The Role of Transmission Grid and Solar Wind Complementarity in Mitigating the Monsoon Effect in a Fully Sustainable Electricity System for India

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Abstract: Various assessments have shown abundant renewable energy (RE) potential for India, especially solar. For a fully sustainable power system, monsoon presents an obstacle with the resultant decrease in solar resource availability. In this study, India is subdivided into ten regions, and these regions are interconnected via power lines. A 100% RE transition pathway in hourly resolution, until 2050, is simulated. The results from this paper indicate that the power system can overcome the monsoon hurdle by solar–wind complementarity and grid utilisation. Wind energy output increases in regions that have the best wind conditions with 62% of the total wind energy generated in monsoon. Solar photovoltaic (PV) and grids can manage the unavailability of wind resources in some of the regions. There is a clear indication that imports increase during the monsoon period. The least affected regions such as India-Northwest (IN-NW) can transmit PV electricity to other regions via transmission grids. In the monsoon period, grid utilisation increases by 1.3% from the non-monsoon period to satisfy the respective demand. The two major exporters of electricity, IN-NW and India-South export about 43% of electricity in the monsoon period. These results indicate that no fossil-based balancing is required in the monsoon period.

1 Introduction

The Indian power sector is evolving rapidly to keep up with the economic growth and fast-changing socio-economic status of the country [1]. The increasing electricity consumption due to the growth in gross domestic product and government's aim to provide reliable electricity to every individual has put tremendous pressure on the power sector. Currently, electricity generation is largely based on fossil fuels, particularly coal. The increased use of coal has consequently contributed to rapid growth in greenhouse gas (GHG) emissions in the past decades [2]. The power sector in India is one of the major contributors to GHG emissions [3]. The major dilemma that India faces today is prioritising its energy goals of a low carbon economy with reduced dependence on coal and increasing renewable energy (RE) usage [2]. The power sector needs to evolve rapidly to keep up with local and global goals.

In the past few years, India has woken up to the issue of climate change and pollution and its devastating effects [4]. In its INDC Q2commitment at COP21, India pledged to reduce GHG emissions by 33–35% until 2030 in comparison with 2005 and 40% of the country's electricity would be generated from renewables such as wind and solar [5]. Commitment to the Paris Agreement will require utilising the available RE resources to achieve the required targets. Assessments [6, 7, 8] have shown India has abundant RE potential, especially solar. With, 250–300 clear sunny days and average solar radiation varying from 1460 to 2555 kWh/(m^2 a) across the country [9], the government has taken steps to utilise this solar potential with an installed capacity of 28 GW, until end of March 2019 and aggressive future targets [10, 11, 12]. The vast coastline of India provides perfect conditions for wind power installations, with the potential mainly concentrated in the states of Tamil Nadu, Gujarat, Karnataka, Maharashtra and Rajasthan. While the current total wind capacity is around 34 GW [10], the potential is estimated at around 2000 GW [13, 14]. Tamil Nadu is the leading state in terms of wind power installations [10].

However, the major drawback of the above technologies is that electricity can be produced only during certain intervals. For example, when the Sun is shining during the day and strong winds in the evening and night or the monsoon season for the specific case of India. Hybrid projects may reduce variability to some extent and power can be generated at night and even in the monsoon months [15]. The Ministry of New and RE has released a draft policy for hybrid solar and wind energy projects [16]. While, at a lower penetration of variable renewable resources, the variability of power generation can be effectively managed by ramping up conventional fossil fuel generators, but for a fully RE-based system having a major share of solar and wind energies, this presents a huge hindrance [17, 18, 19, 20].

On the other hand, increasing flexibility of the transmission lines [21], adding storage capacity and power-to-gas flexibility to the energy system [22, 23] and complementarity of wind and solar [22], would help mitigate the variability of solar and wind resources. Various studies have shown that a 100% RE-based system is possible for India. While TERI [24] puts forward that Q2such a scenario is desirable for India; however, it maintains that financial and technical policies should be in proper order to make such a scenario realistic. On the other hand, according to Röben and Köhler [25], a 100% RE scenario is feasible and more efficient than the current energy system, while Lawrenz *et al.* [26] conclude that it is technically possible to supply energy for the power, heat and transportation sector entirely by renewables. According to Gulagi *et al.* [27], a 100% RE-based system is technically and economically feasible on an hourly resolution [19, 27, 28] and also for countries in the South Asian Association for Regional Cooperation [29], with the cost structure less than the current system based on fossil fuels. According to these studies, a fully renewable electricity system for India will be based mainly on solar photovoltaic (PV) complemented by other RE technologies. However, these studies do not address in detail an important question: ‘How will a solar PV-dominated electricity system perform during the monsoon season’?

The onset of monsoon is from the southwest of India, and then it travels into the western, eastern, northeastern and northern regions. The increase in cloud cover follows this path; as a result,

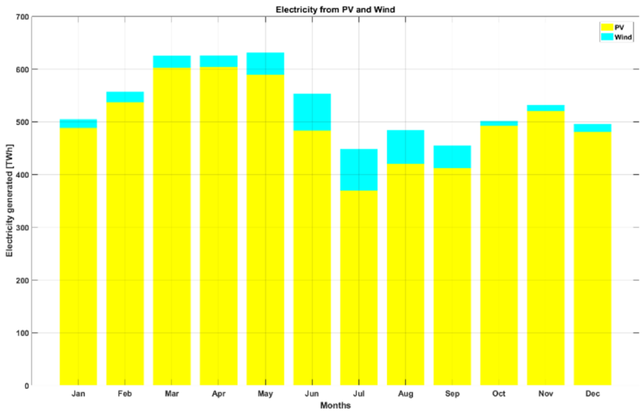


Fig. 1 *Solar PV generation*

Q7 ***(a)*** Solar profile on an hourly basis for India, ***(b)*** Wind profile on hourly basis for India

solar resource availability varies between the different regions based on the position of the monsoon. Strong southwesterly winds accompany the arrival of the monsoon, giving rise to peak wind resources, particularly in the southern and western regions. On the other hand, solar resource is low during the monsoon season, due to the presence of cloudy weather [30]. The decrease in power production from solar PV in a particular region affected by the monsoon can pose considerable challenges for the stability of the power grid. To balance the monsoon effect in a 100% RE system, wind energy will play a vital role in complementing the deficit in solar PV generation (Figs. 1*a* and *b*), along with additional flexibility options provided by transmission grids, storage technologies in particular batteries and hydropower.

Not many studies have shown a fully RE-based scenario for India on an hourly resolution with storage technologies and transmission grids. Furthermore, none of them has a special focus on the energy system analysis during the monsoon season. A study by the National RE Laboratory [31] touches on the aspect of monsoon season and transmission grid utilisation, but does not dwell into the impacts in detail. Also, the study is limited to the year 2022, taking into account the governments RE targets. According to this paper, curtailment is highest in the monsoon months compared with non-monsoon months, and curtailment can be reduced in the regions generating highest RE by evacuating the power generated via additional transmission grids and integrating the different regions.

This paper is a first of its kind to analyse the effects of the monsoon season on a fully RE system. In the first step, this paper analyses the complementarity provided by wind energy to the decrease in solar PV. In the second step, we analyse the role of the transmission grid in evacuating power from different regions to the monsoon-affected regions. Thus, reducing curtailment in these regions. It is acknowledged that hydropower and storage technologies provide some level of flexibility to the system. However, these are not discussed in this paper as Gulagi *et al.* [32] describe the role of hydropower and storage technologies in the monsoon period in greater detail. Historically, India has relied on coal and hydropower for supplying electricity to most of its regions and the monsoon season had less impact on the supply side. However, a rapidly evolving power sector with increasing shares of renewables compels energy planers and other stakeholders to consider the impacts of seasonal variations such as the monsoons on power systems with high shares of renewables.

This paper is organised as follows: Section 2 provides the methodology, the input data and the technologies used for the simulations. This is followed by the assumptions and description of the power scenario used for the simulations in Section 3. All the technical and financial assumptions are provided in Section 4. Section 5 presents the results and discussion. Finally, conclusions are drawn in Section 6.

2 Methods and input data

The model with its equations and constrains used for this paper have been described in detail previously by Bogdanov *et al.* [28] and Gulagi *et al.* [19]. The following section gives a brief description of the main optimisation function and the constraints.

The model is based on linear optimisation and the main constraint is that total power generation should be equal to the total power demand in that particular hour for the selected year, whereas the main objective function is to minimise the total annual energy system costs, calculated as a sum of the costs of installed capacities, energy generation and generation ramping of the different technologies. For every 5 year intervals from 2015 to 2050, the model optimises the least-cost solution. The equations for the objective function (1) and the main constraint are given below (2):

$$\min\left(\sum_{r=1}^{\text{reg}}\sum_{t=1}^{\text{tech}}(\text{CAPEX}_t\,\text{crf}_t + \text{OPEXfix}_t)\,\text{instCap}_{t,\,r}\right. \qquad (1)$$
$$\left.+\text{OPEXvar}_t\,E_{\text{gen},\,t,\,r} + \text{rampCost}_t\,\text{totRamp}_{t,\,r}\right)$$

CAPEX_t is the capital cost of each technology, crf_t is the capital recovery factor for each technology, OPEXfix_t is the fixed operational cost for each technology, OPEXvar_t is the variable operational cost for each technology, $\text{instCap}_\text{t,r}$ is the installed capacity in a region, $E_\text{gen,t,r}$ is the electricity generation by each technology, rampCost_t is the ramping cost of each technology and $\text{totRamp}_\text{t,r}$ is the annual total power ramping values for each technology. The target function was applied in time steps of 5 year from 2015 to 2050

$$\forall h \in [1,\ 8760]\left(\sum_{t}^{\text{tech}} E_{\text{gen},\,t}\right),\ h + \left(\sum_{r}^{\text{reg}} E_{\text{imp},\,r}\right),\ h + \left(\sum_{t}^{\text{stor}} E_{\text{stor, disch}}\right),$$
$$h = (E_{\text{demand}}),\ h + \left(\sum_{r}^{\text{reg}} E_{\text{exp},\,r}\right), h + \left(\sum_{t}^{\text{stor}} E_{\text{stor, ch}}\right),\ h + (E_{\text{curt}}),\ h \qquad (2)$$

It is defined for every hour of a year in a particular region, electricity generation from all the technologies ($E_\text{gen,t}$), imported electricity from the regions ($E_\text{imp,r}$) and electricity from storage discharge ($E_\text{stor,disch}$) should be equal to the total demand for an hour (E_demand), electricity exported to other regions ($E_\text{exp,r}$), electricity for charging storage technologies ($E_\text{stor,ch}$) and curtailed electricity (E_curt). The other abbreviations used in this equation are hours (h), technology (t), all technologies used in modelling (tech), sub-region (r) and all sub-regions (reg).

The other two important constraints applied were:

- The RE-installed capacity cannot grow by more than 20% of the total power generation capacities for each 5 year time step to avoid the disruption of the power system.
- No new nuclear or fossil fuel capacities can be installed after 2015, except gas turbines, which can utilise synthetic gas or bio-methane.

All the applied technologies from electricity generation, storage options used, bridging technologies and transmission of electricity can be seen in Fig. 2.

3 Grid structure and scenario

India was divided into ten sub-regions based on the population distribution, consumption of electricity and the grid structure as in Fig. 3.

The power scenario [19] was studied for the analysis of the Indian energy system during the monsoon period. In this scenario, the energy systems of the different regions are interconnected.

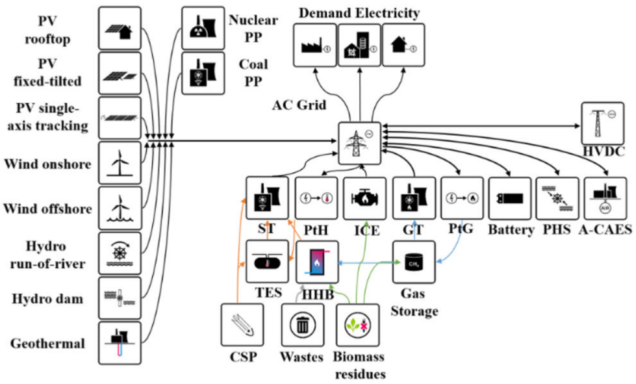


Fig. 2 *Block diagram of the look-up table energy system model [17]*

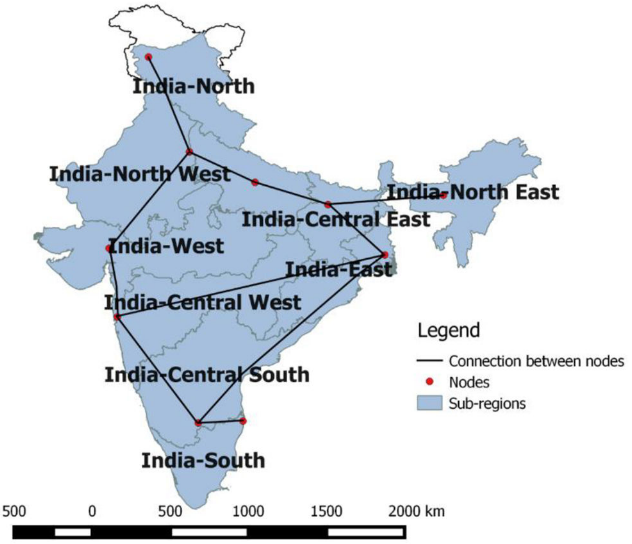


Fig. 3 *Ten sub-regions of India and grid interconnection between them*

4 Assumptions

All the technical and financial assumptions related to the model can be found in the supplementary material of Gulagi *et al.* [19].

5 Results and discussion

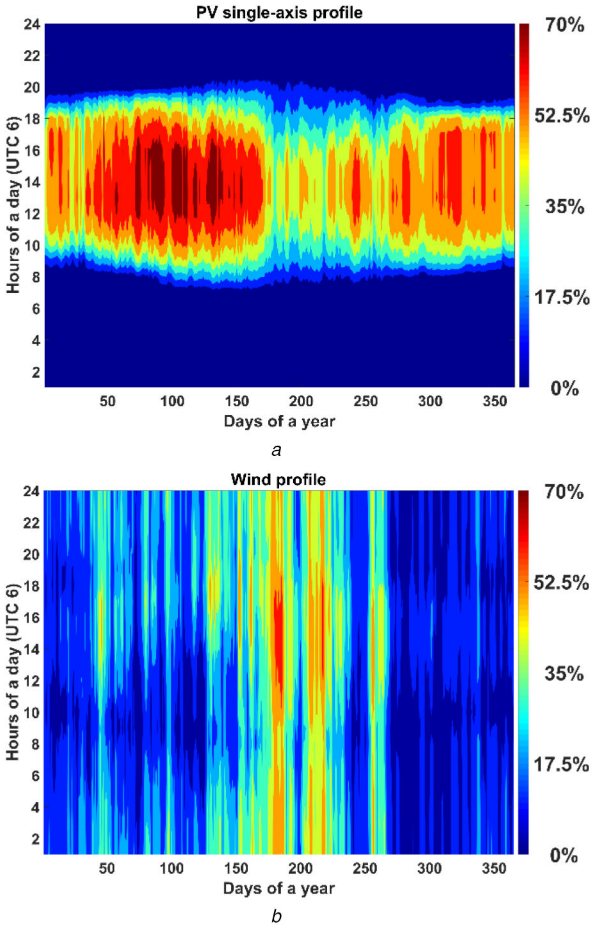
According to Gulagi *et al.* [19, 27], a power system based on fully RE is the least-cost solution, and the system can overcome hindrances created during the monsoon months.

The structure of the system concerning power generation technologies, storage technologies and transmission grids was analysed in detail, and the following sub-sections will explain in detail the roles of power generation, storage technologies and transmission grids in the monsoon and non-monsoon periods.

5.1 Complementarity of solar and wind generation in 2050

The total annual generations from solar PV and wind in 2050 are 6000 and 415 TWh, respectively. These two RE sources contribute to almost 92% of the total electricity generation. Fig. 4 shows the
Q4 monthly solar and wind generation in the year 2050 for the power scenario. Solar generation is highest during March, April and May, which are also the summer months. While generation is at its lowest during the monsoon months of June, July, August and September. On the contrary, wind generation is seasonal, and the peak generation is observed during the monsoon period. The lowest generation of electricity from solar is seen in July when the monsoon is at its peak in most parts of India. The highest generation from solar is observed in March, April and May when summer is at its peak in most parts of India.

Owing to cloudy and rainy weather in the monsoon period (June–September), a decrease in the solar energy output was observed for all the regions. The decrease in solar energy output is dependent on a particular region; some regions that were affected the most by the monsoon saw a steep decrease in solar energy output and vice versa. The total power generation in the monsoon months from solar PV decreases by almost 14% in comparison with non-monsoon months. The regions India-West (IN-W), India-Central West (IN-CW) and India-Central South (IN-CS) are the most affected by the monsoon season with a decrease of 19, 34 and 23%, respectively. On the other hand, regions India-Northwest (IN-NW), India-South (IN-S) and India-Central-East (IN-CE) seem to be least affected by monsoon season with a decrease of 4, 5 and 5%, respectively.



a

b

Fig. 4 *Monthly electricity generation from solar PV and wind in 2050 across India for the power scenario*

It was observed that the monsoon months (June–September) produce 62% of the total wind energy generated in India while representing only one-third period of the year. The regions of IN-W, Central West, Central South and the South regions produce more than 95% of the total wind energy generated. The electricity generated from wind energy particularly picks up in 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 across India. The above findings are in agreement with Solomon *et al.* [22, 33], wherein the solar–wind complementarity analyses were done for Israel and California, and Gerlach *et al.* [34] for global–local resolution. Here, the authors conclude that complementarity has multiple benefits such as stable high share RE system and grid. Complementarity provides a fully RE system to function without hindrances.

5.1.1 Analysis on a regional level: Significant variation of wind generation exists across the regions in India. The southern and western regions are expected to install and generate most of the wind energy in India due to the availability of excellent wind resources. This can be observed in the current-installed capacities of wind, which are concentrated in these regions. In comparison, the solar resource is well-distributed all over India, except the

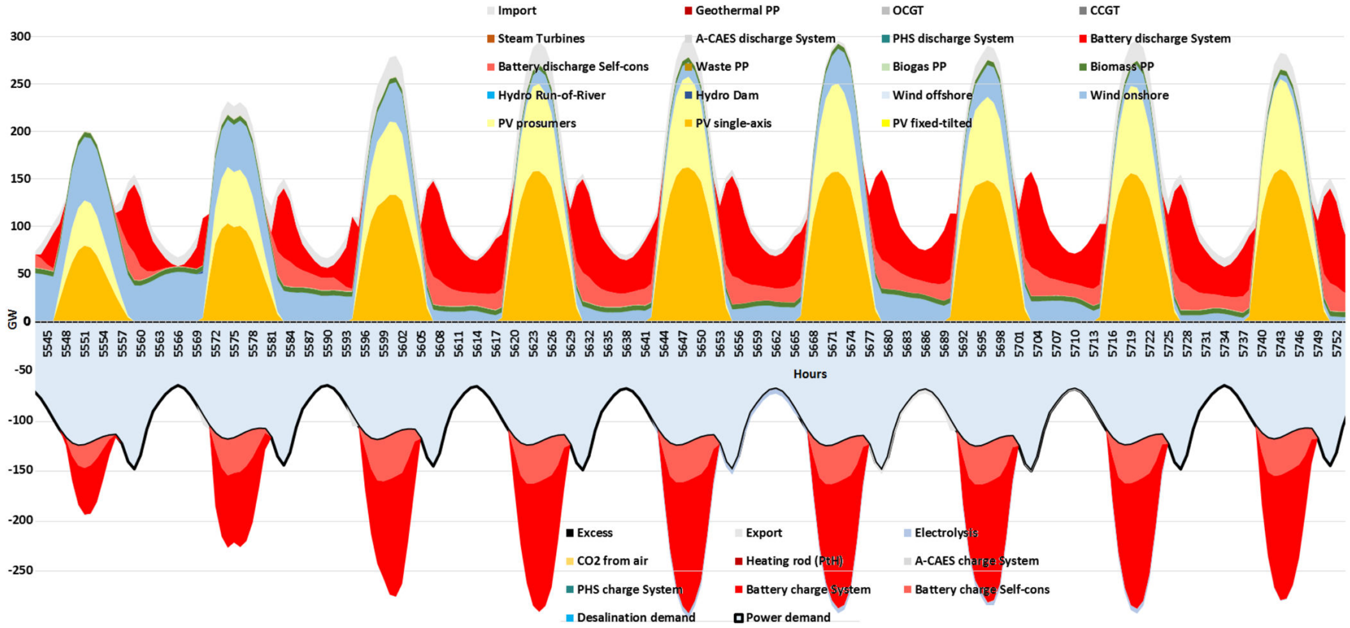


Fig. 5 *Dispatch for the region IN-CW in a monsoon week in 2050*

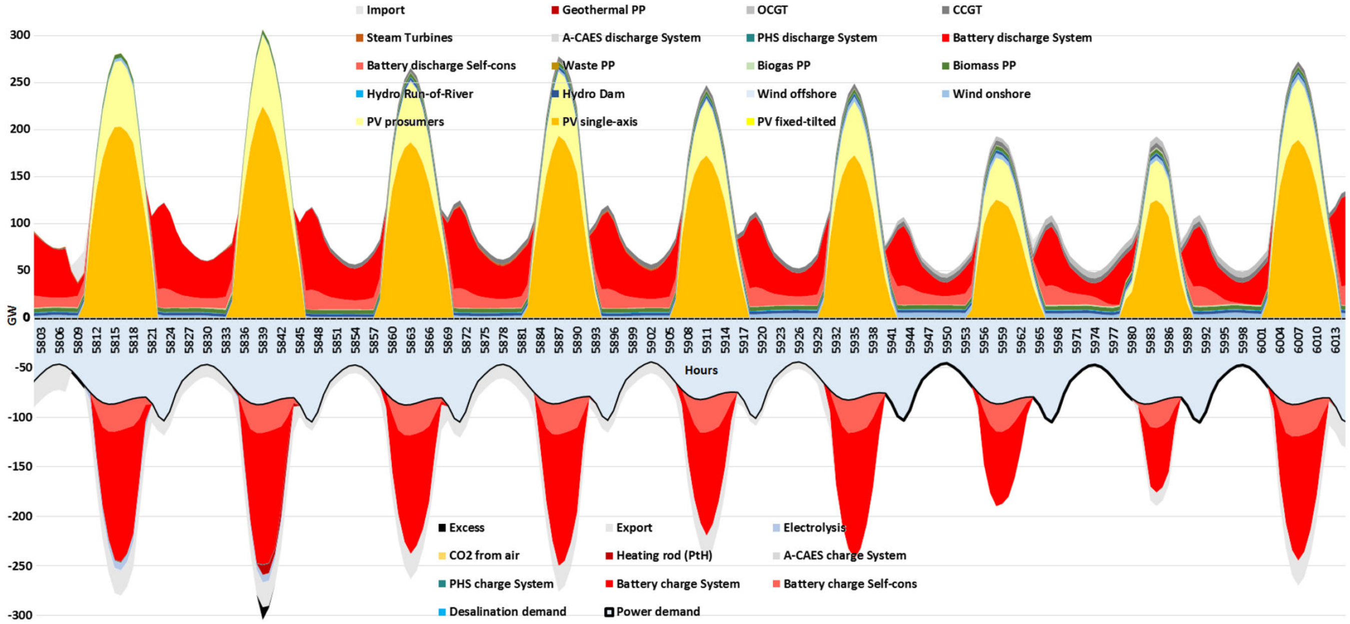


Fig. 6 *Dispatch for the region IN-S in a monsoon week in 2050*

Northeast region. For regional analysis, two regions are selected that have the following characteristics:

- A region where PV generation decreases the most and where wind generation is the highest in the monsoon period: IN-CW.
- A region where PV generation is least affected by the monsoon period: IN-S.

The dispatches of IN-CW and IN-S in a monsoon week can be observed from Figs. 5 and 6, respectively. It can be observed for the region Central West that the decrease in the solar PV output in the initial hours of the week is effectively complemented by an increase in electricity generation from wind. If solar is available, wind generation decreases as seen from the later hours of the week. As solar PV is the least-cost generation source, the system first utilises all the available energy from solar, and if wind is available in those hours it utilises wind, and the remaining energy is imported from neighbouring regions to satisfy the demand. Wind overcomes the decrease in solar PV output for the Central West region in the monsoon period.

For the region IN-S, which is least affected by the monsoon period, it is observed that the solar PV output is constant for all hours of the week with even export of excess electricity in these hours. Such regions help to balance the demand of the neighbouring regions with whom they are connected by transmission lines via electricity exports in the monsoon season.

Solar being the major energy source for India in 2050, curtailment is reduced in all the regions during the monsoon period with an overall decrease in solar generation in most parts of India. The highest curtailment is observed in the summer months as this is the peak duration for solar generation. From the onset of the monsoon season, curtailment decreases drastically in most of the regions and goes down to zero in almost all the regions, except IN-S. As seen earlier, this is the region that is least affected by monsoon and the decrease in solar PV generation is the lowest. In the monsoon months, increase in electricity generated by wind supports the system even when the electricity generated from solar PV decreases.

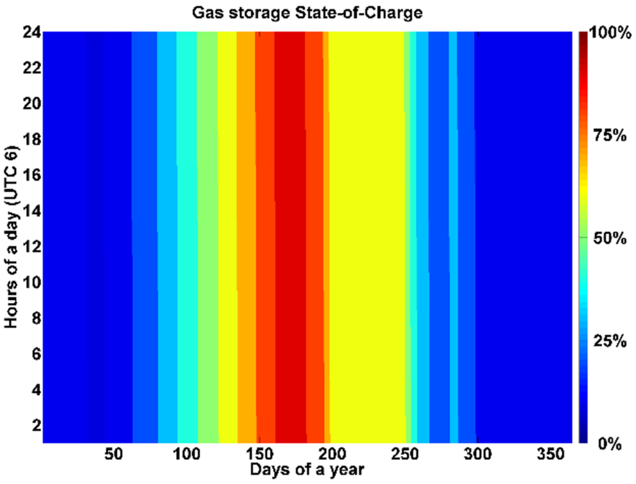
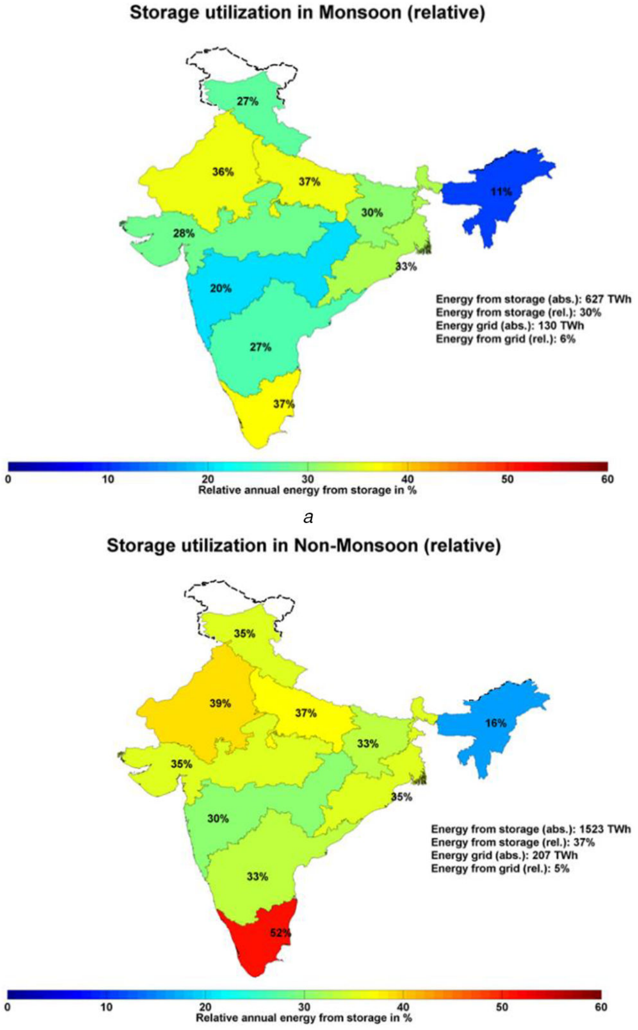


Fig. 7 *Hourly state-of-charge profile of gas storage for India in 2050, for the power scenario [19]*



b

Fig. 8 *Relative storage utilisation*

(a) Utilisation of storage technologies in the monsoon months for the power scenario in 2050 [19], ***(b)*** Utilisation of storage technologies in the non-monsoon months for the power scenario in 2050 [19]

5.2 Role of storage technologies

A fully RE 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 other storage technologies [19]. Gas storage, which is utilised as long-term storage, contributes 7% of the total storage output [19].

In the monsoon period, battery output is 85% of the total storage output in comparison with 92% in the non-monsoon period. The reduced solar resource availability contributes to less energy stored in the batteries since it is utilised as short-term storage that perfectly complements solar availability and discharge in the night-times.

One interesting observation, which was made, is the increase in output of stored gas to produce electricity via combined cycle gas turbines (CCGTs). An increase of almost 10% is observed in the gas output in the monsoon period. CCGT plants can be ramped up to provide electricity in the night-times and periods of low solar radiation. From Fig. 7, it can be observed that gas storage is fully charged before the start of the monsoon season and starts discharging to cover demand in the monsoon months and fully discharged until the monsoon is over. The relative utilisation of the storage technologies in the monsoon period was 30% in comparison with the non-monsoon period, where it was 37%. Figs. 8*a* and *b* give the relative storage utilisation in all the sub-regions of India. While in the monsoon season, the utilisation of storage technologies decreases, still, storage technologies play an important role in a 100% RE system in India, as found by Lawrenz *et al.* [26].

5.3 Role of transmission grids

In a fully RE system, there are a lot of import and export of electricity between the regions. Some regions act as net importers of electricity due to huge demands that cannot be satisfied by local generation, higher costs of primary generation and flexibility provided by different renewable power generation sources in other regions. Transmission grids are important as they help to balance the power demands in the different regions and decrease the need for storing electricity since it can be cost-effective to import electricity rather than storing it for later usage.

The net electricity is drawn from the grid to satisfy the respective demand increases in the monsoon period. In the monsoon period, the net electricity utilised from the grid was 6.2% in comparison with 4.9% in the non-monsoon period. The net imports and exports for all regions in India are 338 and 360 TWh, respectively. However, some regions are importing more than the others are, for example, IN-CW, IN-W and IN-CS are the largest importers of electricity. For these regions, the costs of primary generation are higher than the neighbouring regions with which they are connected and have high electricity demand. From Fig. 9, the imports and exports for all regions according to months of the year can be observed.

In the monsoon period, the net import and export are 130 and 137 TWh, respectively, representing about 38% of the total net electricity transfer. It can be seen that during the monsoon period, which represents only one-third of a year, there is a lot of transfer of electricity between the regions due to overall reduction in the major source of electricity generation for India, which is solar.

5.3.1 Analysis on a regional level: From Fig. 9, it is seen that the imports and exports increase in some regions during the months of the monsoon. The region of IN-W has its peak imports in June and overall higher imports in the monsoon months than the non-monsoon months. As this region is one of the most affected by the monsoon with a decrease in solar PV output of 19%. This region has good potential for wind energy generation. However, the increase in wind output is not enough to satisfy the total electricity demand in the region. Therefore, importing electricity from neighbouring regions benefits the IN-W region and decreases overall cost of the system.

The region of IN-S is a net exporting region, and it can be seen with the increase of exports in the monsoon period. This region is blessed with good solar as well as wind resources. As this region is not affected by the monsoon and the decrease in solar PV output is one of the lowest in the country. The wind output is increased considerably so that the excess electricity is exported to IN-CS. The energy flow in one of the transmission lines is shown in Fig. 10. The India-Eastern (IN-E) region imports electricity mainly from the Central-East (IN-CE) region.

The positive numbers indicate imports and negative exports of electricity in the transmission lines. 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. This is also observed in Fig. 9 (imports). In the region IN-E, over 90% of the power generated is by solar, and this region does not have good wind resource. Therefore, the exported electricity is used directly to satisfy the daytime 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.

To satisfy its demand, the IN-E region has to import electricity from IN-CE. This example shows how the system balances itself due to transmission grids in the monsoon months. The grid utilisation of the region IN-W increases in the monsoon period. This region has solar PV as the major power generation source and complemented by wind power, as this region is situated in one of the best wind sites in India having good wind potential all year round. However, in the monsoon months, the demand cannot be fulfilled by the available renewable resources due to the decrease in solar resource availability. Therefore, this region imports electricity from the IN-CW region, where wind energy is available, which can be seen from Fig. 11. From 4000 to 6500 h, the IN-W region imports wind energy from IN-CW to satisfy its power demand in the monsoon period.

The regions that are least affected by the monsoon and with a slight decrease in solar PV electricity production support the other regions that are strongly affected, through transmitting electricity via interconnected grids. A perfect example of this is the regions of IN-NW and IN-W, as shown in Fig. 12. The region IN-NW is least affected by the monsoon, as major parts of the area consist of the desert, where the solar conditions are almost constant all year round with a slight decrease during the monsoon period. In comparison, IN-W is most affected by the monsoon with electricity from solar PV decreasing by almost 19% in comparison with the non-monsoon period. The region IN-W imports electricity generated by solar PV directly daily from IN-NW and more so in the monsoon period with the absolute value of imports increasing (see Fig. 12). The same can be observed for the region IN-S, which is least affected by the monsoon and is one of the largest exporters of electricity. The export of solar PV-generated electricity to IN-CS is daily in the noon and afternoon hours. For the regions, IN-NW and IN-S batteries are charged daily in the daytime and discharged to satisfy the local demand or sometimes transmitting electricity via grids to the other regions.

The regions of IN-NW and IN-S are the top two exporters of electricity amongst the ten regions. In the monsoon period, these two regions combined export about 43% of the total electricity in 2050. The exported electricity is mainly solar PV generated, as it is the cheapest source for electricity and is abundantly available. To minimise the overall cost of the system, it is more cost-effective to export electricity from PV 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 utilising batteries to export power even during the night-times to other regions for balancing the load in the monsoon period in a cost-effective way.

The net energy transfer between the ten regions for a fully RE system in 2050 is 678 TWh. For the monsoon period, the net energy transfer is 250 TWh and for the non-monsoon period it is 428 TWh. Fig. 13 gives an overview of the imports and exports between the different regions in the monsoon and non-monsoon periods. In Fig. 13, the thickness of the flow indicates the amount of electricity exchanged between the regions in TWh. The exporter region ribbons and the flows have the same colour. For example, the blue ribbon of IN-S, an exporting region, extends a blue flow of export to IN-CS, a net importing region. Interesting observations can be made from Fig. 13 in terms of major importing and exporting regions. IN-NW is a major exporting region in the monsoon period with exports to the regions of IN-W and IN-UP.

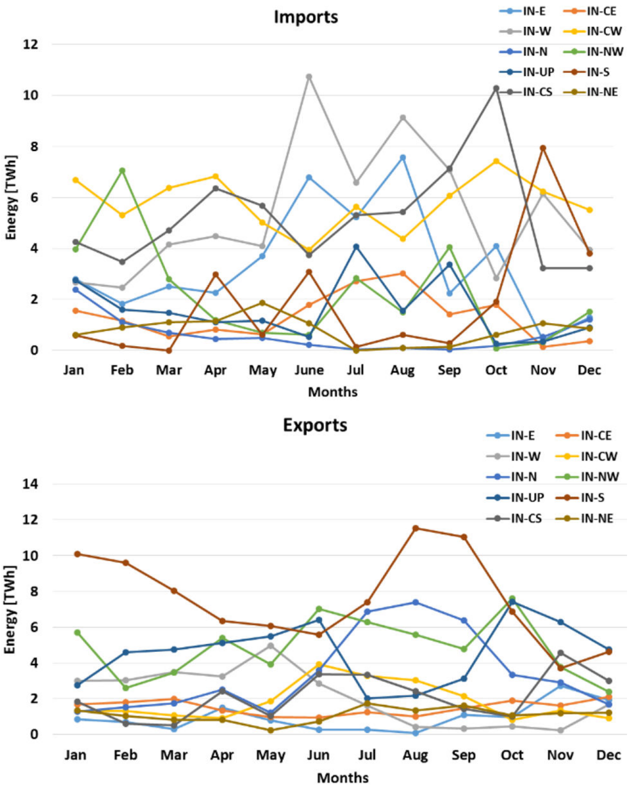


Fig. 9 *Imports (top) and exports (bottom) for the ten regions in India on a monthly scale in 2050*

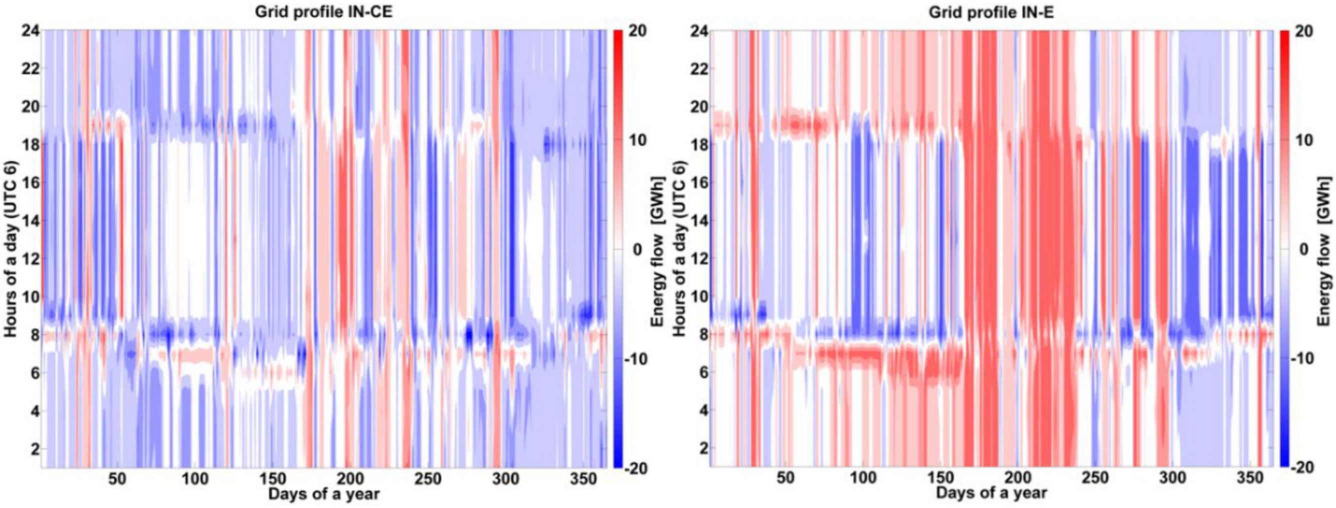


Fig. 10 *Grid profiles for the power scenario in 2050 for IN-CE (left) and IN-E (right). Import (+) and export (−)*

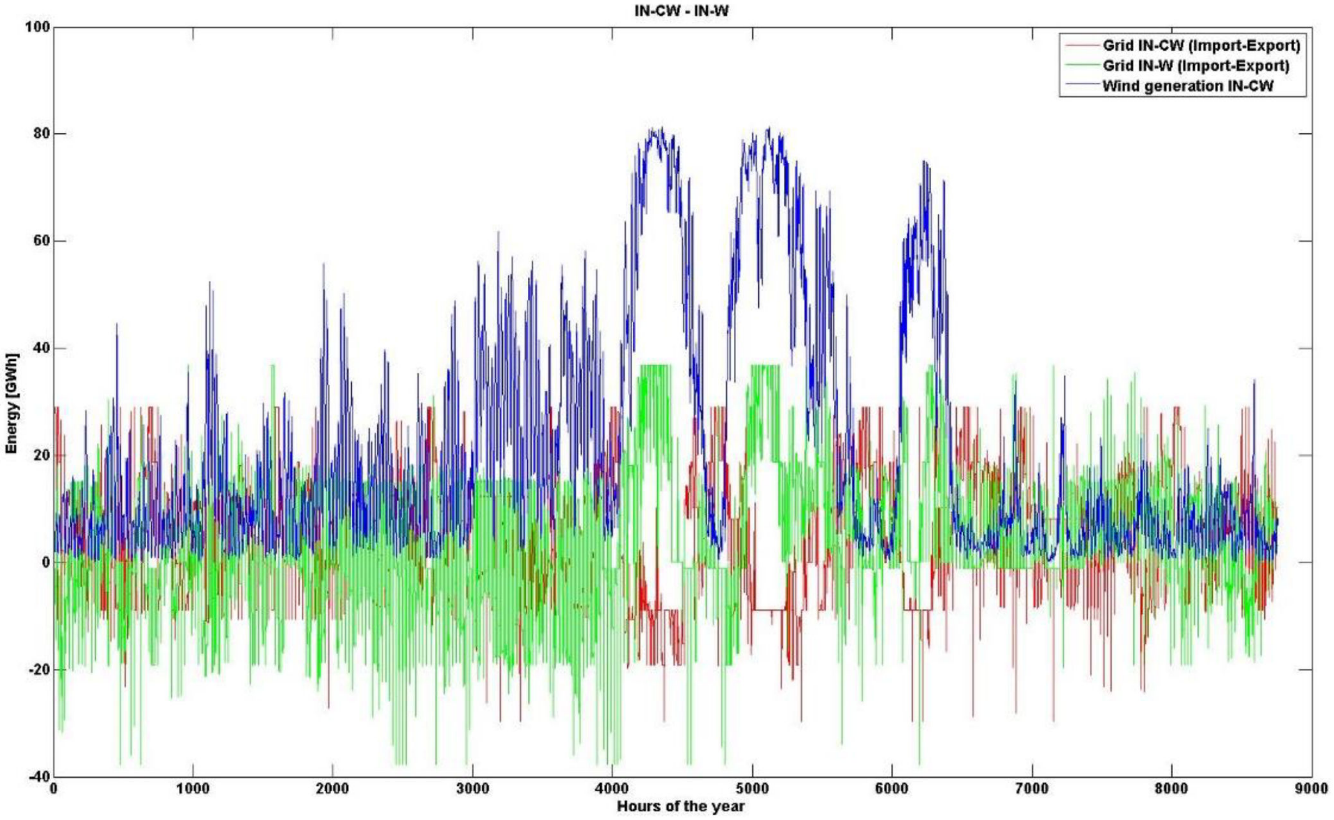


Fig. 11 *Grid energy flows and wind energy generation on an hourly basis for the power scenario in 2050. The blue line is wind energy generation in the IN-CW region. The red and green lines are the annual import and export by IN-CW and IN-W, respectively*

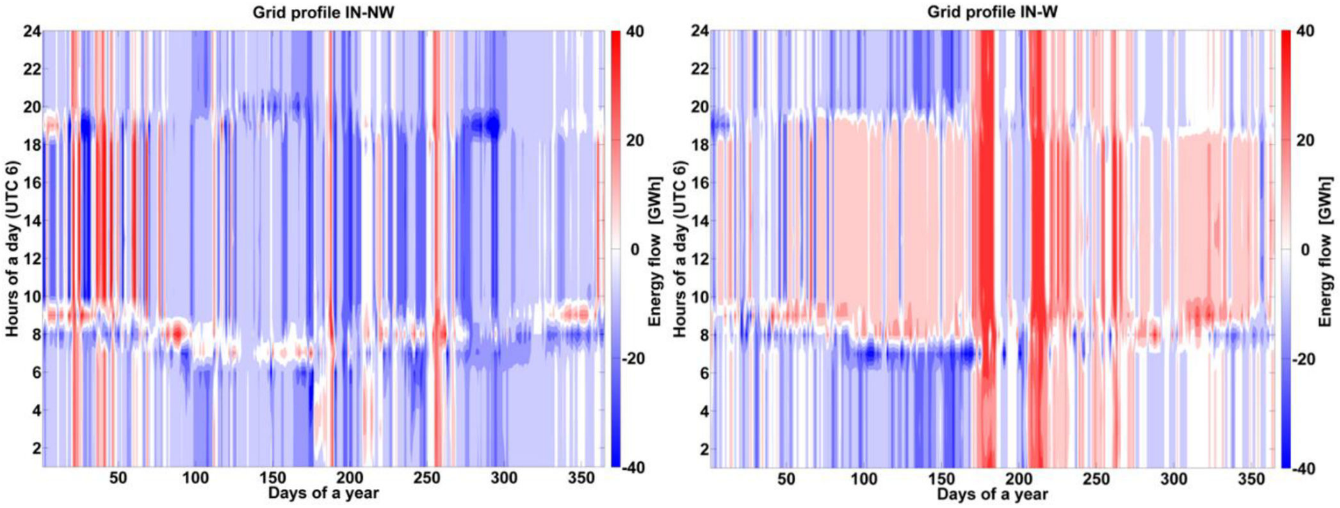


Fig. 12 *Grid profiles for the power scenario in 2050 for IN-NW (left) and IN-W (right). Import (+) and export (−)*

As the effects of the monsoon on this region are the lowest in terms of solar power production, this region exports electricity to the regions impacted most by the monsoon. In the monsoon period, IN-W is a major importing region, importing from IN-CW and IN-NW. However, in the non-monsoon period, IN-W exports electricity to IN-CW, while importing from IN-NW.

6 Conclusion

A fully renewable electricity system for India is possible in 2050 in an hourly resolution. Besides, the proposed system can effectively handle the decreased solar power generation during the monsoon season by effectively utilising transmission grids and increased wind power availability.

The reduced power generation from solar PV in the monsoon period can be effectively complemented by an increase in power generation from wind, in some regions. Total power generation from wind in the monsoon period is 62% of the total wind power generated in India. The region of IN-CW, where the wind generation increases considerably in comparison with the other regions, satisfies its demand and exports excess wind energy.

The interconnection of regions via transmission grids helps to balance the power demand in regions that are most cost-effectively affected by the monsoon. Total imports to satisfy the demand in the monsoon period increases by 1.3% in comparison with the non-monsoon period. It is observed that in the monsoon period, which represents only one-third of a year, the net electricity transfer happening in the grids is 38% of the annual net electricity transfer. The energy flow between the regions of IN-E and IN-CE clearly shows an increase in imports during the monsoon period by IN-E, due to the decrease in its solar energy production. The decrease in solar PV availability in the region IN-W is compensated by increasing its imports from IN-CW and IN-NW. The electricity

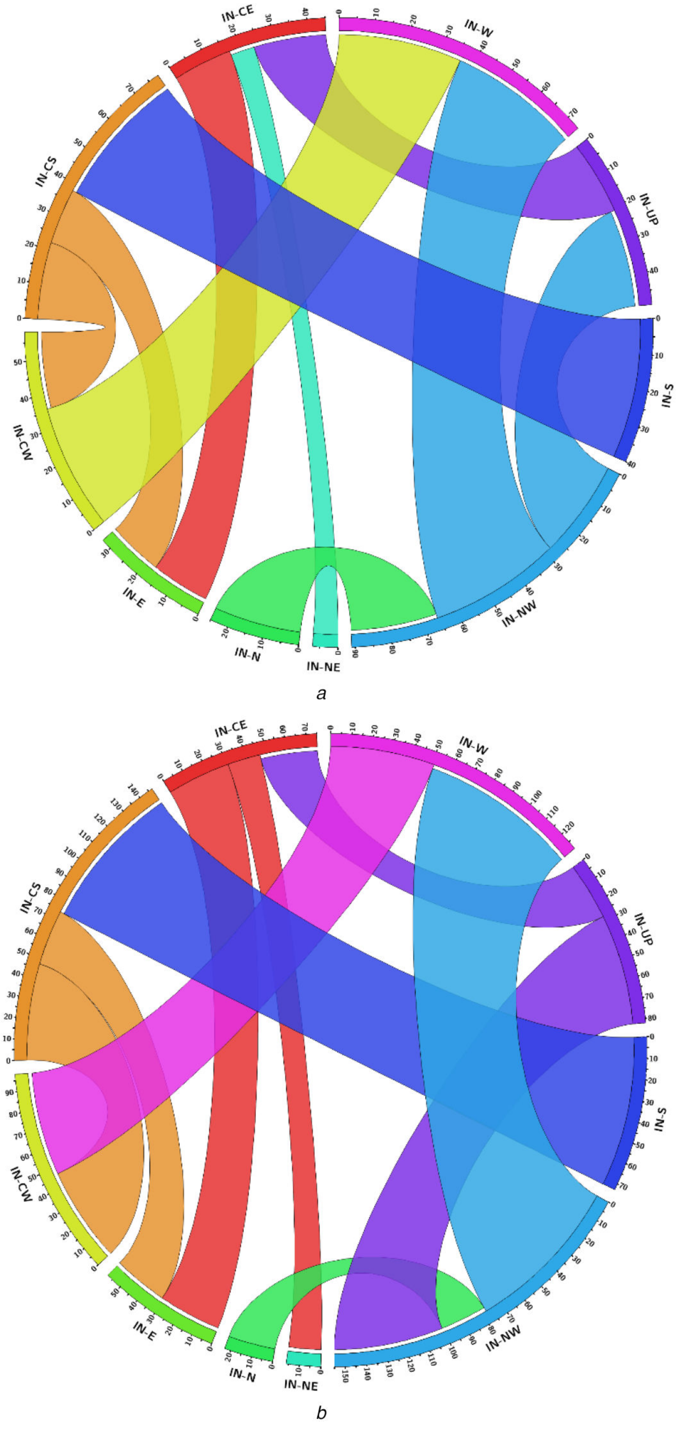


Fig. 13 *Electricity exchange for the monsoon period (top) and non-monsoon period (bottom) among the ten regions in 2050 for the power scenario. The thickness of the flow indicates the amount of electricity exchange denoted as TWh*

exported from IN-CW mainly being wind and solar and from IN-NW.

These results prove that RE options are the most competitive and least-cost solution for achieving a zero GHG emission-based electricity system, even in the monsoon season without utilising balancing power based on fossil fuels.

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