500	
Strong Coal	2	Ramping capacity (GW)	71	20	10	0	0	0	0	101
	3	Incremental New Capacity (GW)	156	0	0	0	0	0	0	
	4	CapEx ($mil) [1x3]	35100	0	0	0	0	0	0	35100
	5	Incremental Fuel Reqd/ year in Million Tons (Mt)	-52	0		0				
	6	Incremental fuel cost (Million $)	-1562	0		0				-1562
Strong Gas	7	Ramping capacity (GW)	47	40	10	5	0	0	0	102
	8	Incremental New Capacity (GW)	104	25	0	5	0	0		
	9	CapEx ($mil) [1x8]	23400	30000	0	4500	0	0	0	57900
	10	Incremental Fuel Reqd/	-34	232688		6				

[5] For coal Incremental new capacity is the amount of capacity that needs to be retrofitted for flexibility upgrades. This applies to all three scenarios.
[6] For Natural Gas, the incremental capacity is the new green field capacity that needs to be added.
[7] For Hydro, incremental capacity is the amount of large hydro capacity that needs to be converted to pumped hydro.
[8] BAU scenario considers 175 GW renewable target (100 GW Solar, 60 GW Wind & 15 GW other) will be achieved by the year 2030. Nuclear, Diesel and other forms of generation is not considered in BAU mix.
[9] Number inclusive of all types of Coal generation technologies.

		year (Mt)								
	11	Incremental fuel cost (Million $)	-1034	1512		169				648
Strong RT/ET	12	Ramping capacity (GW)	47	20	20	8	6	0	0	101
	13	Incremental New Capacity (GW)	104	0	10	8	6	0		
	14	CapEx ($mil) [1x13]	23400	0	7500	7200	6000	0	0	44100
	15	Incremental Fuel Reqd/ year (Mt)	-34	0		9				
	16	Incremental fuel cost (Million $)	-1034	0		271				-763

Table 5: Solution alternatives for Low RE Penetration Scenario

Intermediate RE Penetration scenario which modeled 200 GW of Solar PV and Wind energy by 2027 resulted in a total ramping need of 115 GW on the system. The Strong coal alternative for this scenario resulted in 79 GW out of 115 GW of ramping need be supplied from retrofitted coal. This scenario also shows 20 GW of ramping would be supplied from existing Natural Gas plants, 10 GW from existing hydro. 5 GW of biomass and 1 GW from grid connected battery storage. 79 GW of ramp up capability from coal translates to 158 GW of retrofitted capacity for coal plants.

Strong gas alternative resulted in 35 GW of new green field natural gas capacity along with 104 GW of coal plant retrofits, 5 GW new biomass capacity and 1 GW of grid connected battery storage. The strong RT/ET alternative, resulted in 10 GW of new pumped hydro conversions along with 15 GW of new biomass, 9 GW of grid connected and 1 GW of retail level battery storage. As the penetration of RE increases from low to intermediate scenario, it can be seen that the role of energy storage technologies also starts to increase.

Intermediate RE Penetration Scenario	ID		Coal	Gas	Hydro	Biomass	Battery - Grid	Battery - Retail	Other Emerging Tech	Total
BAU mix (GW)			248	30	60	10	0	0	0	
	1	CapEx ($ Mil) / GW	225	1200	750	900	1000	1500		
Strong Coal	2	Ramping capacity (GW)	79	20	10	5	1	0	0	115
	3	Incremental New Capacity (GW)	158	0	0	5	1	0	0	
	4	CapEx ($mil) [1x3]	35550	0	0	4500	1000	0	0	41050
	5	Incremental Fuel Reqd/ year (Mt)	-58	0		6				
	6	Incremental fuel cost (Million $)	-1738	0		169				-1569
Strong Gas	7	Ramping capacity	52	47	10	5	1	0	0	115

		(GW)								
	8	Incremental New Capacity (GW)	104	35	0	5	1	0		
	9	CapEx ($mil) [1x8]	23400	42000	0	4500	1000	0	0	70900
	10	Incremental Fuel Reqd/ year (Mt)	-38	325763		6				
	11	Incremental fuel cost (Million $)	-1144	2117		169				1143
	12	Ramping capacity (GW)	52	20	20	13	9	1	0	115
	13	Incremental New Capacity (GW)	140	0	10	15	9	1		
	14	CapEx ($mil) [1x13]	31500	0	7500	13500	9000	1500	0	63000
Strong RE	15	Incremental Fuel Reqd/	-38	0		15				

		year (Mt)								
	16	Incremental fuel cost (Million $)	-1144	0		440				-704

Table 6: Solution alternatives for Intermediate RE Penetration Scenario

High RE penetration scenario represents an ambitious goal of integrating 250 GW of Solar PV and wind into the grid by the year 2027. The ramp up requirement on the grid is 134 GW. This is an extremely challenging requirement for the grid operator and would require almost every non-variable generation unit to provide the maximum ramping capability they can. The grid will need to technologically evolve to leverage the demand side flexibility by the way of adopting Time of Use metering, smart grid and demand response technologies. It has been assumed that these emerging technologies will be able to reduce the ramping requirement by 5% translating to 7GW ramping reduction on the net load curve.

The Strong coal alternative for this scenario resulted in 89 GW of ramping be supplied from retrofitted coal. This scenario also shows 5 GW of ramping biomass and 2 GW from grid connected and 1 GW from retail level battery storage. 89 GW of ramp up capability from coal translates to 198 GW of retrofitted capacity for coal plants. Strong gas alternative resulted in 40 GW of new green field natural gas capacity along with 131 GW of coal plant retrofits, 5 GW new biomass capacity and 2 GW from grid connected and 1 GW from retail level battery storage. The strong RT/ET alternative, resulted in 10 GW of new pumped hydro conversions along with 15 GW of new biomass, 13 GW of grid connected and 2 GW of retail level battery storage.

High RE Penetration Scenario	ID		Coal	Gas	Hydro	Biomass	Battery - Grid	Battery - Retail	Other Emerging Tech	Total CapEx
BAU mix (GW)			248	30	60	10	0	0	0	
	1	CapEx ($	225	1200	750	900	1000	1500	500	

		Mil) / GW								
Strong Coal	2	Ramping capacity (GW)	89	20	10	5	2	1	7	134
	3	Incremental New Capacity (GW)	198	0	0	5	2	1	7	
	4	CapEx ($mil) [1x3]	44550	0	0	4500	2000	1500	3500	56050
	5	Incremental Fuel Reqd/ year (Mt)	-65	0		6				
	6	Incremental fuel cost (Million $)	-1958	0		169				-1789
Strong Gas	7	Ramping capacity (GW)	59	50	10	5	2	1	7	134
	8	Incremental New Capacity (GW)	131	40	0	5	2	1	7	
	9	CapEx ($mil)	29475	48000	0	4500	2000	1500	3500	88975

		[1x8]								
	10	Incremental Fuel Reqd/ year (Mt)	-43	372300		6				
	11	Incremental fuel cost (Million $)	-1298	2420		169				1291
	12	Ramping capacity (GW)	59	20	20	13	13	2	7	134
	13	Incremental New Capacity (GW)	131	0	10	15	13	2	7	
	14	CapEx ($mil) [1x13]	29475	0	7500	13500	13000	3000	3500	69975
	15	Incremental Fuel Reqd/ year (Mt)	-43	0		15				
Strong RE	16	Incremental fuel cost (Million $)	-1298	0		440				-858

Table 7: Solution alternatives for High RE Penetration Scenario

Table 8 presents a summary of the incremental GHG emissions saved and the price of carbon for each of the scenarios as compared to the BAU scenario. It can be seen that the strong coal alternative has the highest incremental GHG emissions savings, since the retrofitted plants are now kept running throughout, albeit at lower loads during ramping down and ramping up. Improvements in retrofitting technologies could reduce the 8% efficiency losses to below 5%, making this option even more attractive [20,27,28]. It has to be noted here that the capital investment involved for coal power plants is the cost of retrofits as against the capital investment to setup entirely new plants in the case of strong gas and strong RE/ET alternatives. Since India will have about 248 GW of coal power capacity installed by 2027, the strong coal alternative essentially reflects the option of leveraging that capacity to facilitate the integration of renewables into the grid.

Strong Gas alternative has the higher prices of carbon due to the fact that setting up new gas plants is highly capital intensive. This alternative also have the least incremental GHG emissions savings. Given the total power production from natural gas is very small in the BAU scenario, the emissions from the new gas capacity additions are incremental in nature and offset some of the benefit coming from the efficiency improvements of coal plant retrofits.

		Strong Coal	Strong Gas	Strong RE / ET
Low	Incremental GHG emissions saved (Million Tons/Yr) **	92	44	52
	Price of Carbon ($/ton CO2)	$ (4.28)	$58.51	$ 13.69
Intermediate	Incremental GHG emissions saved (Million Tons/Yr)	96	46	52
	Price of Carbon ($/ton CO2)	$ (2.08)	$76.02	$ 26.62
High	Incremental GHG emissions saved (Million Tons/Yr)	109	53.1	61
	Price of Carbon ($/ton CO2)	$ 0.73	$80.38	$ 23.98

Table 8: Summary of the incremental GHG emissions saved in each of the three solution alternatives for each of the three RE penetration scenarios.

** Incremental GHG = Incremental GHG from (Coal + Biomass + Gas). Biomass is ideally considered carbon neutral, but we have just indicated the emissions here. They may be treated as Memo items and not reported as per IPCC (2006) guidelines.

Detailed calculations for Incremental GHG emissions are demonstrated below for Strong Gas alternative in High RE penetration scenario

Coal plants will run 12 hrs @ 33% efficiency (normal efficiency) and 12 hrs @ reduced efficiency of 25% (during ramping up and down). Since the coal plant is serving only the net peak load only during the ramp up and ramp down operations, We assume that 1 GW plant creates 12 GWh during the normal load running and around 6 GWh during the net load period. It may be noted that the actual generation may be slightly different than these and would depend upon the actual net load curves. We assume that the base load coal plant will be running for 24 hours and producing 24 GWh normally. In reality, this would be different depending upon the plant load factor and other parameters.

Therefore total Coal Savings due to new RE capacity/GW/day = (24-18) x 650 Tons of Coal / GW/day

= 3900 Tons of Coal/GW/day

Coal wasted due to Efficiency loss/GW/day = 12 Hrs x (650*8/33) Ton / Hr = 1891 Tons/GW/day

Actual coal savings/GW/day = 3900-1891 = 2009 Tons / GW/day

Incremental fuel savings = Ramping capacity * Actual fuel savings / GW/Day * 365/1000000 million ton

Incremental fuel savings (Coal) = 59 GW * 2009 ton/ GW/Day * 365 days/1000000 = 43.3 Mt savings

Incremental fuel burnt (Biomass) = 5 GW * (6000-2910) tons of biomass/ GW/Day * 365 days/1000000 = 5.6 Mt burnt additional

Incremental GHG emissions saved = Incremental fuel savings * tons of CO2 / Ton of fuel

Incremental GHG emissions (Coal) = -43.3 * 1.76 = -76.2 mt CO2 (negative sign to in dicate that these emissions are saved)

Incremental GHG emissions (Biomass) = 5.6 * 1.0 = 5.6 Mt CO2 emitted

Incremental GHG emissions (Gas) = Incremental gas capacity x Capacity factor x Gas consumption rate x 8760 x Emissions / unit from gas

Incremental GHG emissions (Gas) = 40 x 0.25 x 4.25 x 8760 x 47.12 / 1000000 = 17.5

Total Incremental GHG emissions saved (coal + biomass + gas) = -76.2 + 5.6 + 17.5 = -53.1 Mt additional emissions (if biomass is considered carbon neutral, then 47.5 Mt emissions saved)

The ramping requirements can also be taken care of through the Renewable technologies and Emerging technologies alternative. As can be seen from table 3, the incremental GHG emissions in the RT/ET alternative is better than natural gas alternative but less than strong coal alternative. It can also be seen that the carbon price is lower than the gas alternative but higher than coal alternative. This is due to the fact that the incremental capacity additions in RT/ET alternatives do not contribute in incremental GHG emissions, except for Biomass (refer to exhibit 1 for details).

Table 8 shows that leveraging the existing coal capacity by retrofitting them for flexibility and efficiency upgrades is the cheapest option available to India to facilitate the integration of renewables onto the grid. However it should also be noted that the strong coal alternative for high RE penetration scenario assumes that the entire 248 GW of coal capacity will be available for flexibility retrofits. This may not be entirely practical since a significant amount of sub-critical coal capacity is old and may need to be retired for economic and efficiency reasons. It can be infered that as the penetration of renewables starts to increase, optimal path for flexibility will be in following the strong RT/ET alternative where in the flexibility from retrofitted coal plants will be supplemented with technologies like offshore wind, energy storage etc.

It should also be noted that the breakeven price of carbon for RT/ET alternative is in the range of \$13 - \$27. Given that the carbon price forecasts for the year 2027 are in the range of \$30 - \$40 range [25,26], the RT/ET alternative looks economically very attractive. It is noted here that carbon prices for strong coal scenarios remain below \$10/t-CO2 even if retrofitting costs go up to \$ 400 million/GW and coal prices go up to \$ 45/ton of Indian coal.

Conclusions

While India is pushing ahead with its aggressive goal of quickly integrating large amounts of renewable energy into the system, the grid side challenges of maintaining generation - load balance with such large amounts of VG sources remain. The paper modeled the net load curve on the Indian grid and quantified the ramp up and ramp down requirements on the Indian grid at three different levels of RE penetration. Ramp up requirements were found to be 101 GW on the low side and 134 GW on the high side in 2027. The paper explored Coal, Natural Gas and Renewable & Emerging Technologies as the solution alternatives available for the policy makers to build the needed generation flexibility into the system. Incremental costs, incremental emissions and carbon price was calculated for each of the 9 solution scenarios and conclusions were drawn.

The paper takes cognizance of the fact that India has large coal reserves and vast amounts of coal capacity already built on the system. While retrofitting existing coal option seems to have very attractive returns and negative carbon prices, it also requires that a majority of the old inefficient coal power plants are capable of being retrofitted. A sizable amount of coal capacity might be too obsolete for flexibility upgrades given that 52 GW of coal capacity will be older than 35 years by 2027. Using Natural gas as a source of flexible generation was found to be the least desirable option, since the cost of green field Natural Gas plants is high as compared to coal plant retrofits or new capacity based on Emerging technologies. It was found that the breakeven carbon price for Renewable & Emerging Technologies alternatives will be in \$13 - \$27 range. This is very attractive given that the carbon price forecasts for 2027 are in the range of \$30 - \$40.

Natural gas is generally considered as the bridge fuel for world economy to move from carbon intensive coal to zero carbon energy production. This is due to the fact that GHG emissions from natural gas are about 65% lower than that of coal plants as well as the fact that thermal efficiency of natural gas (upwards of 50% - 60%) is much higher than that of coal plants (33%). However, power generation from natural gas needs heavy capital investments into both the gas power plants as well as the storage and transportation infrastructure for the gas. The costs involved in building the transportation and storage infrastructure have been ignored in this paper. Considering only the capital investments needed to build gas plants, it has been shown that the natural gas alternative is inferior to both the flexible coal option as well as the RT/ET option. In addition Natural gas infrastructure typically has a life time of 30 - 60 years [29]. This means any new gas power plants built today will continue to operate through 2050 and beyond. Investing in Natural gas option may create a new carbon lock in cycle in India, especially from high RE integration into the grid perspective that may be detrimental to the goal of quickly moving towards zero carbon future. Given the lack of Natural gas resources, India would have to rely on imports for its power production creating energy security issues.

This paper shows that the optimal path for India to integrate ambitious RE capacity into the national power grid and to subsequently move into a low carbon future based on renewables would be to rely on flexible coal plants that provide high thermal efficiency as the bridge to directly leap frog into renewable energy heavy grid. For this to come to fruition, the Coal generation technology needs to quickly move from the concept of Coal serving as base-load plants to coal acting as Peaker plants. Concomitantly, India's power policy needs to quickly operationalizing other Renewable & Emerging technologies like Off-shore wind that have complementarity to Solar PV profile as well as energy storage technologies like pumped hydro, battery storage etc. Making the load responsive to grid requirements through the use to smart grid and deep energy efficiency technologies will also go a long way in achieving ambitious renewable energy goals on the grid.

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