# Solar-Wind Complementarity with Optimal Storage and Transmission in Mitigating the Monsoon Effect in Achieving a Fully Sustainable Electricity System for India

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***Abstract*— India is investing heavily in the renewable energy sector to keep up with its climate pledge at COP21. Assessment has shown abundant potential for renewable energy especially solar. However, for a 100% renewable energy system, monsoon presents an obstacle with decrease in solar resource availability. In this study, India is subdivided into 10 regions and these regions are interconnected via power lines. A 100% RE transition pathway on hourly resolution, till 2050 is simulated. The results from this study clearly indicate that the monsoon hurdle can be overcome by resource complementarity with grid utilization and storage technologies. Wind energy output increases in regions which have best wind conditions with 62% of the total wind energy generated in monsoon. However, wind resource is not same all over India. The unavailability of wind resource can be managed by solar PV and grids. The least affected regions such as India-Northwest can transmit PV electricity to other regions via transmission grids. In the monsoon period grid utilization increases by 1.3% from the non-monsoon period. The two major exporters of electricity India Northwest and India South export about 43% of the electricity in the monsoon period. These results clearly indicate that RE options are the most competitive and least-cost solution for achieving a net zero emission based electricity system even in the monsoon season without utilizing fossil based balancing power.**

***Keywords: 100% renewable energy; India; monsoon; energy transition; storage; grid***

## I. Introduction

Substantial changes have been observed in the power sector of India in recent years, keeping up with the reforms introduced by the government and the fast developing socio-economic status [1]. To keep up with the increase in electricity consumption, electricity generation in India has grown at 6% CAGR from 2012-2016 [2]. However, increase in demand has put tremendous pressure on the government to provide reliable electricity to each and every person in a sustainable way and to comply with the INDC commitments of the COP 21 at Paris [3].

A major transition is taking place in the power sector of India to keep up with India's climate pledge as it is evident from increased investment in the renewable energy (RE) sector [4,5]. Assessments [6,7,8] have shown India has abundant renewable energy potential, especially solar with 250-300 clear sunny days and average solar radiation varying from 1460 kWh/($m^2$·a) to 2555 kWh/($m^2$·a) over India [9]. The steps taken by the government to utilize the solar potential are in the right direction with installed capacity of 13 GW till June 2017 [10]. At the same time, cost of solar energy has dropped drastically in the last decade to 2.44 INR/kWh (0.035€/kWh[1]) in May 2017, a 73% fall since 2010 [11]. The government has a target of 100 GW of installed solar capacity till 2022 [2] and 250 GW till 2030 [12]. Wind energy potential is mainly concentrated in the states of Tamil Nadu, Gujarat, Karnataka, Maharashtra and Rajasthan and recent estimates indicate that wind potential could be higher than 2000 GW [13]. India has made a commitment at COP21 to have 40% share of non-fossil fuel in capacity mix by 2030 [14].

Large scale deployment of variable and intermittent solar and wind energy in the future would require various flexibility options such as different storage technologies, transmission grids and sector integration [15]. In a fully sustainable energy system for India these flexibility options would help balance the variation created by monsoon season which would impact the power generation from different RE sources.

The month of June is characterized by beginning of monsoon in different parts of India. The monsoon season is characterized by heavy rainfall in the central and southern part, along with strong westerly winds accompanying it, with periods of low solar radiation in these regions [16]. To balance the monsoon effect, wind energy will play a vital role in complementing the deficit in solar PV generation, with additional flexibility options provided by hydro power, storage technologies in particular batteries and transmission

[1] 1€ = 70 INR

of electricity via grids. Figures 1 and 2 show the solar and wind resource respectively for all hours in a year [17]. It can be clearly seen the increased wind availability in the monsoon months and decrease in solar resource availability.

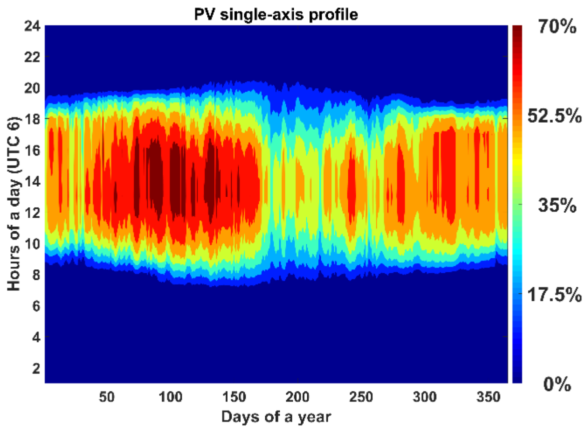


Figure 1. Solar profile on hourly basis for India

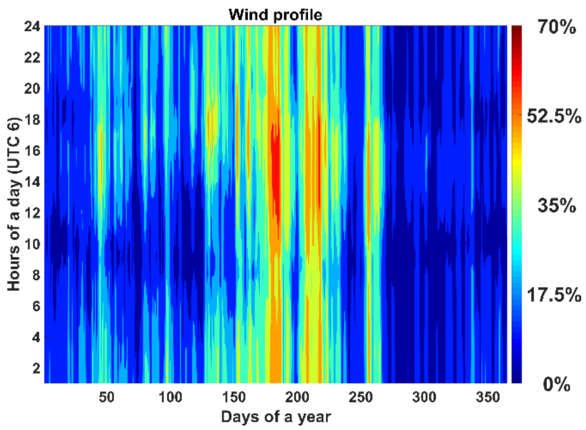


Figure 2. Wind profile on hourly basis for India

From previous studies Gulagi et al., [17,18] have shown that a fully renewable energy system is feasible and a least cost option in the future for India, overcoming the obstacle of monsoon and providing electricity on hourly basis. However this research goes further to analyse the monsoon period and the complementarity provided by solar PV, wind and hydro to the energy system and the role of storage technologies and transmission grid in overcoming the effect of monsoon.

The paper is organised as follows: Section II gives the methodology, the input data and the technologies used for the simulations. This is followed by the assumptions and the description of the power scenario used for the simulations. Section V gives the results and discussions. Finally, conclusions are drawn in section VI.

## II. Methodology and Input Data

The model with its equations and constrains used for this study has been described in detail previously by Bogdanov and Breyer [19] and Gulagi et al., [18]. The model is based on linear optimization and the main target is to minimize the total annual energy system costs, calculated as sum of costs of installed capacities, energy generation and generation ramping of the different technologies. For every 5 years from 2015 to 2050, the model optimizes the least cost solution. All the applied technologies from electricity generation, storage options used, bridging technologies and transmission of electricity can be seen from Figure 3.

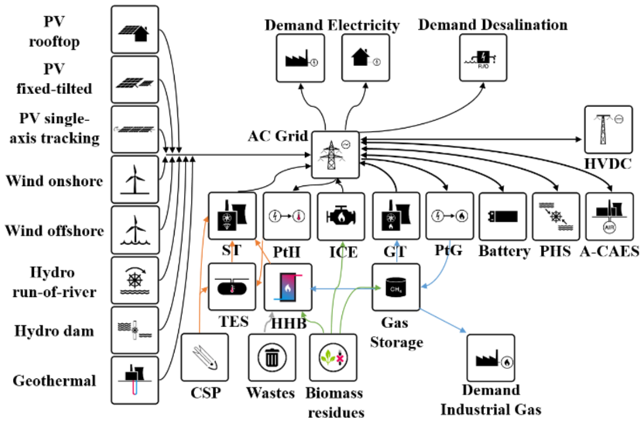


Figure 3. Block diagram of the LUT energy system model [20]

## III. Grid Structure and Scenario

India was divided into 10 sub-regions based on the population distribution, consumption of electricity and the grid structure. The sub-regions with intersection between the regions can be observed from Figure 4.

Power scenario [18] was studied for the analysis of the Indian energy system in the monsoon period. In this scenario, energy systems of the regions are interconnected.

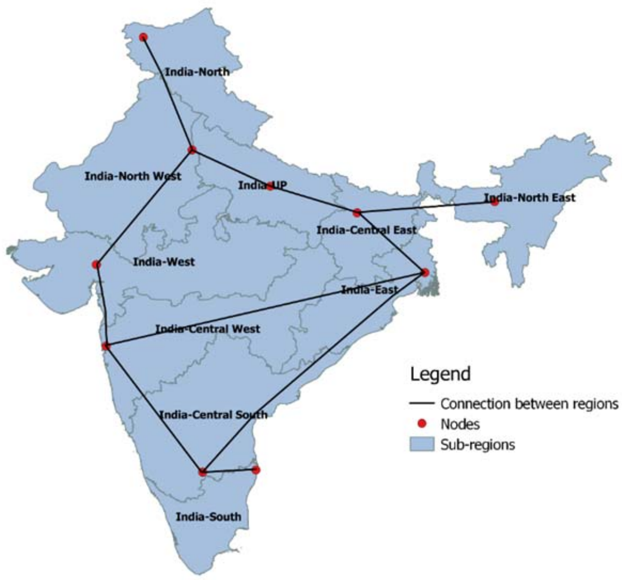


Figure 4. The 10 sub-regions of India and grid interconnection between them.

## IV. Assumptions

All the technical and financial assumptions related to the model can be found in the Supplementary Material of Gulagi et al., [18].

## V. Results and Discussion

According to Gulagi et al., [17,18], a power system based on fully renewable energy is a least cost solution and the system can overcome the hindrance created by the monsoon months.

The structure of the system with regards to power generation technologies, storage technologies and transmission grids was analyzed in detail and the following sub-sections will explain in detail on the role of power generation, storage technologies and transmission grids in the monsoon and non-monsoon period.

*A. The role of different power generation technologies*

Due to the cloudy and rainy weather in the monsoon (June-September), a slight decrease in the solar energy output was observed for all the regions. It was observed that the monsoon months (June-September) produce 62% of the total wind energy generated in India, while representing only one third of the year. The regions of India-West, Central West, Central South and the Southern region of India produce more than 95% of the total wind energy generated. Figure 5 shows the wind energy generated on hourly basis for the above mentioned four regions and also it can be observed from hour 3500 to 6500 of the year the electricity generated from wind increases particularly for the regions of Central West and Central South. The coastal and some inland regions of Gujarat, Maharashtra, Kerala and Tamil Nadu have the best wind potential of all the sites available in India.

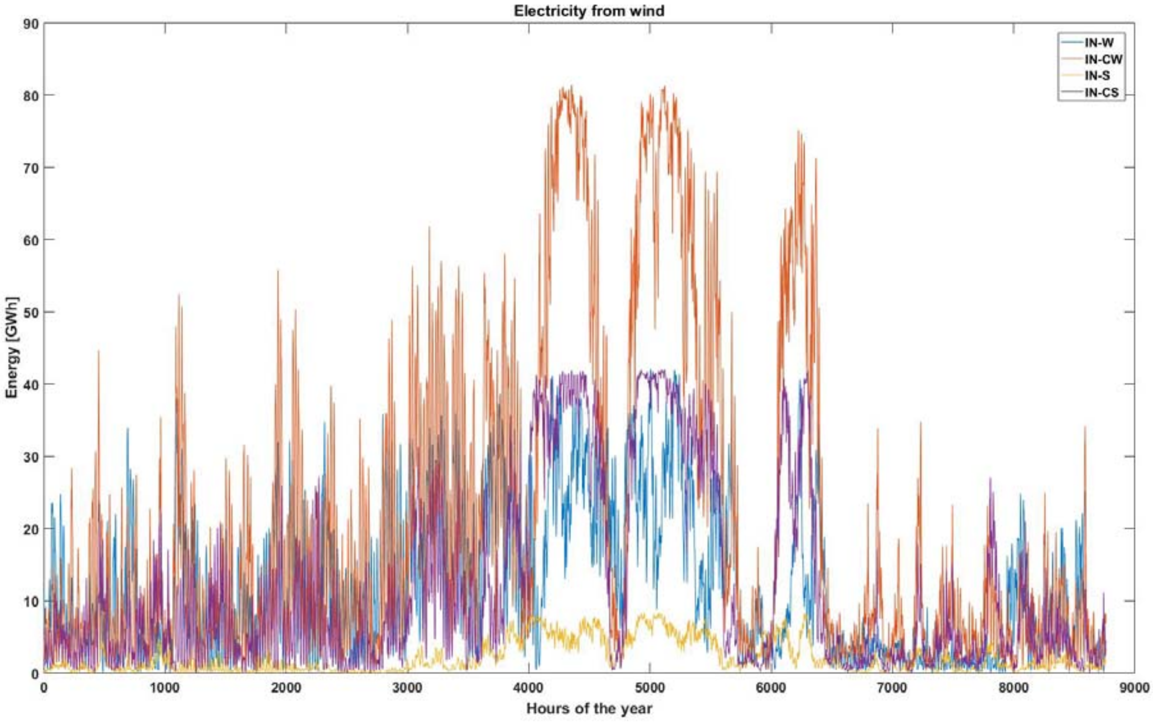


Figure 5: Electricity generated from wind on hourly basis in four regions for the power scenario in 2050.

The total power generation in the monsoon months from solar PV decreases by almost 14% in comparison to non-monsoon months. The regions IN-W, IN-CW and IN-CS are the most affected by the monsoon season with a decrease of 19%, 34% and 23% respectively. On the other hand, regions IN-NW, IN-S and IN-CE seem to be least affected by monsoon season with a decrease of 4%, 5% and 5%. As a result of overall decrease in solar generation in most parts of India, excess energy generated in the monsoon period was less and it can be observed from the utilization of the storage technologies in all the regions. The monsoon season is associated with more rainfall in the four months than in the remaining months combined. The water flow of the rivers increases as a result of increased rainfall and the regions with good hydro potential, electricity generation from hydro increases considerably. Of the total power generated by hydro, 48% is in monsoon season as compared to 52% in the remaining 8 months.

In the monsoon months, increase in wind and hydro generation can cover the total demand of the system even when the electricity generated from solar PV decreases.

*B. The role of storage technologies*

A fully renewable energy system for India is based on a solar PV-Battery hybrid, with batteries (prosumer and system) contributing to almost 90% of the total storage output and the remaining 10% from remaining storage technologies [18]. The gas storage which is utilized as long-term storage contributes to 7% of the total storage output [18].

In the monsoon period, battery output is 85% of the total storage output in comparison to 92% in the non-monsoon period. The reduced solar resource availability contributes to less energy stored in the batteries as batteries are utilized as short-term storage which complement perfectly with solar availability and discharge in the night time.

One interesting observation which was made is the increase in the output of stored gas to produce electricity via combined cycle gas turbine (CCGT). An increase of almost 10% is observed in the gas output in the monsoon period. The CCGT plants can be ramped up to provide electricity in the night time and in period of low solar radiation. From Figure 6, it can be observed that the gas storage is fully charged before the start of the monsoon season and starts discharging to cover the demand in the monsoon months and fully discharged till the monsoon is over.

The relative utilization of the storage technologies in the monsoon period was 30% in comparison to non-monsoon period where it was 37%. Figure 7 gives the relative storage utilization in all the sub-regions of India.

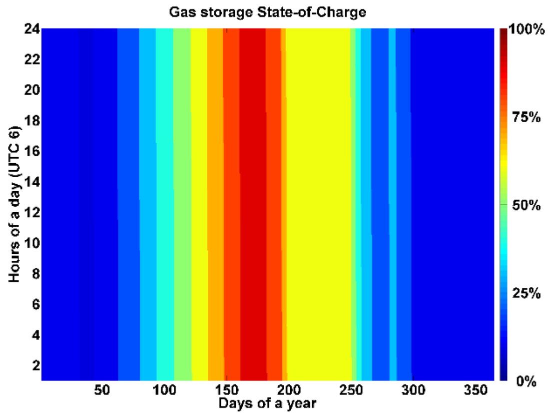


Figure 6: Hourly state-of-charge profile for gas storage for India in the year 2050 for the power scenario [18]

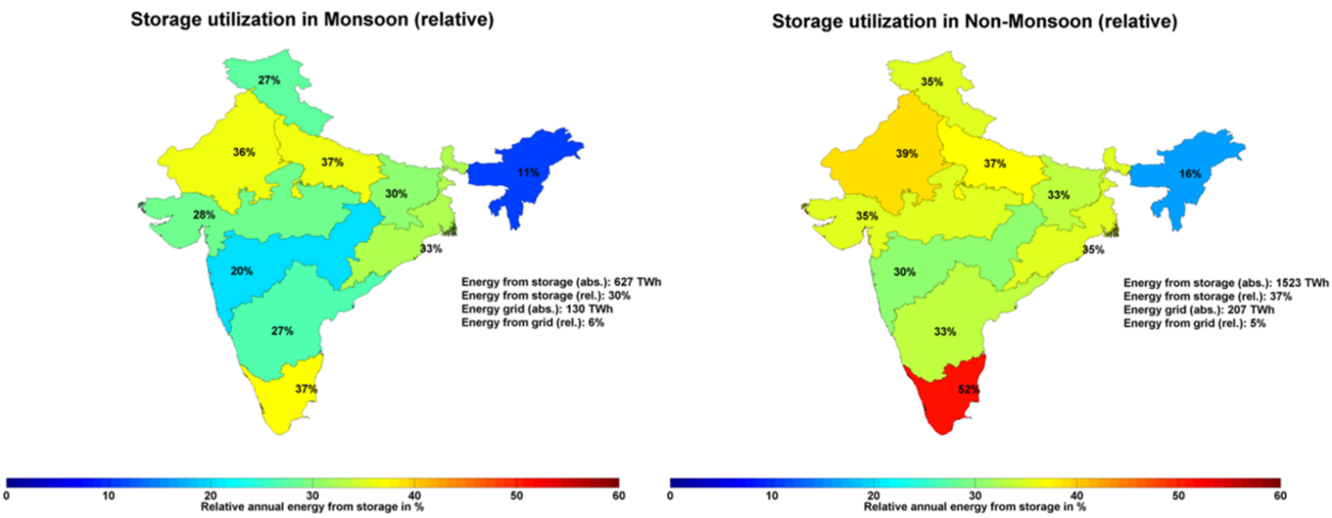


Figure 7: The utilization of storage technologies in the monsoon (left) and non-monsoon (right) months for the power scenario in 2050 [18]

### *C. The role of transmission grids*

The 10 regions in India are connected via transmission grids as shown in Figure 4. The transmission grids help to balance the power demand in different regions and decreases the need of storage technologies since energy shifted in time can be cost effectively substituted by energy shift in location. This is shown by two examples of regions IN-E and IN-W how decrease in solar resource is effectively managed by grid utilization.

The grid utilization increases in the monsoon period in comparison to storage technologies. In the monsoon period grid utilization was 6.2% in comparison to 4.9% in the non-monsoon period. Figure 9 shows the grid utilization in the different regions in the monsoon and non-monsoon months. The Eastern (IN-E) region imports electricity mainly from the Central-East (IN-CE) region and the energy flow in the grid for the two regions is shown in Figure 8. The positive numbers indicate import and negative export of electricity in the transmission line. In the monsoon period, export of electricity takes place for most hours in a day from the region IN-CE due to solar resource unavailability in the region IN-E as over 90% of the power generated is by solar and this region does not have good wind resource. This exported electricity is used directly to satisfy the day time demand or stored to satisfy the night time load. During the non-monsoon months, electricity is exported during the daytime by IN-CE which is consumed directly or stored in gas storage in the IN-E region. So to satisfy the demand the IN-E region has to import electricity from IN-CE. This example shows how a system balances itself due to transmission grids in the monsoon months.

The grid utilization of the region IN-W increases in the monsoon period in comparison to non-monsoon period. This region has solar PV as a major power generating source and wind complementing as this region is situated in one of the best wind sites in India having good wind potential all year around. However in monsoon months the demand cannot be fulfilled by the available renewable resources and the import of electricity is mainly taking place from the IN-CW region, where wind energy is available which can be seen from Figure 10. From hours 4000 to 6500 the IN-W region imports wind energy from IN-CW to satisfy its power demand in the monsoon.

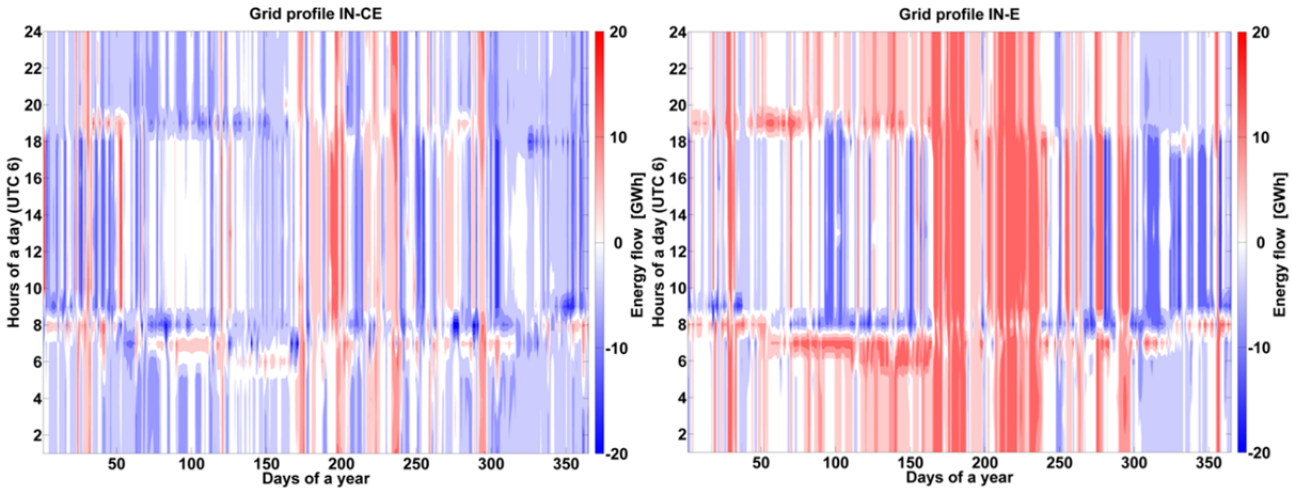


Figure 8: Grid profile for the power scenario for year 2050 for IN-CE (left) and IN-E (right). Import (+) and Export (-)

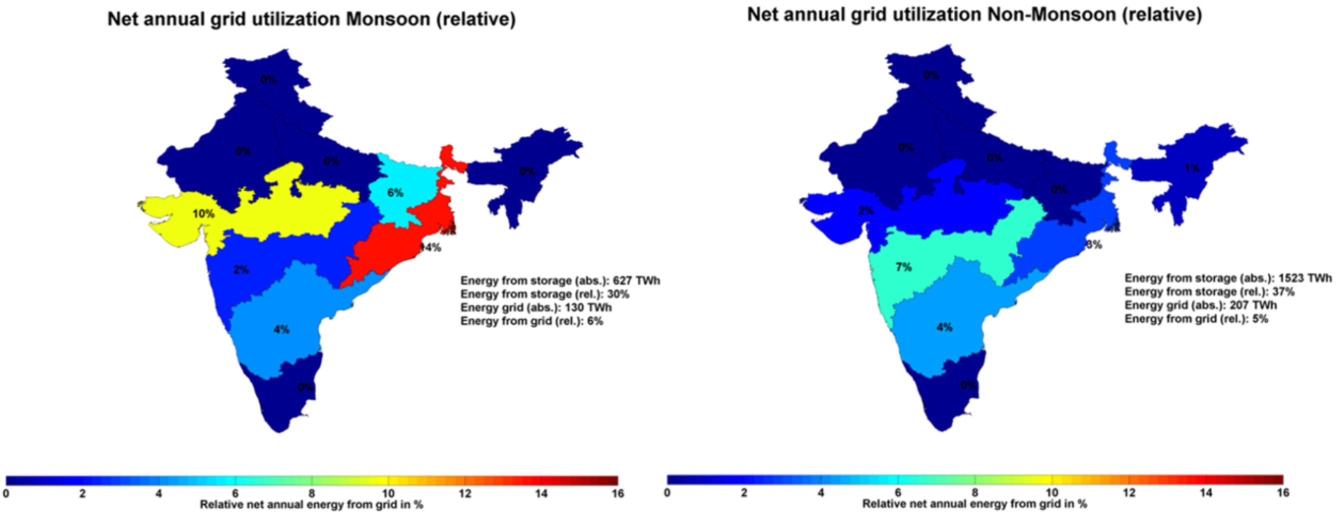


Figure 9: The utilization of storage technologies in the monsoon (left) and non-monsoon (right) months for the power scenario in the year 2050 [18]

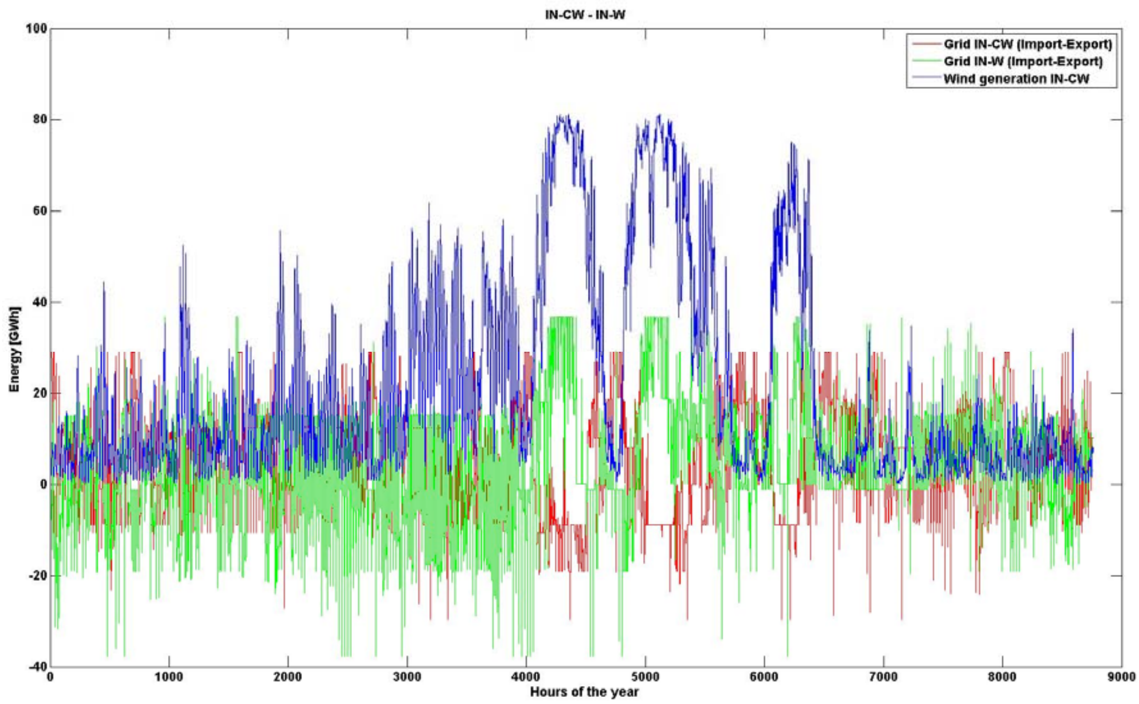


Figure 10: Grid energy and wind energy generation on hourly basis for the power scenario in the year 2050. The blue line is the wind energy generation in the IN-CW region. The red and green line is the annual import and export by IN-CW and IN-W respectively.

The regions which are least affected by monsoon and with a slight decrease in solar PV electricity production support other regions which are strongly affected by transmitting electricity via grids. A perfect example of this is IN-NW and IN-W which can be seen from Figure 12. The region IN-NW is least affected by monsoon and receives less rainfall due to desert conditions so the solar conditions are almost constant all year around with a slight decrease in the monsoon period. The region IN-W is the most affected by monsoon with electricity from solar PV decreasing by almost 19% in comparison to non-monsoon period. The region IN-NW transmits electricity generated by solar PV directly on a daily basis to IN-W and more so in the monsoon period with the import of electricity increasing for IN-W regions (Figure 12). The same can be observed for the region IN-S which is least affected by monsoon and which is one of the largest exporter of electricity. The export of electricity to IN-CS is on the daily basis and more so in the noon and afternoon hours. For the regions, IN-NW and IN-S, batteries are charged on daily basis in the noon and afternoon hours and discharged for satisfying the demand or transmitting electricity via grids to other regions.

The regions of IN-NW and IN-S are top two exporters of electricity among the ten regions. These two regions combined export is about 43% of the total electricity exported in the monsoon season for a fully renewable energy system in 2050. The electricity exported is mainly PV electricity as it is the cheapest source for electricity and to minimize the total cost of the system, it is cheaper to export PV electricity than wind. For IN-NW, the electricity generated from wind is negligible and this further proves that electricity from solar PV is exported also by utilizing batteries to export 24/7 to other regions to balance the load in monsoon in a cost effective way.

The net energy transfer between the 10 regions for a fully renewable energy system in 2050 is 698 TWh. From Figure 11 it can be seen that the major importing regions are IN-CW, IN-W and IN-CS and the major exporting regions are IN-S, IN-UP and IN-NW. However, in the monsoon period net energy transfer is about 38% of the total net energy transfer in the year 2050.

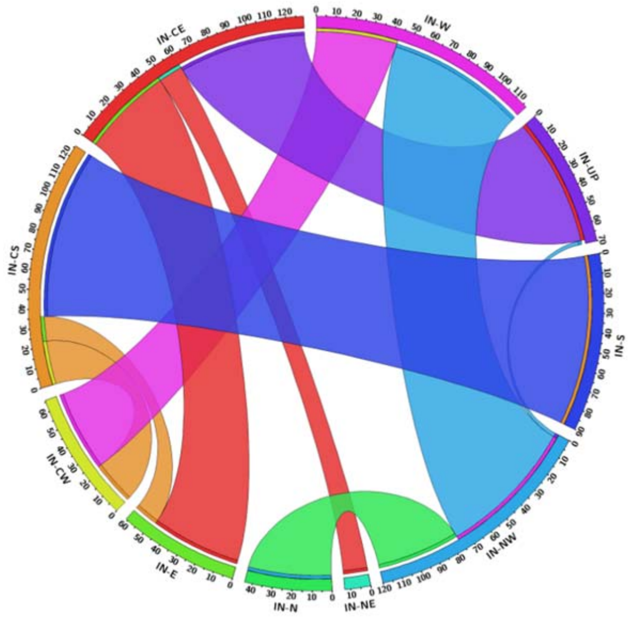


Figure 11: Electricity exchange among the 10 regions in the year 2050 for the power scenario. The thickness of the flow indicates the amount of electricity exchange denoted by numbers in TWh. Exporter regions and the ribbon of importing region have the same color (e.g. 90 TWh of electricity is exported from IN-S to IN-CS).

## VI. Conclusion

A 100% renewable energy system for India is possible and the proposed system can effectively handle the monsoon period.

The reduced power generation from solar PV in the monsoon period can be effectively managed by increase in power generation from wind. Total power generation from wind increases by 64% in comparison to non-monsoon period. Also, of the total power generated from hydro, about 48% is generated in the monsoon period.

The storage technologies utilized provide the required system balancing. The decrease in battery output due to reduced solar availability is effectively managed by gas storage via CCGT plants to satisfy the power demand. The interconnection of regions via transmission grids can effectively overcome the monsoon phenomenon by utilizing

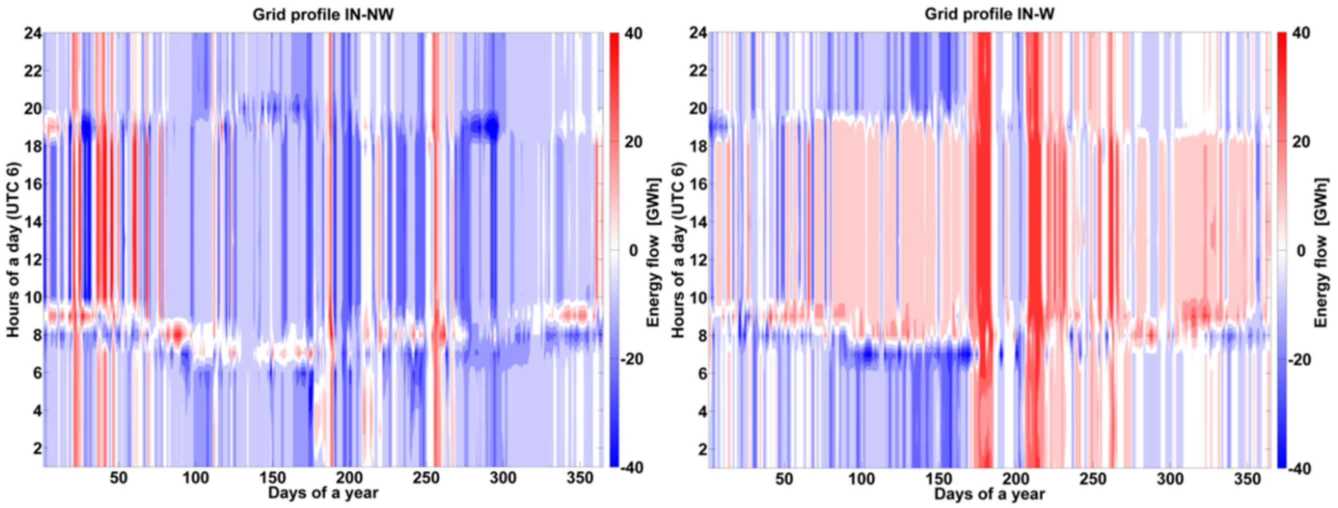

Figure 12: Grid profile for the power scenario for year 2050 for IN-NW (left) and IN-W (right). Import (+) and Export (-)

the resources available in other regions cost effectively, in particular wind energy and hydropower. The net transfer of energy in the monsoon season is 268 TWh.

These results clearly prove that RE options are the most competitive and least-cost solution for achieving a low carbon based electricity system even in the monsoon season without utilizing fossil based backup power.

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