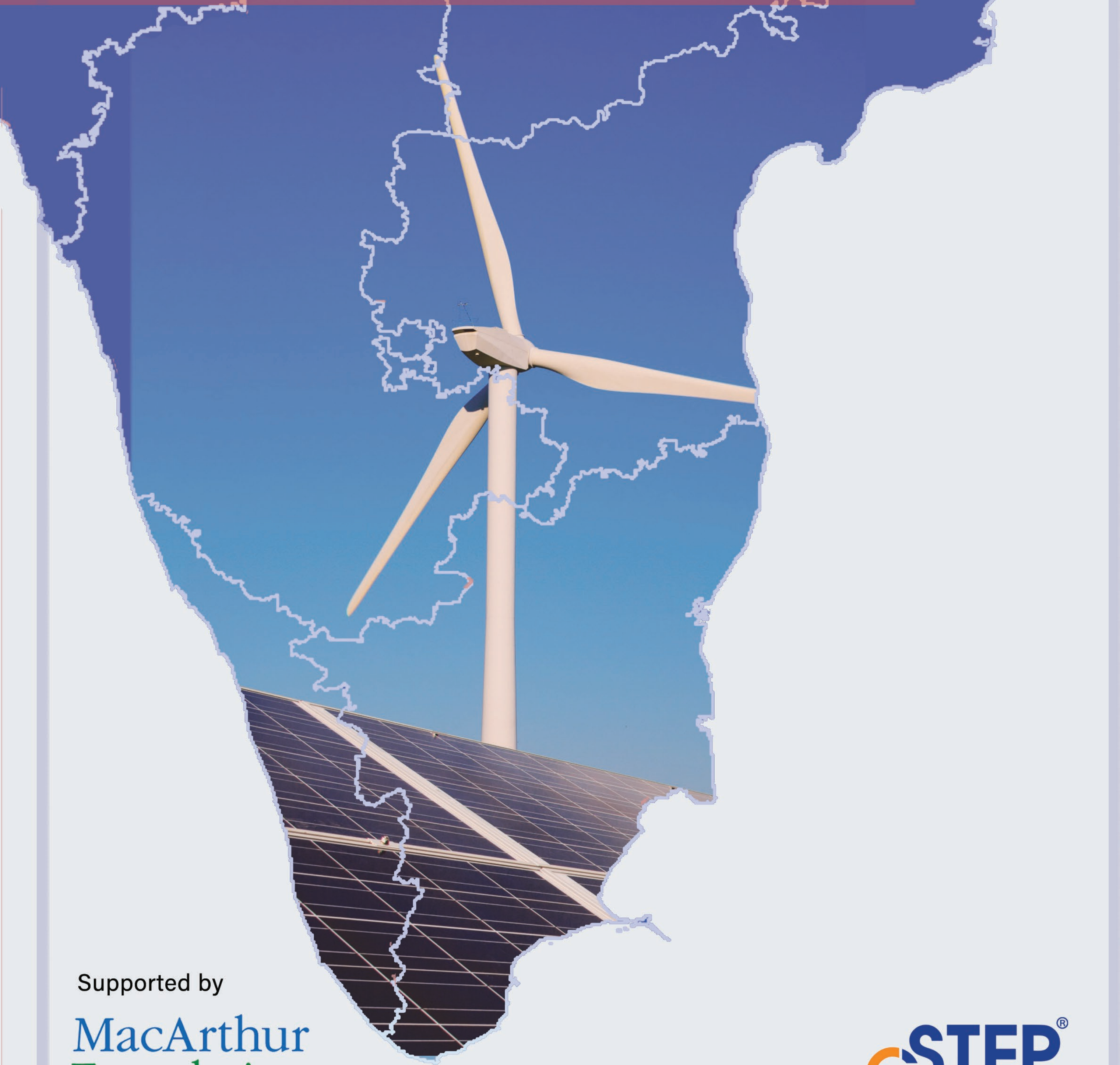
# Grid Impact for High RE Scenarios in Southern India



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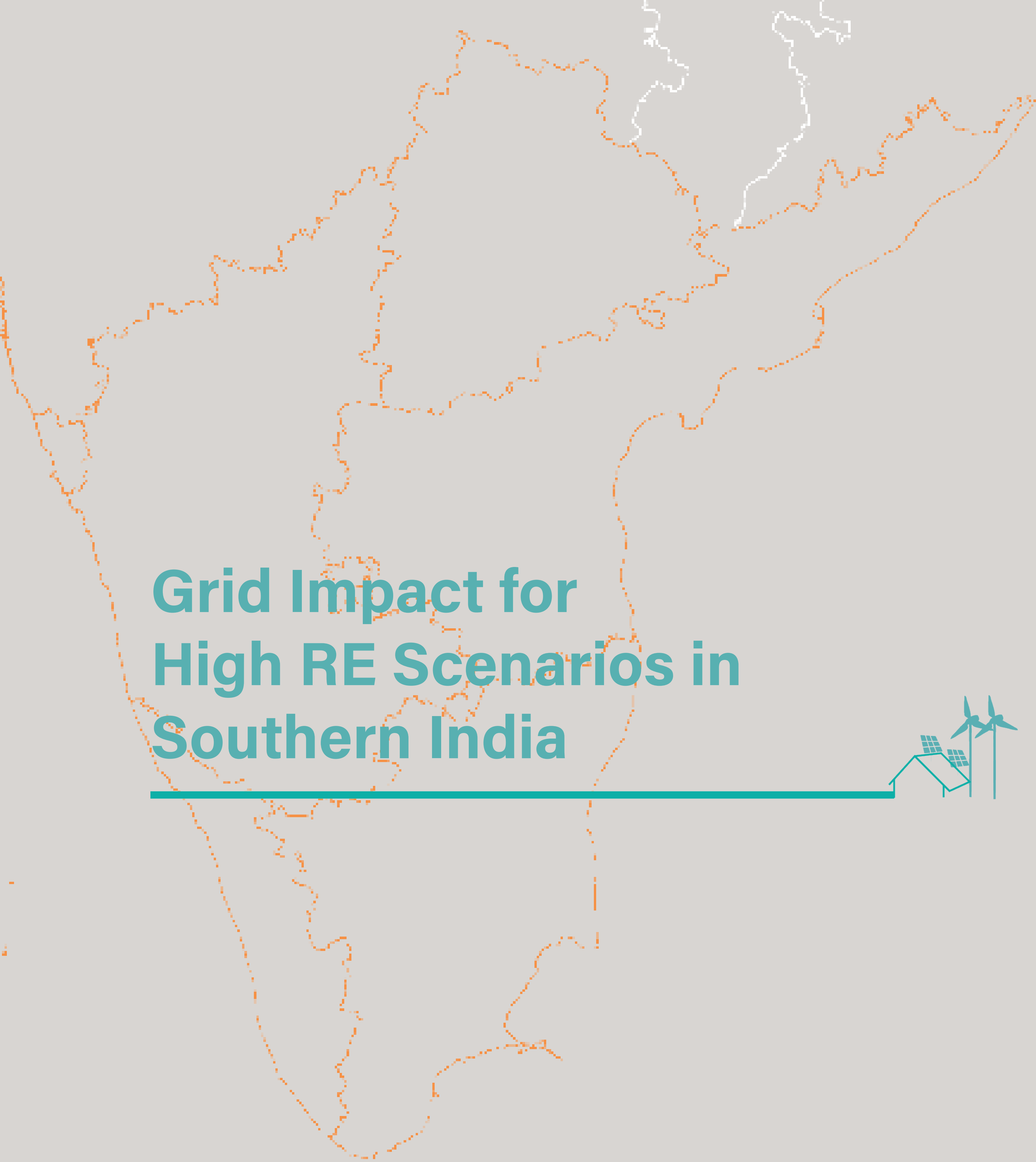

# Grid Impact for High RE Scenarios in Southern India

CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Center for Study of Science, Technology and Policy (CSTEP)
January 2021

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Designed and Edited by CSTEP





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*(The author list provided assumes no particular order as every individual contributed to the successful execution of the project.)*

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# ORGANISATIONS

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# ACKNOWLEDGEMENTS

This study by CSTEP—first of its kind in the public domain—has paved the way for a meaningful discourse on increasing the share of renewable sources in the electrical grid. We are grateful to the MacArthur Foundation for supporting this large and detailed analysis of the Indian grid infrastructure.

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Our study is based heavily on geographic information system (GIS) models, and our resident GIS analyst Mr Pareexit Chauhan was instrumental in building these models. Our colleagues Mr Harshid Sridhar, Ms Vaishalee Dash, Mr Suresh N S, Ms Roshna Nazar, and Mr Manish Yadav contributed to the development of several energy models. Mr Mallik EV, Mr Hanumanth Raju, and Mr Adithya Prasad helped us with data inputs for the study. Finally, Ms Rishu Garg advised and pitched in at critical junctures throughout the project. We thank them all for their valuable inputs for the modelling. We also acknowledge the contribution of Mr Ranganathan P and Ms Shyanjali Kantumuchu of the software development team at CSTEP. And crucially, we thank Ms Merlin Francis and Ms Udita Palit, our editing and graphics experts, who played an instrumental role in crafting and refining this report.

# HIGHLIGHTS

- The Southern Region has enough RE potential to meet the projected load by 2030.

- Sites with the potential of installing around 329 GW of solar and 188 GW of wind capacity were identified in SR states, which are distributed over an area of 6,654 sq. km and 39,405 sq.km, respectively.

- We propose network strengthening for the 2022 model, which includes measures to relieve overloaded elements, as observed during our simulations. These network strengthening measures would incur an investment of around INR 385 crores.

- Capacity addition of only about 52.6 GW of RE (solar - 34.4 GW and wind - 18.2 GW) is required to meet the projected energy demand of the SR for the year 2030. However, our study indicates that such an addition would threaten both the technical and commercial viability of conventional generators (violating technical minima and causing low plant load factors).

- To cater to the grid demand for 2030, we propose network strengthening measures (beyond the 2022 network upgrades given above), which would require an investment of INR 8,860 crores.

- Studies for both 2022 and 2030 show that SR acts as a net exporter in all scenarios except the peak-load scenario. To evacuate the proposed additional RE generation from the SR (total capacity of renewables being 109 GW), the inter-regional transmission infrastructure requires significant upgrades (to transfer power of the order of 50 GW to other regions, assuming that there is capacity and demand to absorb this power).

- We also conducted an analysis assuming 75% plant load factor for thermal plants, in which the calculated RE capacity required for 2030 is reduced to 13.9 GW.

# EXECUTIVE SUMMARY

The Southern Region (SR) leads renewable energy (RE) deployment in India, having an installed capacity of about 34 GW as of March 2018. Recognising the immense RE potential of this region, the Ministry of New and Renewable Energy (MNRE), Government of India, has set an ambitious RE target of 59 GW for SR by 2022. However, the implications of injecting this additional power into the grid have to be understood. Because of the intermittent nature of renewables-based power, grid integration of RE has distinct technical implications. Thus, detailed transmission planning and flexible operation of generation sources are needed to ensure reliable power supply.

To address this, the Center for Study of Science, Technology and Policy (CSTEP) conducted a multistep RE planning study, involving a comprehensive examination of the power-transfer capacity of the existing and upcoming transmission network. Our objective was to evaluate the implications of integrating large amounts of renewables-based power into the grid. The first step was to identify the current and potential RE zones (solar and wind only) in different southern states, considering resource availability and factors such as proximity to the grid infrastructure. This was followed by generating solar and wind profiles for both existing and potential solar and wind farms.

The core element of this study was to conduct system power flow studies considering the injection of large amounts of RE into the transmission grid. In the study, we looked at eight scenarios for two horizon years 2022 and 2030. We also assessed the impact of pumped storage for managing RE availability. Considering that RE-rich states may not always have the capacity to absorb the electricity generated, we also evaluated the feasibility of exporting power to other regions.

Our study found that with minimal network upgrades, renewable energy available in 2022 (in accordance with MNRE's targets) can be absorbed by the grid. However, during the monsoon season, the southern region is expected to generate excess energy. While there is a potential for exporting this energy to other regions in India, inter-regional transmission corridors need to be strengthened first.

For 2030, we have proposed an addition of renewable capacity (only) required to meet the demand projected by CEA. Our study found that with this additional capacity, the southern region can meet the projected demand without any new conventional generation. We found that the southern regional transmission network can handle this additional generation with an investment of INR 8,860 cr to upgrade network infrastructure. Similar to 2022, the southern region can act as an exporter to other regions in India, provided inter-regional transmission corridors are suitably upgraded.

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# ABBREVIATIONS

| | |
|---|---|
| APTRANSCO | Transmission Corporation of Andhra Pradesh Limited |
| CEA | Central Electricity Authority |
| CECL | Consolidated Energy Consultants Limited |
| CERC | Central Electricity Regulatory Commission |
| Ckm | Circuit Kilometre |
| CPI | Climate Policy Initiative |
| CSTEM | CSTEP's Solar Techno-Economic Model |
| CSTEP | Center for Study of Science, Technology and Policy |
| CTU | Central Transmission Utility |
| DC | Double Circuit |
| EPS | Electric Power Survey |
| ER | Eastern Region |
| ETAP | Electrical Transient and Analysis Program |
| FOR | Forum of Regulators |
| GHI | Global Horizontal Irradiance |
| GIS | Geographic Information System |
| GoI | Government of India |
| GPS | Global Positioning System |
| GW | Gigawatt |
| HAWT | Horizontal Axis Wind Turbine |
| HVDC | High Voltage Direct Current |
| KPTCL | Karnataka Power Transmission Corporation Limited |
| KSEB | Kerala State Electricity Board |
| MNRE | Ministry of New and Renewable Energy |
| MoP | Ministry of Power |

# ABBREVIATIONS

| | |
|---|---|
| MVA | Mega Volt-Ampere |
| MW | Megawatt |
| NEP | National Electricity Plan |
| NITI | National Institution for Transforming India |
| NREL | National Renewable Energy Laboratory |
| PGCIL | Power Grid Corporation of India Limited |
| PLF | Plant Load Factor |
| PoC | Point of Connection |
| POSOCO | Power System Operation Corporation |
| PSLF | Positive Sequence Load Flow |
| PV | Photovoltaic |
| RE | Renewable Energy |
| RPO | Renewable Purchase Obligation |
| SAM | System Advisor Model |
| SC | Single Circuit |
| SCADA | Supervisory Control and Data Acquisition |
| SR | Southern Region |
| SRLDC | Southern Region Load Despatch Center |
| SRPC | Southern Region Power Committee |
| SS | Substation |
| SUNY | State University of New York |
| TSTRANSCO | Transmission Corporation of Telangana Limited |
| TANTRANSCO | Tamil Nadu Transmission Corporation Limited |
| WR | Western Region |

# 01 | Introduction

India has an ambitious renewable energy (RE) target of 175 GW (solar 100 GW, wind 60 GW, biomass 10 GW, and small hydro 5 GW). In recent years, the cost of RE (especially solar) has rapidly declined and has almost achieved grid parity. RE contributes to 20% of the generation capacity mix in India, as of March 2018 (Central Electricity Authority, 2018a). The proportion of non-fossil generation capacity (of which RE is a subset) is expected to rise from 33% in 2018 to 40% by 2030 (GoI, 2015). However, India's RE potential is much higher, with wind being 300 GW (National Institute of Wind Energy, 2015), and solar being 748 GW (MNRE, 2014). Therefore, there is an immense scope to scale up RE generation at the national level. Moreover, the rapidly declining RE cost provides a great opportunity for India to go beyond 175 GW and have RE as the primary source of electricity.

Typically, RE resources are more geographically dispersed than fuels used for conventional generation. In India, only seven out of 29 states generate RE. Currently, the Southern Region (SR) stands first in the installed capacity of renewables in India. While scaling up RE deployment is a must for reducing India's carbon emissions, large-scale integration has significant technical implications on the grid.

A key factor expected to cause such issues is the 'must-run' status granted to RE generators. This status is a policy mandate to grid operators, forbidding them from curtailing power from RE plants. In the face of sharp increases in RE integration, this mandate adversely affects the operations and economics of thermal power plants. As an illustrative example, some thermal generators are being forced to keep idle round-the-clock by grid operators due to over-injection of RE. The technical (and the resulting financial) effects due to rapid growth in RE would be important factors, ultimately determining the extent of RE integration into the grid.

In this context, the Center for Study of Science, Technology and Policy (CSTEP) conducted this study to examine from a technical perspective the pertinent question: ***Can RE become India's mainstream electricity source by going beyond 175 GW?***

In this study, we have tried to answer this question by focusing on the RE-rich Southern Region, by first assessing the feasibility of current RE targets. The study also evaluates longer-term scenarios of high RE-penetration levels. We have analysed the investments required for a robust grid infrastructure, capable of enabling RE as the mainstream electricity source. Energy storage is crucial for absorbing high RE injections and we have looked at the contribution from upcoming storage projects as well.

Our aim is to inform policy decisions and planning, through this study. We hope that this study emboldens India to embark on a high-RE trajectory and paves the way for a future where RE is India's mainstream energy source.

Table 1: CSTEP's reassessment of solar and wind potential (GW)

<table>
<tr><th>State</th><th>Solar</th><th>Wind</th></tr>
<tr><td>Karnataka</td><td>915</td><td>534</td></tr>
<tr><td>Tamil Nadu</td><td>380</td><td>201</td></tr>
<tr><td>Telengana</td><td rowspan="2">220</td><td>87</td></tr>
<tr><td>Andhra Pradesh</td><td>283</td></tr>
<tr><td>Kerala</td><td>9</td><td>18</td></tr>
<tr><td>Puducherry</td><td>2</td><td>1</td></tr>
</table>

Table 2: 2017-18 SR states' peak demand and energy consumed

| State | Peak Demand (MW) | Energy Consumed (MU) |
|---|---|---|
| Andhra Pradesh | 8,983 | 58,290 |
| Telangana | 10,284 | 60,237 |
| Karnataka | 10,802 | 67,702 |
| Kerala | 3,870 | 24,916 |
| Tamil Nadu | 14,975 | 1,05,839 |
| Puducherry | 387 | 2662 |

# 02 | Southern Region Profile

The major states in southern India—Karnataka, Andhra Pradesh, Telangana, and Tamil Nadu—all have high solar or wind energy potential.  The Southern Region grid is characterised by high renewable penetration and several major load centres. The five southern states are also home to a significant proportion (roughly 20%, or around 27 crore) of India's population (UIDAI, 2018).

## 2.1 RE Potential

Both solar and wind energy are abundant in the SR, especially relative to the northern, eastern, and north-eastern regions. As per a 2016 CSTEP study, the four southern states (Karnataka, Kerala, Tamil Nadu & united Andhra Pradesh) have 1,526 GW of solar potential and 1,124 GW of wind potential (CSTEP, WFMS, SSEF, 2016). State-wise solar and wind potential is provided in Table 1 (facing page).

## 2.2 Status of RE Deployment

As of December 2018, Tamil Nadu has the highest wind power installed capacity of 8,631 MW, while its solar power generation capacity stands at 2,228 MW. Karnataka has the highest overall renewable capacity (including biomass, co-generation, and small hydro) of 12.8 GW, with wind and solar contributing to 4,683 MW and 5,255 MW, respectively (Press Information Bureau, Government of India, 2019). Andhra Pradesh also has appreciable wind (4,076 MW) and solar (2,642 MW) generation capacity. Telangana has very high solar capacity (3,410 MW) but almost negligible wind capacity (128 MW). Kerala has comparatively low deployment of RE (138 MW solar and 52 MW wind), primarily because of limited resource potential—there is insufficient area with adequately high energy resource (solar radiation and wind speed). Puducherry has very little solar (1.73 MW) generation capacity. A geospatial distribution representation of the existing and planned RE capacity up till 2022 is shown below in Figure 1 (pg 4).

## 2.3 Power and Energy Demand

The SR had a peak load of around 47 GW in the year 2017-18, which occurred in the month of March. The peak demand and energy consumed in each state in the year 2017-18 is provided in Table 2 (facing page).

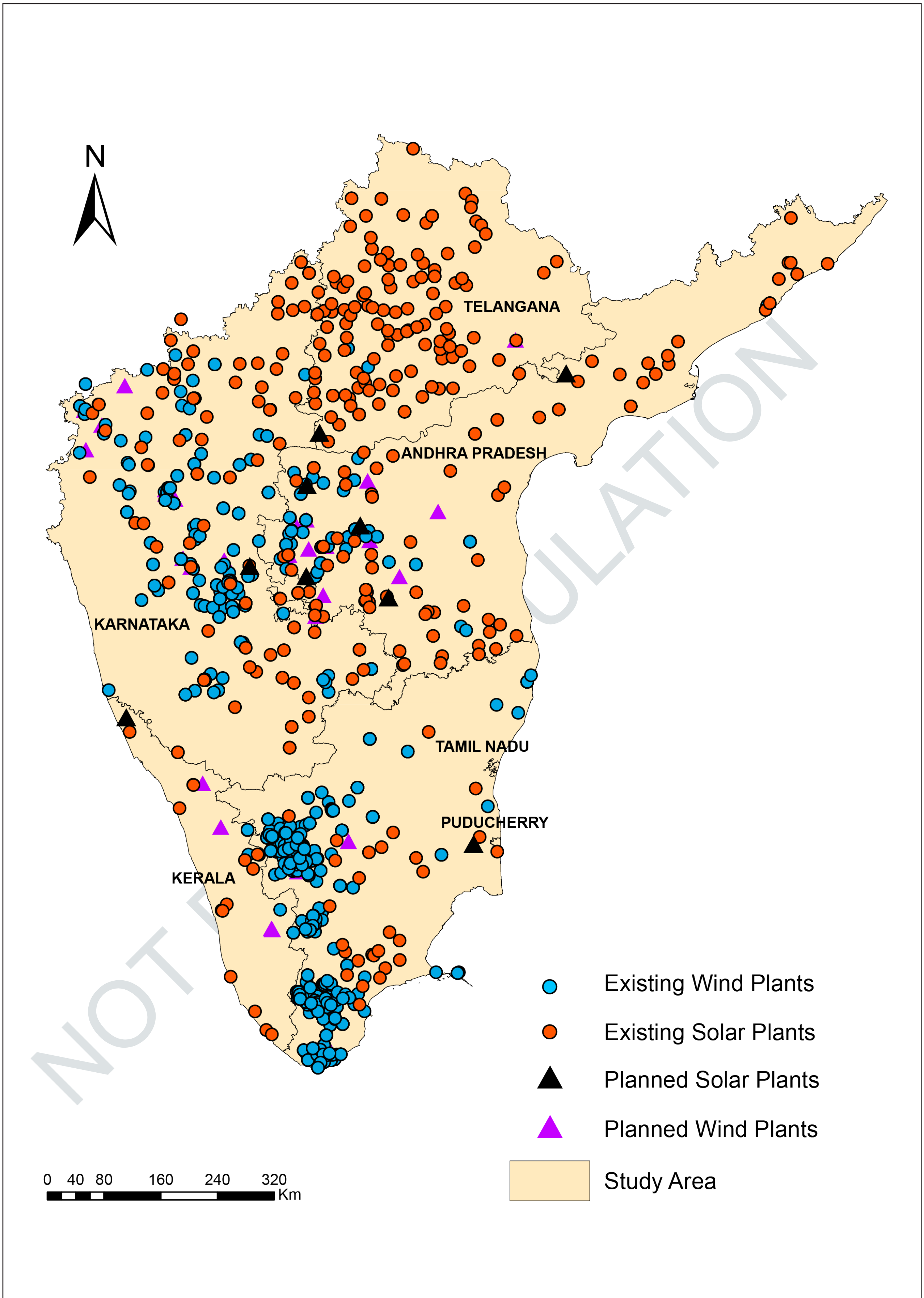



Figure 1: Existing and planned RE plants

## 2.4 Generation Mix

This section highlights the existing installed capacity of renewables and transmission infrastructure of the SR. Renewable generation (solar, wind, small hydro, and bio power) forms around 36% of the installed capacity mix of the SR. State-wise generation installed capacity (MW) in the SR is given in Table 3 (below).

Table 3: Generation installed capacity (MW) – SR as on 31 Dec, 2018

| No. | Mode of Generation | State/Union Territory | | | | | | Total Southern Region |
|---|---|---|---|---|---|---|---|---|
| | | Andhra Pradesh | Telangana | Karnataka | Kerala | Tamil Nadu | Pudu-cherry | |
| 1 | Thermal | 14,644 | 9,510 | 9,961 | 2,452 | 14,886 | 281 | 51,733 |
| 2 | Nuclear | 127 | 149 | 698 | 362 | 1,448 | 86 | 2,870 |
| 3 | Hydro | 1,674 | 2480 | 3,587 | 1,857 | 2,178 | 0 | 11,775 |
| 4 | Solar | 2,642 | 3410 | 5,255 | 138 | 2,228 | 2 | 13,676 |
| 5 | Wind | 4,076 | 128 | 4,683 | 53 | 8,631 | 0 | 17,571 |
| 6 | Small Hydro | 162 | 91 | 1,231 | 222 | 123 | 0 | 1,829 |
| 7 | Bio Power | 500 | 178 | 1,800 | 1 | 1,004 | 0 | 3,482 |
| **Total** | | 23,825 | 15,945 | 27,214 | 5,084 | 30,449 | 369 | 1,02,936 |

Source: (Central Electricity Authority, 2018b) , (Press Information Bureau, Government of India, 2019)

Several aspects are notable in this table. Thermal generation forms exactly half of the entire region's installed capacity. The table clearly shows that thermal generation is the major contributor to the power supply mix of Andhra Pradesh, Telangana, and Puducherry. Hydro generation is a major power source in Kerala, contributing to around 37% of the capacity mix. Tamil Nadu has the highest wind generation capacity (8.6 GW), forming around 28% of its capacity mix. The total installed capacity of renewables in Karnataka is around 48%, of which, solar generation and wind generation account for 19% and 17%, respectively. It is the only state where the wind generation deployment target given by MNRE has been achieved well before the target year of 2022.



## 2.5 Transmission Infrastructure

Transmission network is the backbone of any power system and enables transfer of bulk power from the generating stations to the load centres. Over the years, the transmission infrastructure in the SR has grown substantially with the addition of a large number of extra high voltage (EHV) substations and transmission lines.

Information on transmission lines and substations (at different voltage levels) in the southern region of both state transmission utilities (STU) and central transmission utilities (CTU) in circuit kilometre are given in Table 4 and Table 5 (page 6), respectively (as of March 2018). CTU substation and line details have been collected from Transmission elements - Southern region (May 2018) document.

Table 4: Transmission lines (STU & CTU) in SR

| State | STU lines (ckm) | CTU lines (ckm) | Source |
|---|---|---|---|
| Andhra Pradesh | 26,313 | | (Salient Features of A.P.Transco / A.P.Genco / Discoms, 2018) |
| Telangana | 21,568 | | ('Telangana State Transmission Company', n.d.) |
| Tamil Nadu | 33,526 | 38,794 | ('Tamil Nadu Transmission Network', n.d.) |
| Karnataka | 36,124 | | ('About Us', n.d.) |
| Kerala | 10,333 | | ('Transmission', n.d.) |

Table 5: Number of substations (STU & CTU) in SR

| State | Substation voltage level | | | | Source |
|---|---|---|---|---|---|
| | 765 kV | 400 kV | 230/220 kV | 132/110 kV | |
| Andhra Pradesh | 4 | 17 | 91 | 206 | (Salient Features of A.P.Transco / A.P.Genco / Discoms, 2018) |
| Telangana | 2 | 14 | 74 | 223 | ('Telangana State Transmission Company', n.d.) |
| Tamil Nadu | 6 | 32 | 100 | 857 | ('Tamil Nadu Transmission Network', n.d.) |
| Karnataka | 1 | 16 | 101 | 413 | ('About Us', n.d.) |
| Kerala | 0 | 11 | 22 | 151 | ('Transmission', n.d.) |

## 2.6 Transmission Losses

Over the years, power transmission losses in the SR states have been gradually decreasing because of improvements in technology and operations. The transmission loss of the Karnataka grid is the least and the Kerala state grid is the highest, according to the respective state tariff orders. The transmission loss for the SR states from FY '12 to FY '17 are tabulated in Figure 2 (below).

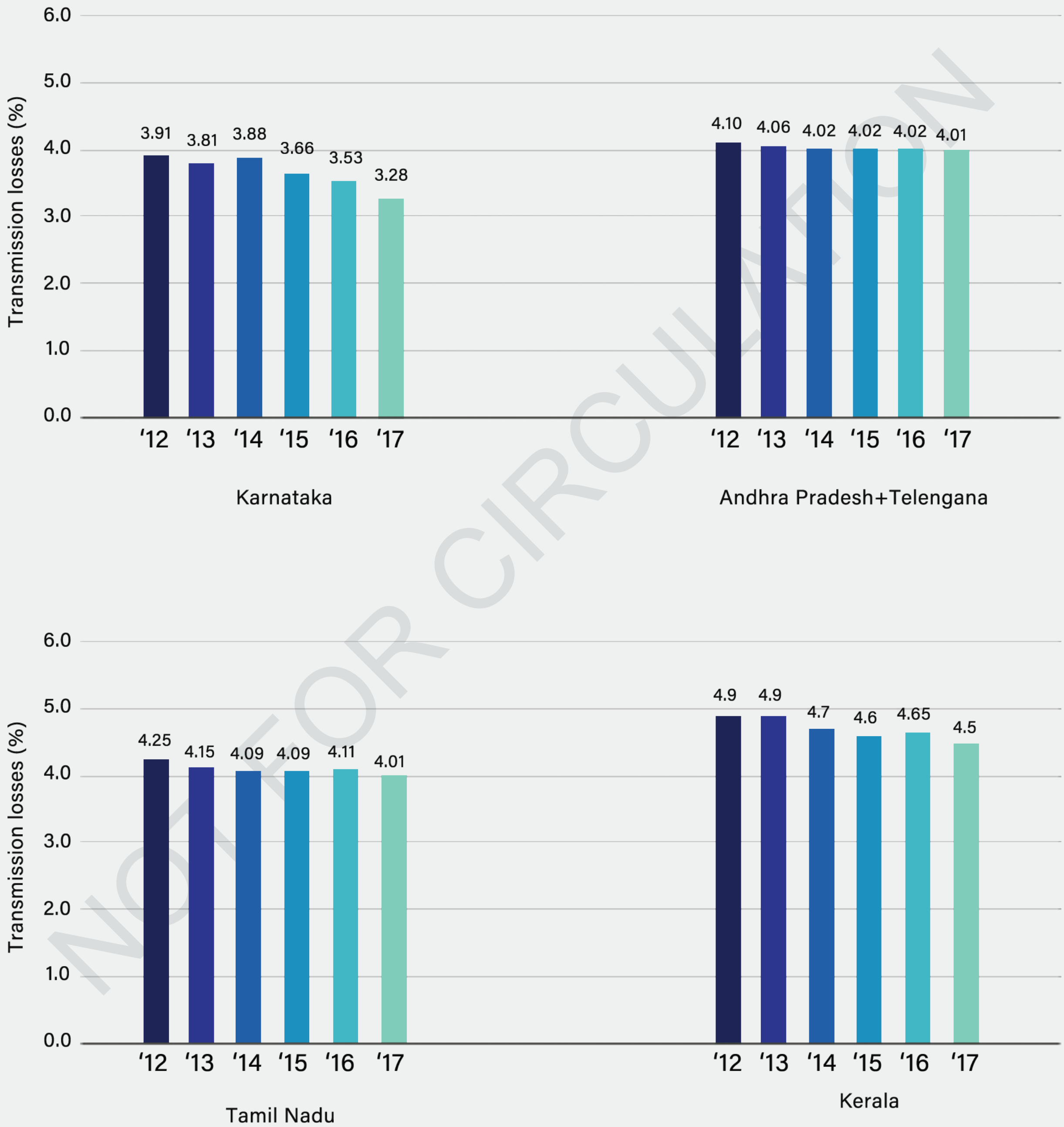





Figure 2: Transmission losses for Southern Region states

# 03 | Previous Power Sector Studies

Anticipating for the rise of RE in India, several studies were conducted in the early years to facilitate its growth. Several other studies were conducted, based on the experience of stakeholders directly involved in handling RE. This section summarises some of these previously conducted studies, which have similar areas of analysis. All studies point towards the need for supporting policies and suitable regulations for the seamless integration of RE, but have approached the problem with widely varying methodologies.

## 3.1 Greening the Grid (GtG)

**Title**: *Greening the grid: Pathways to Integrate 175 GW of Renewable Energy into India's Electric Grid*

**Organisation**: *National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (Berkeley Lab); in association with Power System Operation Corporation Limited (POSOCO)*

'Greening the Grid' was a broad programme co-led by India's Ministry of Power (MoP) and the U.S. Agency for International Development (USAID). The main objective of this programme was to analyse the operational challenges and cost-saving opportunities in integrating 175 GW RE into the Indian electric grid by 2021-22; it also assessed strategies to increase variable RE integration. In this exercise, a production-cost model was used to simulate optimal schedule and dispatch for the year 2022 by keeping the total production cost minimum, subject to operational and physical constraints (Palchak et al., 2017). A national model study was carried out to understand inter-regional power flows and the role of coal plants in terms of system balancing due to RE-generation intermittency. A regional model study was performed to understand the operational impacts in states with a strong potential for growth in RE capacity.

## 3.2 CEA Report on Locating RE & Storage (RESD)

**Title**: *Study of optimal location of various types of balancing energy sources/energy storage devices to facilitate grid integration of renewable energy sources and associated issues*

**Organisation**: *Technical Committee, Central Electricity Authority (CEA)*

The committee, constituted in January 2017, considered the impact of variability and the financial implications of this variability on RE-rich states. The final report (Central Electricity Authority, 2017b) of the committee concluded that balancing responsibility needs to be shared via a well-defined regulatory framework. The committee analysed minute-wise RE generation from Gujarat and Tamil Nadu, with regard to variability and consequent ramping requirements. The report also calculated charges for deviation from committed generation schedules by RE generators, caused by high RE variability. It concluded that, even after including financial implications on account of variable RE generation, electricity from RE sources is cheaper than fossil fuel–based electricity. The report recommends the adoption of ancillary services framework on permanent basis, with increasing RE generation. It also recommends policy & regulatory interventions required to deal with the increasing variable RE to the grid.

## 3.3 Green Energy Corridor (PGCIL-GEC)

**Title:** Green Energy Corridors - Transmission Plan for Envisaged Renewable Capacity

**Organisation:** Power Grid Corporation of India Limited (PGCIL)

Observing the increasing deployment of RE in the Indian grid, MNRE and the Forum of Regulators (FOR)/ Central Electricity Regulatory Commission (CERC) entrusted PGCIL to conduct studies to identify the transmission infrastructure and other control requirements for the RE capacity addition in the immediate future. This study (Powergrid Corporation of India, 2012) comprehensively looked at RE integration challenges in RE-rich states for the 12th Five-Year Plan (up to 2016-17). Based on the power flow simulation results for high-RE and high-demand scenarios, the study proposed transmission system upgrades at intra-state and inter-state levels to effectively transmit RE to load centres. The study recommended upgrades for transmission lines, transformers, and reactive compensation. In addition, the study also calculated investment costs and proposed suitable financing options.

## 3.4 NITI Aayog RE Roadmaps (NITI-RE)

**Title**: *Report on India's Renewable Electricity Roadmap for 2030; State RE Capacity Addition Roadmap*

**Organisation**: *National Institute for Transforming India (NITI) Aayog*

For this study, NITI Aayog consulted a wide variety of stakeholders for their suggestions on integrating RE into the Indian grid. The scope included legal, financial, commercial, and technical issues. One of the issues examined was grid integration of RE and efficient grid operation. The report (NITI Aayog, 2015) details the current process of grid planning and operations followed, involving entities like CEA, Central Transmission Utility (CTU), load dispatch centres, as well as developers, distribution companies, and traders. It also made recommendations for the upgradation of grid equipment, enlarging balancing areas, change in operational protocols, and encouraging flexibility in demand and supply. In 2017, NITI followed up with another report (NITI Aayog, 2017), putting together State Action Plans (SAPs) for select states to help achieve their 2022 RE targets.

## 3.5 GE Study on RE Modelling (GE-ProdSim)

**Title**: *Integrated RE modelling with power sector planning for India*

**Organisation**: *Shakti Sustainable Energy Foundation (SSEF); General Electric (GE) Energy Consultancy*

This production cost modelling exercise investigated the impact of RE generation on the overall generation and transmission. The report (Shakti Sustainable Energy Foundation, GE India Exports Pvt. Ltd., 2018) studied the cost of transmission bottlenecks on the total energy cost. The study also looked into the expected impact on reliability (region-wise) due to high RE influx. The study predicted a drop in total production cost accompanied by an increase in the cyclic operation of thermal plants, due to the growth of RE installation after 2015.

## 3.6 Prayas Update on 175 GW Target (PEG-175U)

**Title**: *175 GW Renewables by 2022: A September 2018 Update*

**Organisation**: *Prayas (Energy Group) (PEG)*

The report narrated the progress of RE deployment over the past one-two years, with respect to achieving MNRE's 175 GW target. The report [Prayas (Energy Group), 2018] elaborated on the rate of growth, challenges, and policy solutions. It identified transmission planning as a problem plaguing Tamil Nadu's wind power deployment. RPOs and their compliance are dealt with in detail. Applicable tariff rules and amendments, as well as their likely impacts, are also discussed. Progress on the use of solar power for agriculture has also been covered.

## 3.7 GIZ Green Energy Corridor Study (GIZ-GEC)

**Title**: *Green Energy Corridor*

**Organisation**: *Consortium led by Ernst & Young (E&Y)*

This was a comprehensive study funded by GIZ that looked at RE forecasting, grid balancing and market design for RE, and regulatory provisions to promote and integrate RE. The study (GIZ, 2016) highlighted the importance of RE forecasting, storage requirement, and renewable energy management centre, while sharing the international experience with regard to the integration of renewables. The study further highlighted the selection and placement of storage technologies and control (reactive) power with high RE integration to the grid.

## 3.8 National Electricity Plan (NEP)

**Title**: *National Electricity Plan*

**Organisation**: *Central Electricity Authority (CEA)*

The Electricity Act, 2003, charges the Central Electricity Authority (CEA) with the responsibility of releasing the National Electricity Plan, every five years, for planning purposes. For achieving the 175 GW target for 2022, the CEA conducted a study on transmission planning, on the integration of 102 GW of solar and 59 GW of wind at an all-India level. The main objective of this study (Central Electricity Authority, 2017a) was to check the adequacy of existing and under-construction transmission facilities and the requirements of additional transmission systems for the year 2021-22. The transmission system for 400 kV and above voltage level was analysed in this study. Region-wise and state-wise demand projections have been obtained from the 19th Electric Power Survey (EPS) report. The study also provided a brief update on the existing and planned cross-border transmission system with neighbouring countries.

## 3.9 CPI Study on Flexibility for RE (CPI-RE-Flex)

**Title**: *An assessment of India's Energy Choices: Managing India's Renewable Energy Integration through Flexibility*

**Organisation**: *Climate Policy Initiative (CPI)*

The study was part of a four-part series on India's energy choices, and looked at the requirement of flexibility in the grid for RE integration. Grid flexibility is essential to counter the variability and uncertainty of RE generators. The report (Vivek Sen, Saurabh Trivedi, & Gireesh Shrimali, 2018) identified low Plant Load Factors (PLFs) of Indian coal plants as an issue, which only gets worse in the presence of RE generation. Around 5% of the generation capacity would need to be flexible, according to the study. The report explored the technical and policy implications of using flexible coal plants to meet the RE integration–induced flexibility requirements for India.

Thus, there have been many studies examining the implications of growing RE generation and demand. The PGCIL-GEC was conducted in 2012-13, and did not include the latest RE targets by MNRE. NEP is a much more recent document, released in 2018. Both involved power flow studies but only at the 400 kV substation level. RESD focussed on optimally locating and siting storage facilities, given a few candidate sites.

GtG, GE-ProdSim, and CPI-RE-Flex were all production simulation studies, which considered states as areas without AC power flow considerations. GIZ-GEC covered a broad range of areas on technical, policy, and regulatory fronts but did not include transmission planning results. PEG-175U tracked the progress in growth of RE capacity and detailed out challenges, both current and upcoming. Similarly, NITI-RE focussed on stakeholder interactions to highlight issues being faced by different utility and regulatory personnel.

Our study is an attempt to contribute further to the technical and policy landscape and inform more exhaustive studies in future. We have incorporated PGCIL-GEC's and NEP's network upgrade recommendations as planned additions in our study.

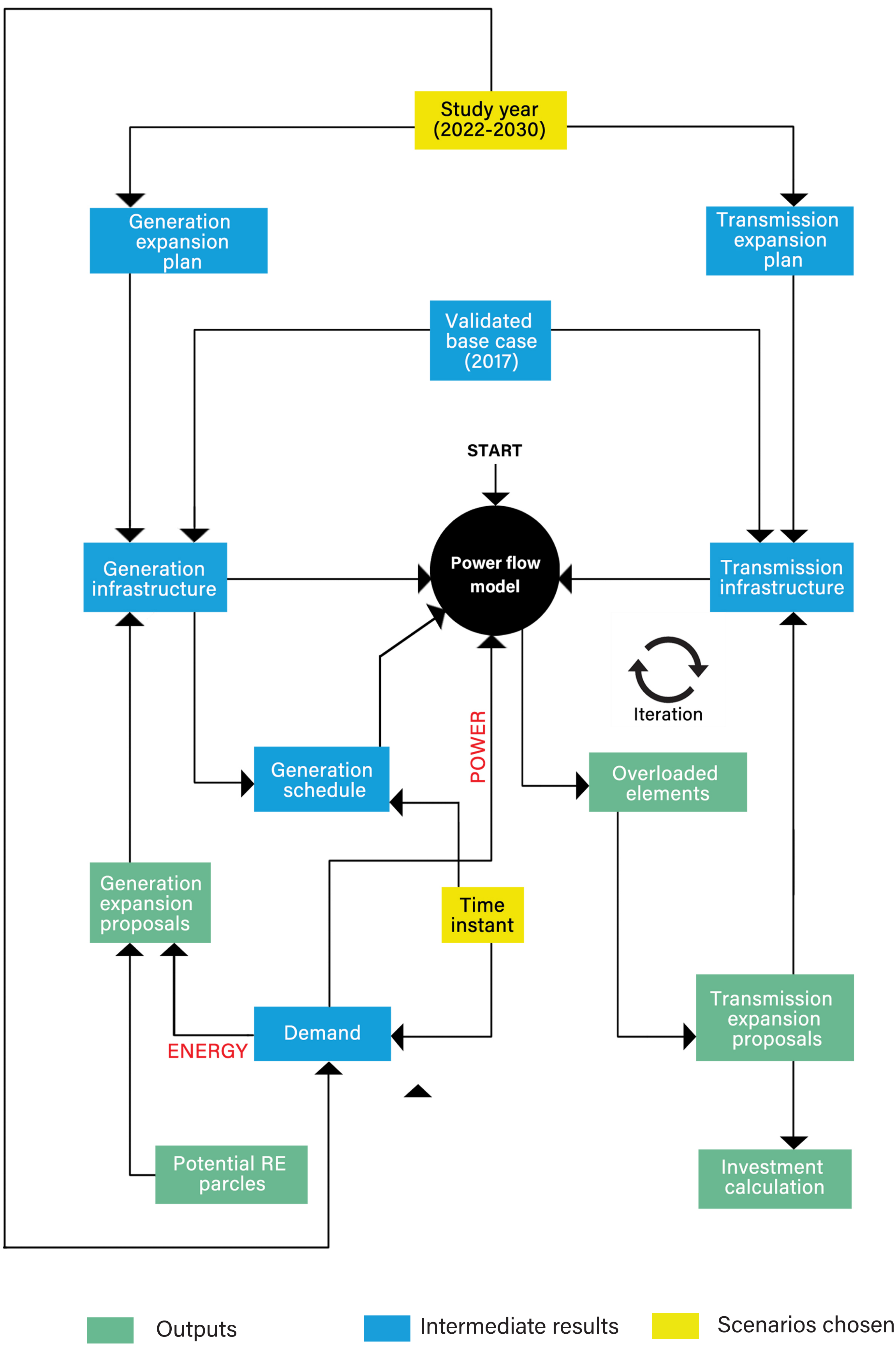



Figure 3: Flowchart of project methodology

# 04 | Approach and Methodology

Our study follows a network-first approach and considers the entire SR transmission network of 220 kV and above voltage level. It keeps in focus the latest policy goals of 175 GW by 2022 and NDC goals of 35% non-fossil-fuelled generation capacity by 2030. Each individual RE plant has been located and modelled with a connection to the appropriate substation.

In a network-first approach, the transmission grid forms the primary component, with inputs from different components for generation and demand. The primary outputs of the study are the constraining elements of the transmission system, impacted by the growth of grid-connected RE sources of electricity identified via scenario-based power flow analyses.

We integrated several components (refer Figure 3 on facing page for a schematic of the different components used) to achieve sufficient detail in this study. These components provided inputs to simulate power flows through transmission system elements for multiple scenarios.

In our study, we considered 2022 and 2030 as 'horizon years', as these are two landmark years for meeting RE capacity additions. We built a complete power-system model corresponding to the infrastructure (both generation and transmission) likely to be available in 2022. For the 2030 analysis, we updated the power-system model incorporating infrastructure upgrades likely to be completed by 2030.

The study considers that for 2022, solar (100 GW) and wind (60 GW) targets fixed by MNRE are achieved[5]. We have assumed that sufficient RE capacity was added by 2030, such that the overall energy demand (projected for 2030) is met. In both years, new renewable generation was proposed at suitable sites (detailed in Section 6.3), based on resource characteristics and land-use considerations.

The two models were run through a number of scenarios, which were selected based on analysis of the resource characteristics as well as discussions with stakeholders. In our study, the scenarios were primarily intended to characterise the grid when it experiences an extreme load/generation situation. Each scenario corresponds to a specific time instant, entailing a certain level of demand from the five states and generation from each generating plant.

Demand time profiles for future years were forecast and state-wise demand values at chosen scenario instants were extracted. Substation-wise demand values were then derived from the overall state demand.

Solar, wind, and nuclear generators were considered as must-run plants that deterministically generate a given power level for any given hour (i.e. each of these plants generates a fixed amount of power at any given hour of the year). Thermal and hydro-electric generators are considered as dispatchable plants that are set at a given power level, based on the load generation balance for a particular scenario.

[5] Some states have already exceeded their allocated target RE deployment. In such cases, no further capacity is added but the 'extra' capacity is retained.

All these inputs were fed into an instantaneous steady-state alternating current (AC) power flow[6] (also called load flow) analysis, yielding fundamental insights about the ability of the grid elements to sustain the situation.

The next chapter provides detailed information on each of the model components.



[6] As opposed to the more approximate so-called "DC power flow analysis

# 05 | Modelling

In this chapter, we describe in detail the modelling of generation, transmission, and demand as well as scenarios. Further, we lay out the processes followed for identifying and selecting land parcels to propose new RE generation plants. We also cover the data sources referred and assumptions for transmission modelling.

## 5.1 Infrastructure

To conduct the modelling exercise, we assumed that each state would meet its targets as listed in MNRE's provisional state-wise allocation of the 2022 target of 175 GW RE capacity (*Tentative State-wise break-up of Renewable Power target to be achieved by the year 2022*, 2018). We incorporated the planned expansion of conventional generation and transmission infrastructure into the model (assuming on-schedule implementation). We assumed that no further thermal power capacity will be constructed beyond what is already planned at present, in line with the objectives of the study. All the existing and planned plant locations as well as transmission substation details for the entire SR were plotted on a Geographical Information Systems (GIS) platform using ArcGIS software.

### *5.1.1 Transmission Network*

The process of network validation assured the accuracy of the transmission network model, as on the validation instant. Information about changes in the network since then were obtained from a May 2018 document on grid elements in the SR. Information about proposed additions or changes to the network were obtained from a variety of sources such as CEA transmission progress reports (detailed out in Table 5 on page 6).

Since analyses in this project are confined to 220 kV and above voltage network, the lower voltage network was replaced by simplified equivalents to reduce network complexity. That is, the 110 kV and below network was aggregated (as an equivalent load or generator) at the 110 kV bus of 220 kV substation. General Electric's (GE) Positive Sequence Load Flow (PSLF) simulation software was used to carry out this task. The main benefits of carrying out network equivalence are:

- Effect of generators and loads connected at lower voltage levels (which are not being considered for this study) will be reflected at higher voltage levels (which have been modelled).
- Overall impedance of the system remains the same, in the form of equivalent impedance, even though the lower voltage level network is deleted.
- Helps to analyse the network at higher voltage level without neglecting the effect of generators, loads, and overall impedance of lower voltage level network.

We have taken into consideration existing and planned inter-regional transmission corridors planned by the CEA. The SR was synchronously interconnected with the rest of the Indian grid on 31 December.

In 2013, the commissioning of 765 kV Raichur - Solapur transmission line was completed, thereby achieving 'One Nation - One Grid - One Frequency.' Following this, many lines have been commissioned. As of now, the SR grid has interconnections within the Western and Eastern Region grids. By considering the planned inter-regional transmission infrastructure, the total transmission corridor capacity available from the SR to the Eastern Region (ER) and the Western Region (WR) would be around 30,150 MW by 2022, depicted in Figure 4 (below).

In most cases, capacitor banks have not been incorporated into the model since they are usually installed at lower voltage (110 kV and below) substations, which have not been modelled. Additionally, reactive power limits were not enforced while modelling inter-regional corridors.

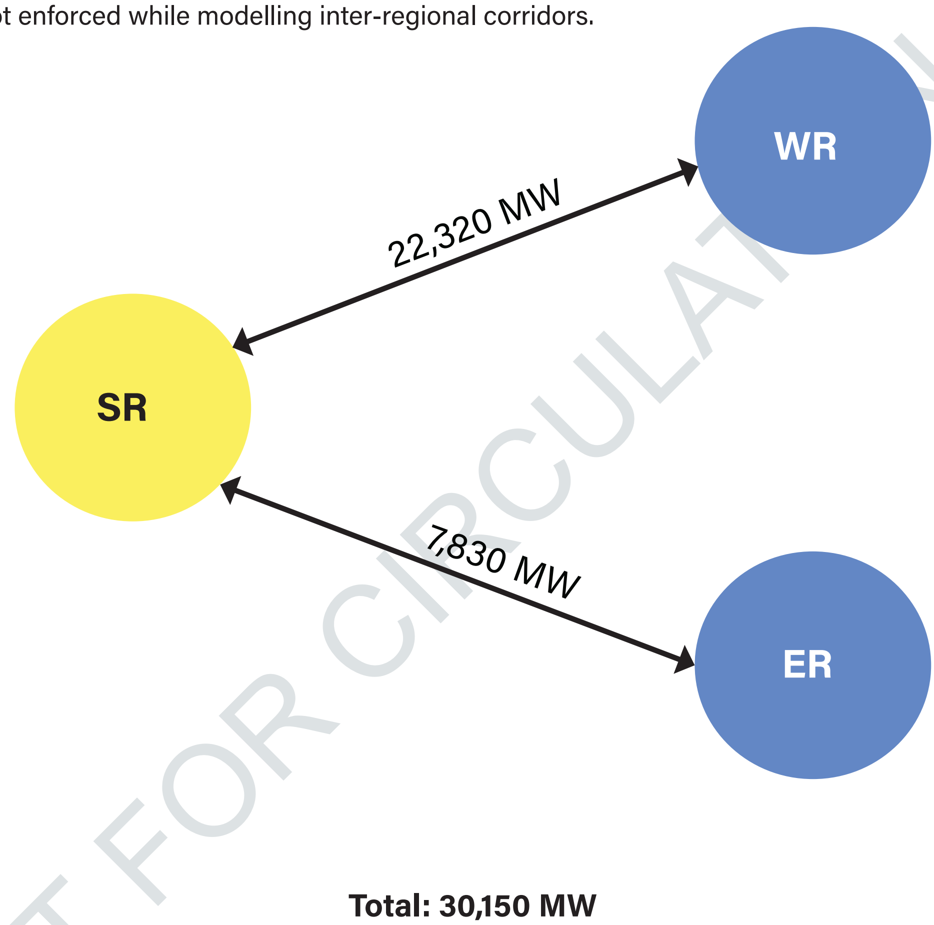





Figure 4: Inter-regional transmission capacity from southern region

### 5.1.2 Existing and Planned Generation

Only generation plants connected at a voltage of 220 kV stations or above were directly incorporated in the model. Lower voltage plants were taken into account as part of an equivalent network.

We obtained information on existing RE plants from websites of state nodal agencies. We collected existing wind plant details from the Consolidated Energy Consultants Ltd (CECL) directory. We chose suitable hub heights for existing wind turbines based on turbine capacity and diameter. Future wind farms are assumed to be at 120 m hub height, as per observed trends of wind farm deployment in the past few years. We collected existing solar plant details from various publicly available documents. All solar PV plants are assumed to be composed of generic panels with polycrystalline silicon-based solar cells.

The planned solar and wind plant details were collected from various CEA documents. They were assigned a geographical location based on the names of the nearest village or district. Some information (on future RE plants) was also gathered from nodal agencies. Apart from this, very large RE parks were incorporated based on other public domain information. We also collected details of both existing and planned conventional generating stations from various sources.

### 5.1.3 New RE Siting

Identifying solar and wind potential in the SR was one of the most important activities in this project. The region's current solar and wind energy potential substantially exceeds the 2022 targets set by the MNRE. To analyse the effects of tapping into this large potential, we simulated the expansion of RE capacity using GIS. Geospatial layers, annotated with land-use and land-cover data, were used to identify potential high-RE areas. To obtain a realistic distribution of RE, certain protected areas were excluded from selection for the installation of new RE capacity.

For new parcel (site) selection, we identified land categories separately for solar and wind. We used the land use and land cover data from the National Remote Sensing Centre (NRSC) with a resolution of 50 m, and the digital elevation model with a resolution of 30 m, to generate slope of the terrain.

Of the various solar power technologies, we took into consideration the flat-panel photovoltaic generation plants, since they have an overwhelming share in the market today. In line with current trends, we assumed all new solar PV plants to be composed of generic panels with polycrystalline silicon-based solar cells. Similarly, we have considered only Horizontal Axis Wind Turbines (HAWTs) for new wind power generation.

### Land-use considerations

We proposed wastelands as the primary type of land for new RE plants. Wasteland includes degraded lands that can be brought under vegetative cover with reasonable effort, lands that are under-utilised, and lands that deteriorate due to lack of adequate water and soil management (refer Appendix I).

*Excluded areas*

In the next step, we eliminated areas which are unsuitable for RE plants. Many areas are unsuitable due to various regulations and safety considerations. We spatially generated layers with required buffer areas based on discussions with MNRE. The buffers include:

- Road layer with a buffer of 500 m
- Rail network with 500 m buffer
- Protected area with a buffer of 1 km
- Airport layer with a buffer of 10 km
- Cyclone layer with 25 km of buffer
- Water bodies with 500 m of buffer

The excluded areas in the SR are depicted in Figure 5 (facing page).

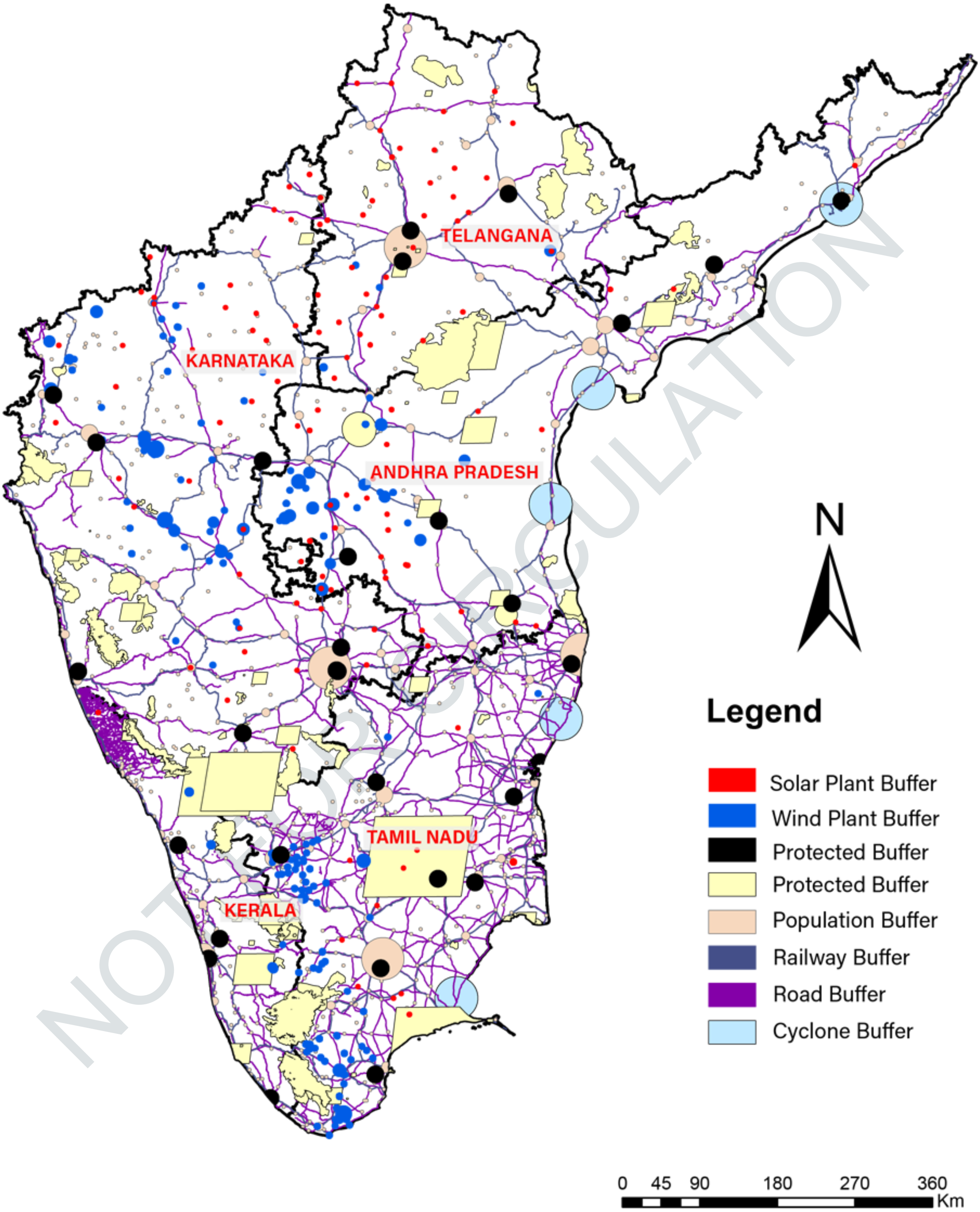



Figure 5: Unsuitable area for parcel selection

**Cities:** Urban areas, in addition to not having enough area for typical utility-scale plants, also tend to grow and engulf hitherto rural/unused land. The presence of buildings and other artificial structures severely hampers solar as well as wind power generation. Thus, new RE plants are typically located far away from urban areas. To simulate this effect, a circular exclusion zone has been added outside each city-area (radius was based on population range). This has been detailed in Table 6 (below).

Table 6: Population range of human settlements and radius of exclusion buffer applied

| Population (Million) | Buffer Applied (km) |
|---|---|
| 0.01 – 0.05 | 2 |
| 0.05 – 0.1 | 5 |
| 0.1 – 1 | 10 |
| 1-5 | 25 |
| 5-10 | 25 |
| Greater than 10 | 50 |

**Existing and planned RE:** RE plants tend to be clustered in areas of higher potential for obvious techno-economic reasons. Since new RE plants are also being proposed in high potential areas, there was a need to make sure that new RE plants do not overlap existing plants. To that end, individual solar and wind plants were associated with a circular exclusion buffer. The area of each such buffer was calculated from plant capacity, using the same capacity density as used for new renewable plants (further in this section).

These exclusion layers were subtracted from the available area to obtain solar and wind parcels. Grid interconnection norms require generating plants to be at least 50 MW capacity to connect to a 220 kV substation. Since we do not consider any lower voltage substations in our study, we enforced a minimum plant size of 50 MW for both solar and wind parcels.

**Solar energy:** We used NREL solar resource map with resolution of 10 km for this study. We have assumed a constant capacity density of 5 acres/MW. For proposing solar power plants, we have considered wasteland and identified land parcels with a Global Horizontal Irradiance (GHI) of more than 5.5 KWh/sqm/day, slope less than or equal to 4 degrees.

Typically, a single land parcel would not be sufficiently large enough to support a 50 MW plant. Thus, we have combined multiple parcels, as required, to a nearby 220 kV substation.

**Wind energy:** 3TIER's wind resource map, with resolution of 5 km, was used for this study. For wind parcel selection, we considered wasteland, along with agricultural land (such as current fallow, kharif, rabi, double/ triple), and scrubland. Parcels with wind speed of more than 6 m/s at 120 m hub height were selected.

Wind turbines (for reasons of minimising wake effects[7] that can severely reduce the power produced) are typically spread out over a large area. In this study, we assumed a rectangular layout of 5D×7D, i.e. wind turbines are spaced five diameters apart sideways and seven diameters in the windward direction. This configuration is commonly assumed in many planning studies, giving a capacity density of 5 MW/sq km.

The most convenient parcels were selected for future RE plants, based on resource strength and the availability of substation capacity, after removing parcels that cannot support the minimum plant size of 50 MW. The state-wise area available for RE parcels along with their potential is given in Table 7 (below).

Table 7: Area available for parcels along with RE potential in SR states

| State | Solar | | Wind | |
|---|---|---|---|---|
| | Area (sq. km) | Potential in GW | Area (sq. km) | Potential in GW |
| Andhra Pradesh | 2,101 | 104 | 12,934 | 62 |
| Karnataka | 2,631 | 130 | 18,447 | 88 |
| Tamil Nadu | 1,029 | 51 | 7,555 | 36 |
| Telangana | 815 | 40 | 213 | 1 |
| Kerala | 78 | 4 | 256 | 1 |
| Total | 6,654 | 329 | 39,405 | 188 |



[7] A wind turbine extracts energy from, as well as introduces turbulence into the wind stream it intercepts. The resulting stream behind the turbine, called a wake, has low speed and is highly turbulent.

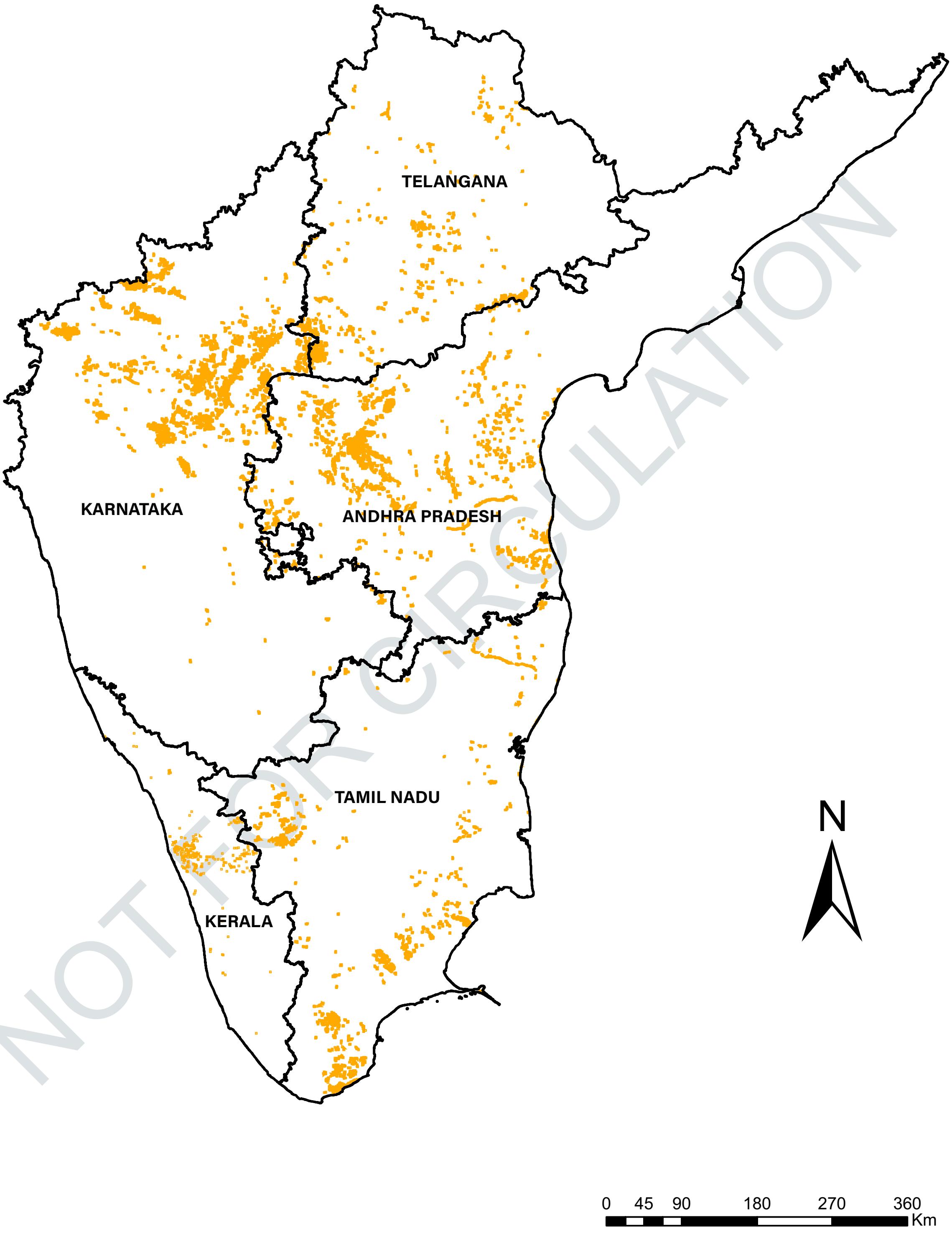



Figure 6: Identified solar parcels in SR states

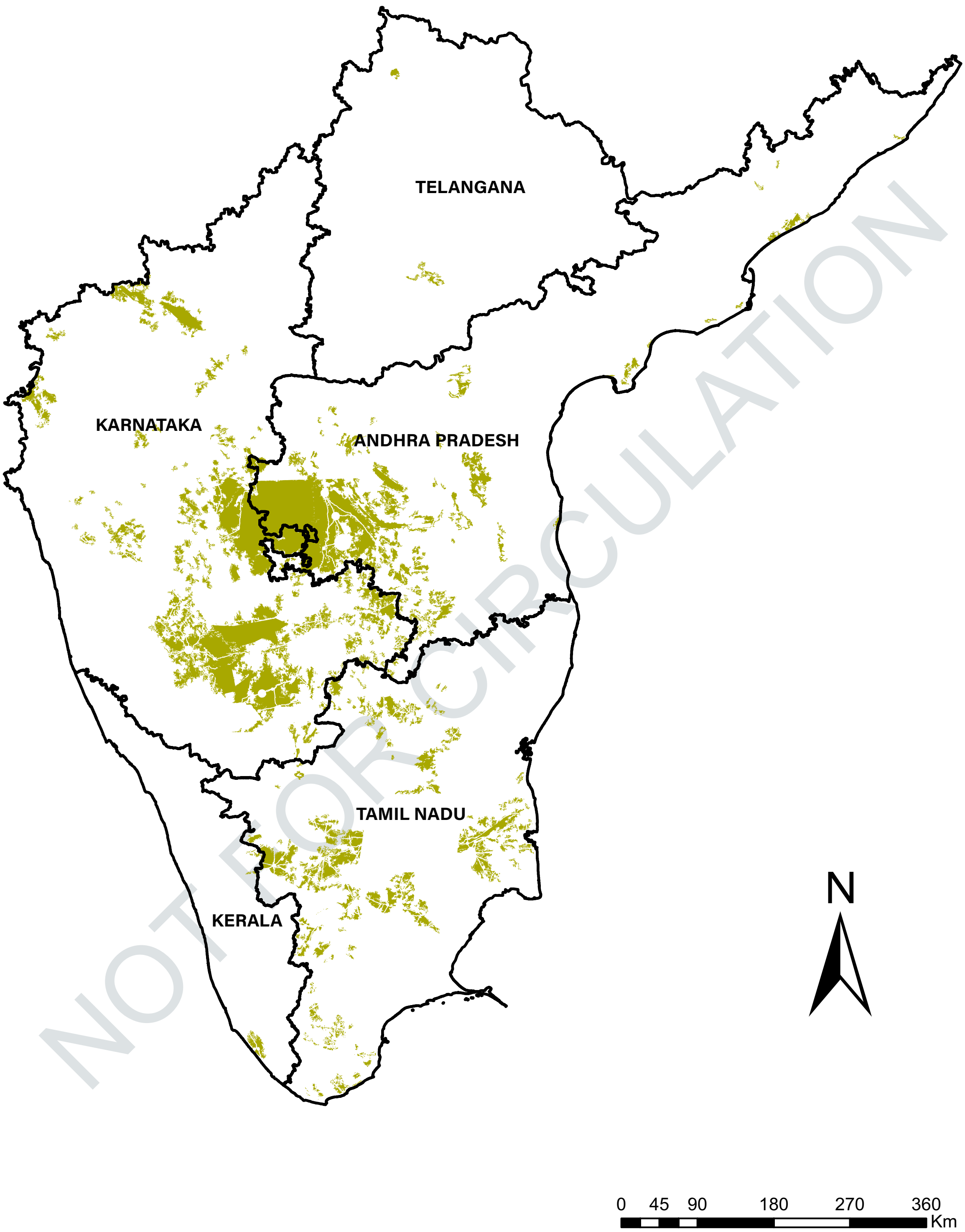



Figure 7: Identified wind parcels in SR states

In this parcel selection and RE siting process, we have tried to capture as much detail as possible with respect to land and resource availability. Authentic datasets have been used for land-use, as well as solar and wind resource distributions. There may have been changes in land-use in the intervening years. Locations and the extent of existing RE plants used for siting proposed RE were based on third-party compilations and may be subject to some errors.

## 5.2 Scenarios

We designed various scenarios in consultation with multiple utility officials. These scenarios incorporated commonly accepted benchmarking conditions for grid planning. The peak load, solar, and wind conditions can cause transmission element overloading; peak load condition in particular tends to cause substation under-voltage. The respective off-peak conditions frequently result in substation over-voltage. The corresponding scenario time-instants were (detailed in Section 5.3) obtained from the base-year data for hourly demand, solar power generation, and wind power generation. Table 8 (below) shows the scenarios with their time instants.

Table 8: Scenario time-instants

| Scenario Name | Date | Time | Scenario Description |
|---|---|---|---|
| Peak Load | March 21 | 10 PM | SR maximum demand instant |
| Off-Peak Load | November 11 | 3 AM | SR minimum demand instant |
| Peak Solar | April 10 | 1 PM | Maximum power generation instant from solar plants |
| Off-Peak Solar | July 15 | 3 PM | Minimum solar power generation instant in day time |
| Peak Wind | July 21 | 2 PM | Maximum power generation instant from wind plants |
| Off-Peak Wind | September 29 | 9 AM | Minimum power generation instant from wind plants |
| Peak of Solar + Wind | June 21 | 11 AM | The instant at which sum of solar and wind generation is maximum |
| Biggest Drop in Wind | August 18 | 12 PM | The maximum drop in wind generation between consecutive instants |

### 5.2.1 Generation

Actual energy generated and fed into the grid from different sources depends foremost on the type of generator. Solar, wind, and nuclear generators are considered as must-run plants that deterministically generate a given power level for any given hour. Thermal plants are scheduled to run at 55% of their rating to maintain technical minimum generation, as per CEA's operation procedure report. The generation from hydro plants for each scenario are scheduled based on the minimum[8] power generation over the past five years in that month. Nuclear plants are assumed to operate constantly at 80% capacity, serving base load.

We used CSTEP's Solar Techno-Economic Model for Photovoltaics (CSTEM-PV) to generate solar power generation time profiles and NREL's System Advisor Model (SAM) to generate wind power time profiles (See Appendix II). For each power flow scenario, we extracted the corresponding power generation from solar and wind profiles.

The methods used in modelling generation from renewable sources have been elaborated below.

**Solar**

Generation profiles of solar PV plants were obtained via simulations run on CSTEM-PV (Sridhar & Thirumalai, 2018). It is a web-based interactive tool built primarily for performing engineering-economic assessments for prospective solar PV plants in India. The tool is based on publicly available data via equipment datasheets. Hourly insolation data used for simulating PV plant profiles (of year 2011) was obtained from NREL, which was developed using the State University of New York (SUNY) semi-empirical model.

**Wind**

Wind power, globally and in India, is primarily generated by HAWTs. India's technical wind potential has been revised upwards multiple times due to better data and viability of higher hub heights (which ensures stronger and steadier winds).

Wind power generation primarily depends on the wind resource characteristics (speed, temperature, and pressure) at the height of the turbine hub, and the turbine characteristics. The simulation of wind plant generation profiles was performed using NREL SAM (J. Freeman, Jorgenson, Gilman, & Ferguson, 2014). A large number of wind turbine power curves were built into SAM, and the most suitable model was used to match the given make and capacity data (refer to Section 5.3 for further information on data sources). Because data on the positions of wind turbines is difficult to obtain, wind farms were assumed to be single-point locations, and wake effects were not modelled explicitly. Instead a constant 10% loss was assumed for each farm to account for wake-related losses. All wind resource characteristics were obtained from an hourly gridded dataset from NREL's Greening the Grid study.



[8]Given the large amount of RE injection into the grid, maximum backing down of all controllable power generators, including hydro, was necessary. Historic data was analysed to enable the simulation to respect exogenous constraints on water release from multipurpose dams and flood control priorities for all storage hydro-power plants.

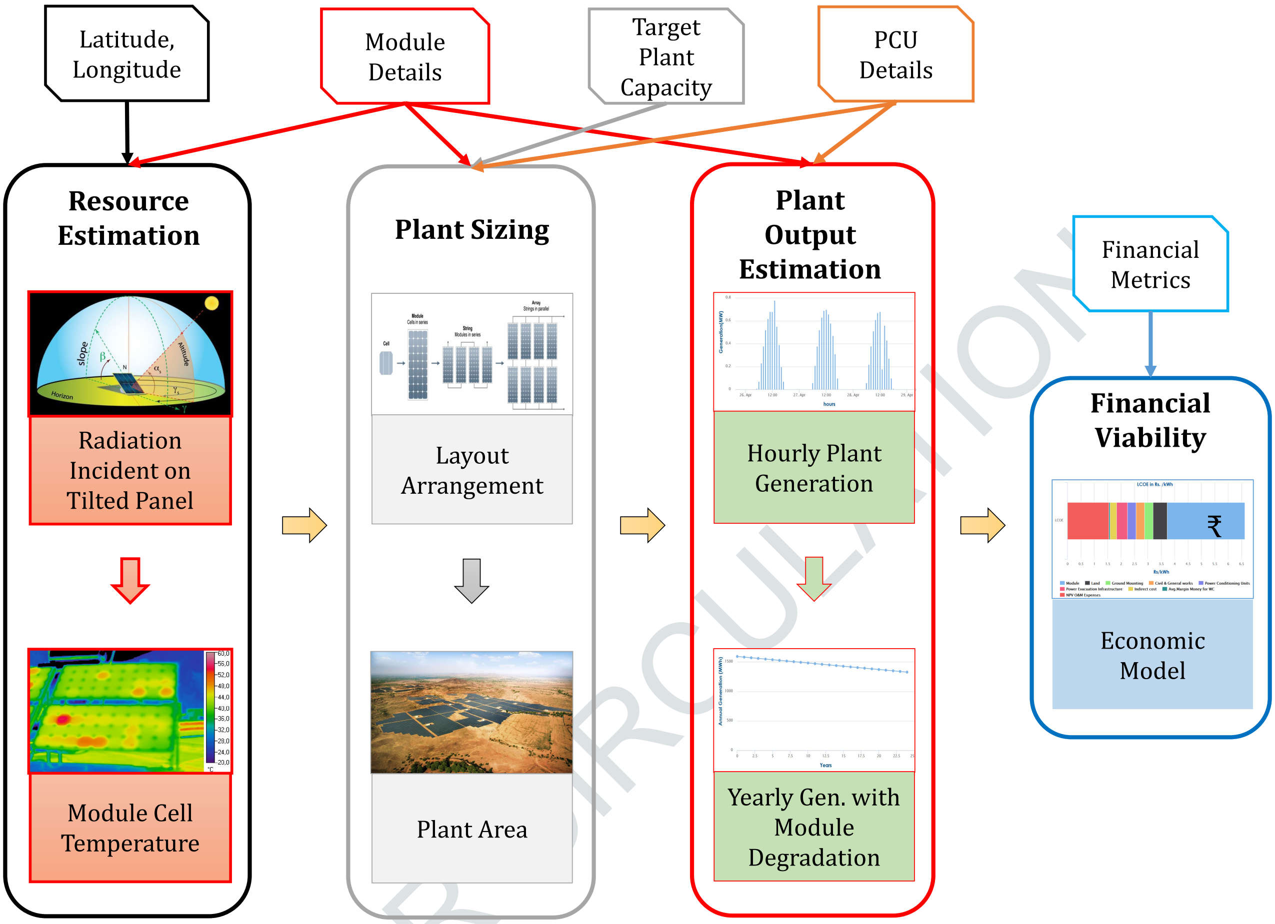





Figure 8: CSTEP PV schematic

In this study, we have tried to capture hourly variations of renewable generation throughout the year. Renewable resource availability in the future is always uncertain and may affect results. Mismatches in data sources for solar, wind, and demand datasets may also cause certain discrepancies.

### 5.2.2 Demand

The state-wise demand profiles for the year of study (2022 & 2030) were calculated from the demand projections in CEA's 19th Electric Power Survey (EPS) of India. The demand pattern was obtained with 15-min block-wise resolution from Power System Operation Corporation Limited (POSOCO) data for the year 2015-16.

Hourly demand curves for future years were forecasted from the time-series data using annual compounding, with growth rates obtained from the 19th EPS. State-wise forecast demand values at the chosen scenario time-instants were used as inputs to the power flow model. Demand values for peak-load scenario, however, were directly obtained from the 19th EPS. The substation-wise demand values for future years were derived from the state-wise values on a proportional basis (as per the demand distribution found in the base case).

**Load transfer**

In transmission planning studies, significant growth in loads (attached to substations) makes it necessary to spin off the growing load from existing substations to future ones. The load transfer process is necessary for modelling proper utilisation of both existing and proposed substation transformation capacity. Utilisation of existing infrastructure through appropriate load transfer methodology helps in the optimal use of existing network, and minimising the requirement for network upgradation (and associated investments). We explain the steps and criteria followed in the load-transfer process below:

1. Apply the growth factor of load (from base study year to future study year) to the individual existing substation in a system (let's call this substation A).

2. Check if the existing substation (A) is able to supply the increased load, satisfying the following conditions:

    a. Substation (A) should supply the increased load without any overloading of transformers during normal operating conditions.

    b. The other transformers in the substations (A) should supply the increased load during the outage of the single largest transformer in a substation (A) without any overloading.

3. If either of the above condition fails, the following solutions can be explored on a case-to-case basis:

    a. If there is any nearby existing substation (let's call this substation B), in which there is a margin (after supplying its own increased demand), then transfer part of the load from existing substation (A) to the substation (B).

b. If the above solution fails, transformer augmentation in substation (A) can be made. We have considered transformation capacity limits prescribed in CEA's Manual on Transmission Planning Criteria.

4. If the above solution fails then, part of the load from existing substation (A) can be transferred to the nearby utility proposed substation. Load should be transferred in such a way that the proposed substation should not get overloaded during normal as well as in N-1[9] operating condition.

5. If there is no nearby proposed substation, a new substation of suitable transformation capacity can be proposed.

As per the above procedure, substation augmentation or new substations were proposed at the appropriate places in the network, to accommodate the load growth.

## 5.3 Data Sources

Numerous data sources have been used at different stages in this study. They are detailed in Table 8 (page 26), Table 9 (below), and Table 10 (facing page).

Table 9: Data sources for generation modelling

| Item/Elements | Source |
|---|---|
| Existing conventional generation (Thermal & Hydro) details | ▪ All India grid model for point of connection (PoC) charges calculation - 2016-17 Q4 PSS E RAW data file<br>▪ State-wise power maps – CEA<br>▪ Generation reports – CEA<br>▪ Daily generation report - CEA (2013 -2016) |
| Existing solar generation plant details | ▪ Renewable development agencies – State-wise |
| Solar irradiance data | ▪ Hourly solar irradiation dataset for 2002-2011 – NREL (this study only used 2011 data) (Sengupta, Perez, Guey mard, Anderberg, & Gotseff, 2014) |
| Existing wind generation plant details | ▪ Directory Indian Windpower 2017 – CECL |
| Wind resource data | ▪ Hourly wind resource dataset for 2014 – NREL |
| Proposed conventional, solar, and wind generation details | ▪ Standing committee meeting reports – CEA<br>▪ National Electricity Plan (Volume I) – CEA<br>▪ Various monthly/quarterly/yearly report – CEA<br>▪ Meeting reports – Southern Region Power Committee (SRPC)<br>▪ Technical coordination committee meeting reports – SRPC |

[9] N–1 condition refers to the state of the network after a contingency involving the loss of any one transmission line or transformer. The equipment in transmission systems is generally required to operate within normal thermal and voltage ranges even under N–1 condition.

Table 10: Data sources for transmission network modelling

| Item/Elements | Source |
|---|---|
| Existing transmission lines, substations, reactors | ▪ All India grid model for point of connection (PoC) charges calculation - 2016-17 Q4 PSS E RAW data file<br>▪ Transmission elements for southern region – POSOCO<br>▪ Manual on Transmission Planning Criteria – CEA (Central Electricity Authority, 2013) |
| Proposed transmission lines, substations, reactors | ▪ Draft National Electricity Plan (Volume II) - Transmission – CEA<br>▪ Various monthly/quarterly/yearly report – CEA<br>▪ Technical coordination committee meeting reports – SRPC<br>▪ Meeting reports – SRPC<br>▪ Discussions with utilities: KPTCL/TSTRANSCO/SRLDC officials |
| Solar irradiance data | ▪ SR SCADA snapshot as on May 5, 2017 at 11:09 AM – SRLDC |

Table 11: Data sources for demand modelling

| Item/Elements | Source |
|---|---|
| Demand pattern | ▪ All India 15-min block-wise demand pattern data for year 2015-16 from POSOCO |
| Proposed demand | ▪ 19th EPS report (Central Electricity Authority, 2017) |

## 5.4 Network Assumptions

We made the following assumptions during the modelling exercise:

- The SR transmission network has been modelled at 220 kV and above voltage level.
- Proposed Raigarh–Pugalur HVDC link has been considered a slack bus.
- Power factor of 0.98 (leading) has been considered for RE plants, as per CEA guidelines.
- Inter-connecting transformer impedance has been considered as 12.5% on its own MVA base.
- Inter-regional import/export transmission lines were modelled either as lumped generators or lumped loads.
- Loads were modelled at 220/132/110 kV buses of 400 kV and 220 kV substations with 0.95 PF lag.
- Existing RE plants were lumped to their geographically nearest 220 kV substations.
- Conventional generations and loads which are connected at 132/110 kV and below voltage stations level are lumped at 220 kV stations through network equivalent and are connected at 132/110 kV buses of 220 kV stations.
- The projected demand has been obtained from the 19th EPS report.
- Retirement of conventional generators were considered, as per the details provided in National Electricity Plan (Volume I) report by CEA.
- To supply the power demand, conventional generators were given last priority for scheduling, considering the primary contribution from RE plants.
- Generator transformer capacity for conventional generators were calculated assuming 0.85 power factor for generators.
- Power scheduling of hydroelectric power stations were considered based on the minimum average monthly power generation over the past four years, as per CEA daily generation reports.
- Power generation from thermal units were considered at technical minimum of 55% of their generation capacity and nuclear plants at 80% of their rated capacity.
- Rated thermal capacity (based on the type of conductor) was chosen as the limit for power flow through transmission lines.

# 06 | Analysis

We performed various analyses to understand the power flow from generation to load through the transmission grid. We started with a base-case network, which was validated, and then built up models of the projected transmission networks for 2022 and 2030.

## 6.1 Base-Case Analysis & Validation

SR transmission network is modelled at 220 kV and above voltage level in Electrical Transient and Analysis Program (ETAP) software. The existing transmission network has been considered as per POSOCO's 2016-17 Q4 RAW data file (all India grid model for PoC charges calculation), which was available in the public domain.

The next step after completion of the base-case model was the validation of the network. To check the correctness of network modelled in the ETAP, we verified power flows for a particular instant, with actual flows of the SR network from a snapshot from the Supervisory Control and Data Acquisition (SCADA) system. Based on advice from SRLDC, the grid model was truncated at 400 kV and above level. The instant chosen for validating the network is 11:09 AM of 5 May, 2017.

Steady state power flow analysis was conducted for this network, which simulated power flows through network branches and bus voltages. These simulated flows and voltages were compared to their corresponding measured values from the SCADA snapshot obtained from SRLDC (a snippet of which is shown in Figure 9 on page 34). Discrepancies were usually indicative of errors or missed-out elements in our model. In consultation with SRLDC officials, the model was refined to achieve errors of less than 10% for most elements.

From the base-case analysis (a segment of the corresponding single-line diagram is shown in Figure 10 on page 34), it is observed that:

- The direction of power flows of all the transmission lines in the simulation are in line with the SCADA power flows.
- Around 70% of the simulated transmission line flows are within 40 MW difference from measured flows.
- Around 1.2% of simulated transmission line flows differ by more than 100 MW from SCADA power flows.

Large differences can be attributed to errors in the SCADA snapshot values. Some power flow values from the snapshot would violate current conservation laws (Kirchhoff's Current Law)[10]; this situation is likely due to meter errors.

[10] Kirchhoff's Current Law: "In any electrical network, the algebraic sum of the currents meeting at a point (or junction) is zero." (Theraja & Theraja, 2010, p. 53)

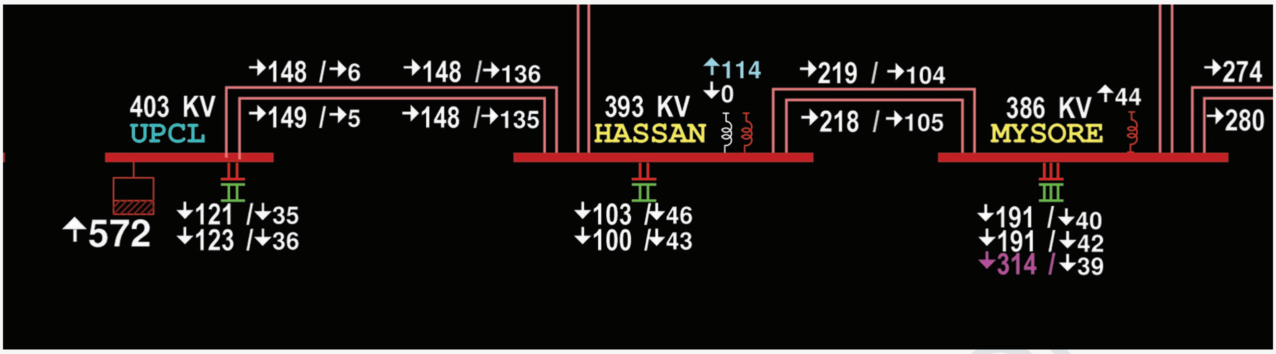



Figure 9: SCADA snapshot of Hassan 400 kV substation as on 5 May, 2017 @11:09 AM

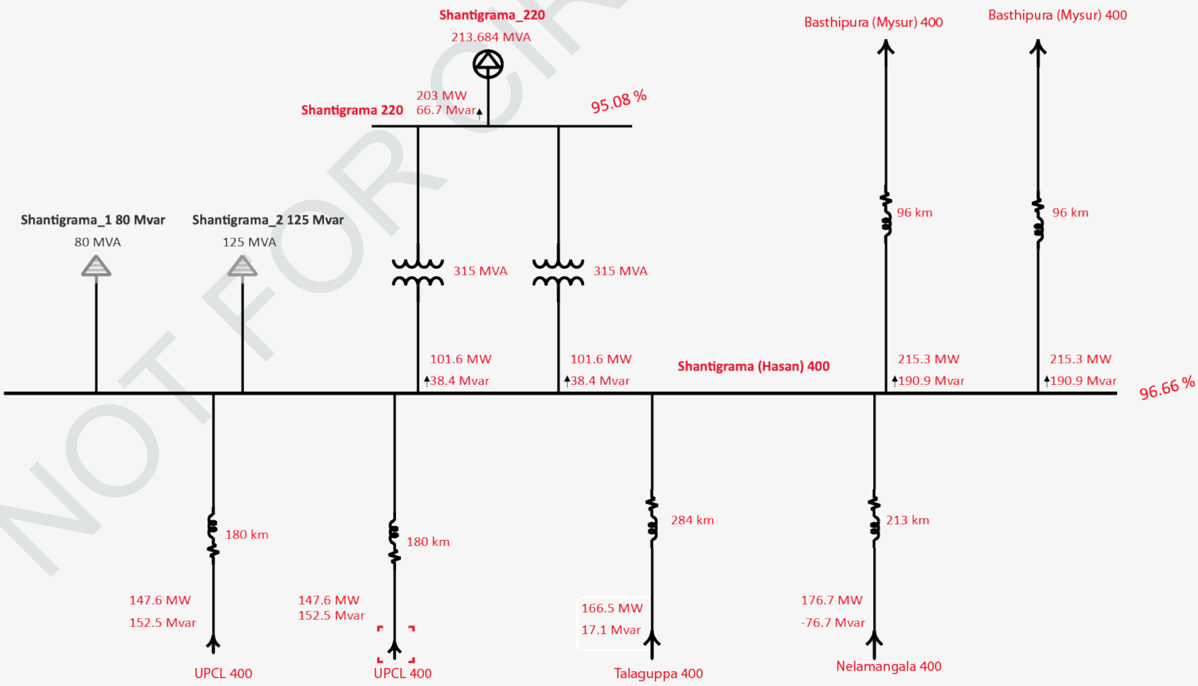





Figure 10: Network power flows for base-case validation instant

All the parameters and interconnections of the existing transmission network elements have been updated in our model. They were cross-verified with POSOCO's Transmission Elements - Southern Region (May 2018) document along with power maps of the southern region (June 2018). The network (both transmission and generation) was then updated as per the network proposal details collected from various documents listed in Section 5.3 above.

We then performed power flow studies for the proposed years, 2022 and 2030.

## 6.2 Generation Capacity for 2022

The RE capacity considered for the 2022 analysis is given in Table 12 (below). Firstly, solar and wind plants commissioned before 31 March, 2017, were built into the model (marked 'existing' in the table). Next, upcoming RE plants, expected to be commissioned by 2022, based on various publicly available documents (marked 'planned' in the table), were incorporated into the model. We then added RE plants (marked 'proposed' in the table) to the model, so as to meet state-wise solar and wind targets mandated by MNRE under the 175 GW RE target.

Because the sum of existing and planned wind plants in Karnataka and Kerala exceeds the MNRE state-wise target for year 2022, no new wind plants are proposed.



Table 12: SR states' RE capacity by 2022

| Particulars | Solar in MW | | | | Wind in MW | | | |
|---|---|---|---|---|---|---|---|---|
| | Existing | Planned | Proposed | Total | Existing | Planned | Proposed | Total |
| Andhra Pradesh | 2,137 | 2,721 | 513 | 5,371 | 3,549 | 4,149 | 401 | 8,099 |
| Karnataka | 2,175 | 2,200 | 1,322 | 5,697 | 3,921 | 3,469 | 0 | 7,390 |
| Kerala | 99 | 500 | 1,271 | 1,870 | 58 | 360 | 0 | 418 |
| Tamil Nadu | 1,214 | 500 | 7,170 | 8,884 | 7,730 | 3,028 | 1,141 | 11,899 |
| Telangana | 2,567 | 500 | 1,390 | 4,457 | 101 | 0 | 1,027 | 1,127 |
| Puducherry | 0 | 0 | 246 | 246 | 0 | 0 | 0 | 0 |
| Total SR | 8,193 | 6,421 | 11,912 | 26,526 | 15,360 | 11,006 | 2,569 | 28,934 |

The composition of overall generation (including conventional generation) is given in Table 13 (following page).

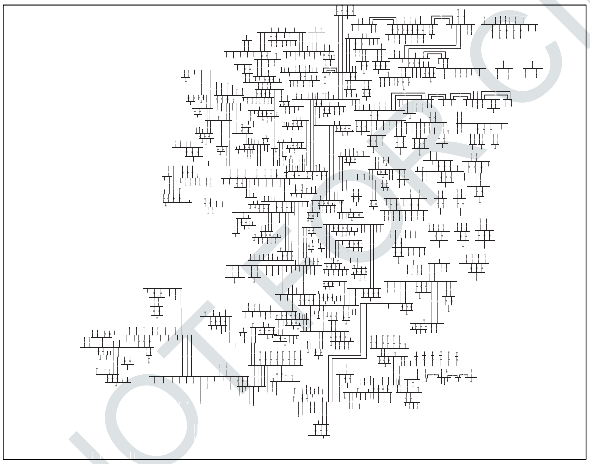
Table 13: State-wise generation capacity for 2022 (MW)

| State/Region | Thermal | Nuclear | Hydro | Solar | Wind | Total |
|---|---|---|---|---|---|---|
| Andhra Pradesh | 19,193 | 0 | 2,430 | 5,371 | 8,099 | 35,093 |
| Karnataka | 8,130 | 880 | 3,260 | 5,697 | 7,390 | 25,357 |
| Kerala | 446 | 0 | 1,335 | 1,870 | 418 | 4,069 |
| Tamil Nadu | 18,111 | 2,940 | 1,675 | 8,884 | 11,899 | 43,509 |
| Telangana | 13,056 | 0 | 2,310 | 4,457 | 1,127 | 20,950 |
| Puducherry | 0 | 0 | 0 | 246 | 0 | 246 |
| Southern region | 58,936 | 3,820 | 11,010 | 26,526 | 28,934 | 1,29,224 |

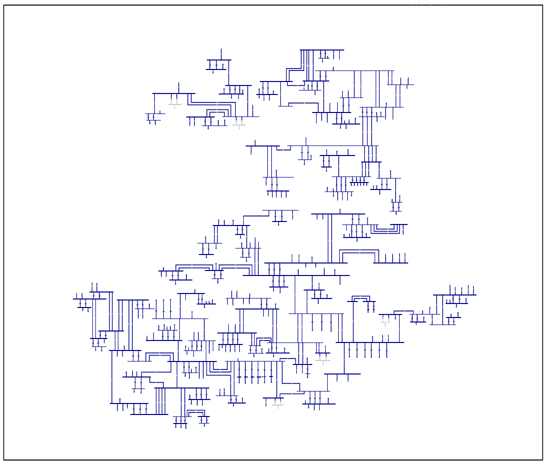
## 6.3 Power Flow Analysis for 2022

Snapshots of state-wise, single-line diagrams of the SR transmission network modelled in the ETAP power system simulation software is shown in Figure 11 (below ). The diagram depicts the transmission network of the 2022 model at 220 kV and above voltage level. A screenshot of the model showing the network in detail for one generating station (Simhadri Stage-1) and one substation (Gazuwaka 400 kV) of Andhra Pradesh is given in Figure 12 (facing page).

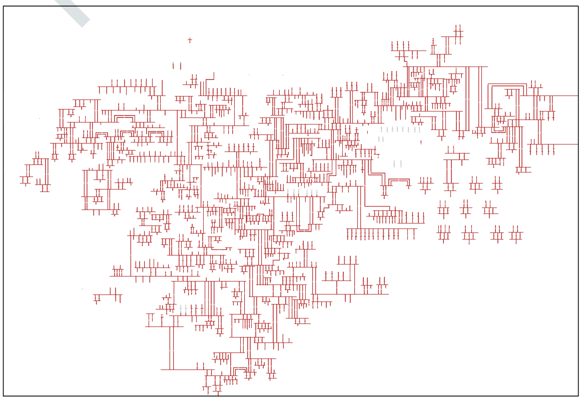




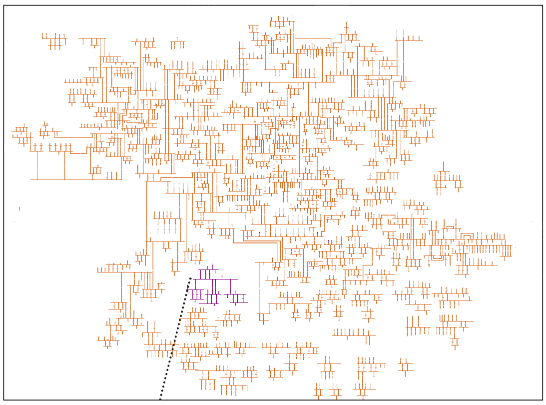
Telengana



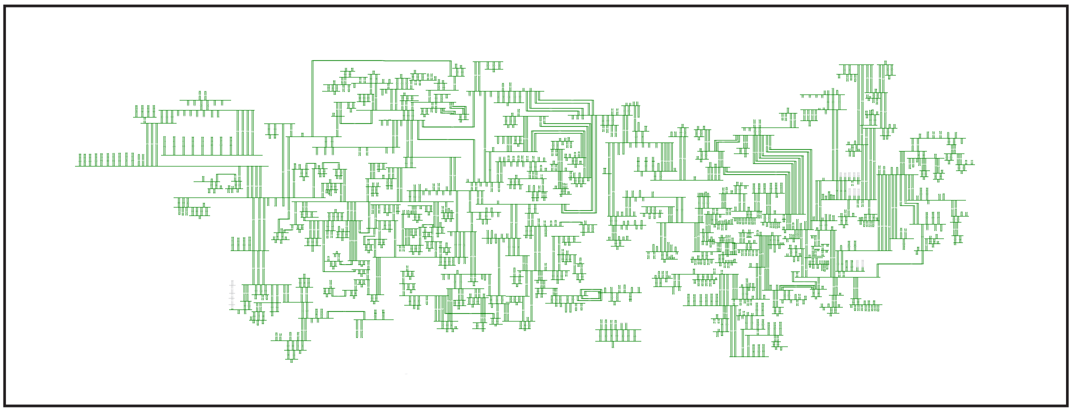
Kerala



Andhra Pradesh



Puducherry Tamil Nadu



Karnataka

Figure 11: Single-line diagrams of state-wise transmission network modelled in ETAP

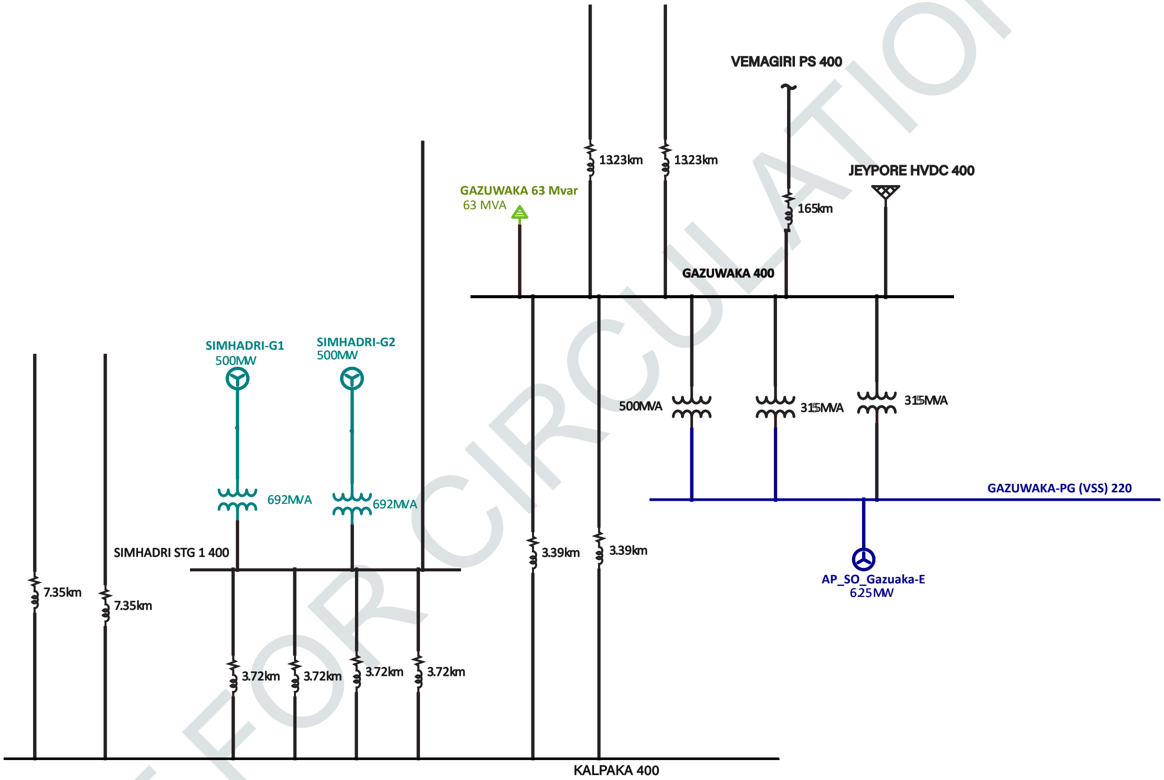



Figure 12: Screenshot of Andhra Pradesh generating station and substation



The number of substations modelled in SR for 2022 analysis is given in Table 14 (below):

Table 14: State-wise substations count for 2022

| Substation voltage level | Karnataka | Tamil Nadu | Telangana | Kerala | Andhra Pradesh | Puducherry |
|---|---|---|---|---|---|---|
| 765 kV | 3 | 6 | 3 | 0 | 6 | 0 |
| 400 kV | 32 | 50 | 27 | 11 | 37 | 1 |
| 220 or 230 kV | 126 | 112 | 72 | 37 | 84 | 3 |
| Total | 161 | 168 | 102 | 48 | 127 | 4 |

Figure 13 (below) gives the total transmission line length and also the total transformation capacity considered for 2022 analysis.

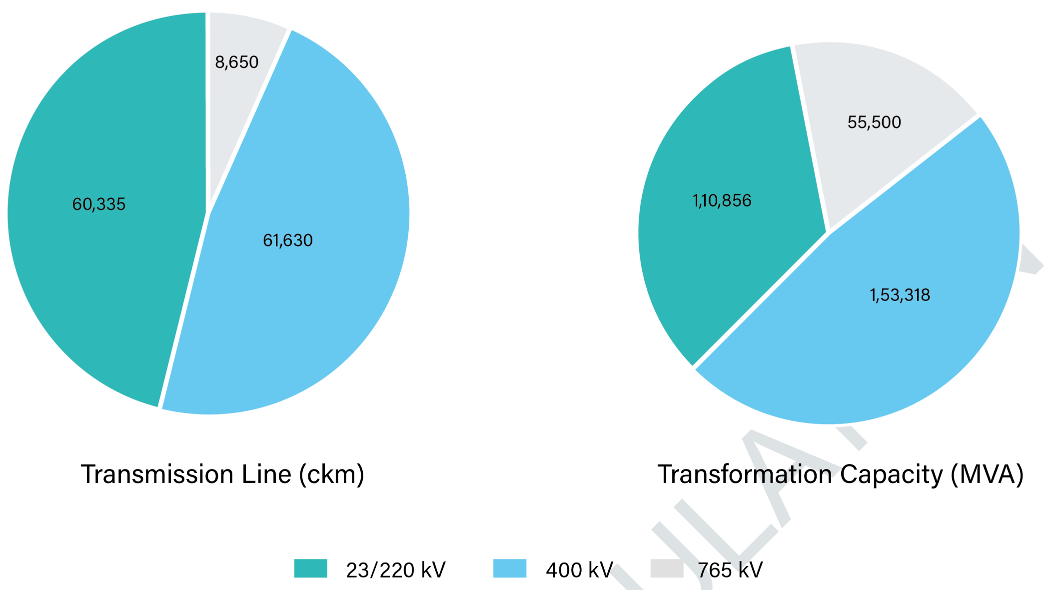



Figure 13: Southern Region grid by 2022

The installed generation capacity considered in SR was around 129.2 GW, of which (refer Table 13 on page 36), thermal generation has a major share (45.6%), followed by wind (22.3%), solar (20.5%), hydro (8.5%), and nuclear (2.9%). The impact on and optimal utilisation of the transmission network was considered while choosing solar and wind parcels.

Power flow analysis was performed for all the eight scenarios described in Section 5.2 of this report. The system loading, losses, and generation schedule for the scenarios considered for year 2022 are given in Table 15 (facing page).

Table 15: Load generation balance for year 2022 (MW)

| Particulars (Total generation capacity) | Peak load | Off-peak load | Peak solar | Off-peak solar | Peak wind | Off-peak wind | Peak of solar + wind | Biggest drop in wind |
|---|---|---|---|---|---|---|---|---|
| Thermal (58,936) | 32,415 | 32,415 | 32,415 | 24,141 | 18,169 | 32,415 | 15,130 | 32,415 |
| Nuclear (3,820) | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 |
| Hydro (11,010) | 410 | 344 | 671 | 312 | 312 | 426 | 208 | 420 |
| Solar (26,526) | 0 | 0 | 14,456 | 5,319 | 9,815 | 9,572 | 8,973 | 8,523 |
| Wind (28,934) | 9,041 | 2,150 | 891 | 27,521 | 27,564 | 74 | 26,309 | 4,455 |
| Import | 5,849 | 500 | 845 | 500 | 1,500 | 845 | 1,500 | 500 |
| Total power available | 50,771 | 38,465 | 52,334 | 60,850 | 60,416 | 46,387 | 55,176 | 49,369 |
| Load | 48,891 | 30,438 | 42,804 | 38,529 | 35,615 | 38,480 | 29,479 | 36,773 |
| Loss | 680 | 410 | 591 | 1422 | 1,187 | 487 | 1,176 | 509 |
| Export | 1,200 | 7,616 | 8,939 | 20,899 | 23,614 | 7,421 | 24,521 | 12,087 |
| **Total power consumed** | **50,771** | **38,465** | **52,334** | **60,850** | **60,416** | **46,387** | **55,176** | **49,369** |
| **Net power exchange*** | **+4,649** | **−7,116** | **−8,094** | **−20,399** | **−22,114** | **−6,576** | **−23,021** | **−11,587** |

* + for export, – for import.

From the above table, we observed that, except for peak load scenario, the SR has excess generation in all other scenarios. During off-peak solar, peak wind, and peak of solar + wind scenarios, the generation from RE plants alone is almost sufficient to meet the SR load. The RE generation and loads for the three scenarios is depicted in Figure 14 (following page).

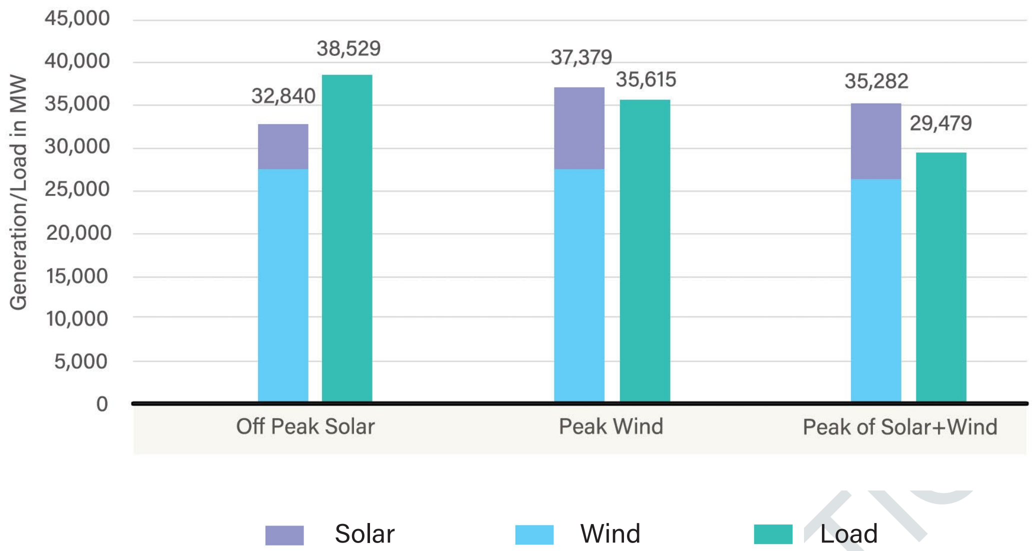



Figure 14: Load & RE generation for off-peak solar, peak wind and peak of solar + wind scenarios (2022)

In these instants, the excess generation in SR has to be exported to other energy-deficit regions or the generation needs to be limited within the region. The inter-regional transmission corridor capacity available from SR to other regions (ER & WR) by 2022 is around 30,150 MW. However, due to insufficient downstream transmission network availability within the region, the maximum excess power that can be transferred from the SR to other regions is around 23,021 MW. The excess generation beyond 23,021 MW needs to be curtailed within the region. Assuming RE continues to retain must-run status, the only option available is the reduction of generation from thermal power plants, beyond the technical minimum. In the above-mentioned scenarios, generation from thermal plants needed to be reduced due to congestion of inter-regional corridors. If inter-regional corridors are not made available, thermal plants cannot maintain even a technical minimum (55% of their capacity).

**“If inter-regional corridors are not made available, thermal plants cannot maintain even a technical minimum.”**

As mentioned in Section 5.2.1, we assumed minimum allowable values for hydro generation in the above analysis. A comparison analysis was carried out, with slight modifications in the generation sources:

- Average hydro generation was considered instead of minimum hydro generation.
- Only existing and planned solar power plants till 2022 were considered (refer Table 13 on page 36).

Table 16 shows the variation in hydro and solar power generation, considering the above modification, along with change in import-export power.

Table 16: Load generation balance for year 2022 considering average hydro (MW)

| Particulars (Total generation capacity) | Peak load | Off-peak load | Peak solar | Off-peak solar | Peak wind | Off-peak wind | Peak of solar + wind | Biggest drop in wind |
|---|---|---|---|---|---|---|---|---|
| Hydro (11,010) | 2,851 | 1,960 | 2,563 | 1,581 | 2,049 | 3,149 | 1,581 | 3,618 |
| Solar (14,614) | 0 | 0 | 8,247 | 3,579 | 6,166 | 5,626 | 5,875 | 5,244 |
| Net power exchange* | +2,204 ↓ | −8,698 ↑ | −3,814 ↓ | −19,919 ↓ | −20,212 ↓ | −5,344 ↓ | −21,336 ↓ | −11,483 ↓ |

* + for export, – for import. Arrows indicate change in magnitude with respect to net power exchange in Table 15.

From the table above, it can be inferred that the addition of proposed solar plants (refer Table 13 on page 36) will further increase export of power during the day time. It is to be noted that hydro generation can be varied so as to reduce the magnitude of power import during peak load conditions.

## 6.4 Modelling Aspects for 2030

This section details certain modelling choices, which are specific to the 2030 simulation.

We incorporated planned pumped-hydro plants, as per data available in various reports. In addition to the state-wise RE targets proposed by the MNRE for year 2022, we have proposed additional solar and wind power plants for the year 2030. With the intention of promoting clean energy production, no new conventional generations have been considered. However, conventional generation plants that have already been planned have been considered for the analysis. The steps involved in calculating the amount of additional solar and wind capacity required by year 2030 to meet the SR's energy projection are explained below.

- CEA's 19th EPS report was used to calculate the state-wise energy demand by 2030.
- Energy contribution from all the existing/planned conventional and RE plants that are expected to be commissioned by 2030 was calculated for each state. Technical minimum of 55% is considered as PLF for thermal plants. Nuclear power energy generation was assumed at 85% PLF. Historical generation data and various documents were analysed to arrive at the %PLF for hydro and RE generations. Based on the analysis, it was found that PLFs of hydro, wind, and solar power generations vary as 14-37%, 24.5-27.5%, and 19%, respectively, throughout the SR.
- SR states facing energy deficit were balanced by adding new solar and wind power plants. Small hydro and biomass generations are not considered in this exercise.
- Solar and wind capacity is added while maintaining the same ratio proposed by MNRE in its provisional breakup of the target of 175 GW for year 2022.

The additional RE capacity proposed is provided in the Table 17 (page 42).

Table 17: Additional RE capacity (GW) requirement for 2030

| State | Solar | Wind | Total |
|---|---|---|---|
| Karnataka | 3.7 | 2.2 | 5.9 |
| Andhra Pradesh | 0 | 0 | 0 |
| Kerala | 6.9 | 2 | 8.9 |
| Tamil Nadu | 9.9 | 5.9 | 15.8 |
| Telangana | 13.2 | 7.9 | 21.1 |
| Puducherry | 0.7 | 0.2 | 0.9 |
| Total | 34.4 | 18.2 | 52.6 |

As per our analysis, during the RE parcel selection, Telangana and Kerala did not have sufficient parcels to accommodate the additional RE capacity required by year 2030. To solve this insufficiency, a few additional parcels from the RE-rich Karnataka and Tamil Nadu were included.

In this analysis, limitations in inter-regional transmission corridors have not been taken into account.

## 6.5 Power Flow Analysis for 2030

Power flow studies have been carried out for SR transmission network conditions in 2030. For this analysis, we took into consideration all proposed transmission network elements and conventional power plants beyond 2022. Table 18 details the number of substations modelled for the year 2030. Figure 15 shows the transformation capacity (MVA) and transmission line length (ckm) considered for the year 2030.

Table 18: State-wise substations count for 2030

| Substation voltage level | Karnataka | Tamil Nadu | Telangana | Kerala | Andhra Pradesh | Puducherry |
|---|---|---|---|---|---|---|
| 765 kV | 4 | 6 | 3 | 0 | 6 | 0 |
| 400 kV | 34 | 56 | 28 | 11 | 41 | 1 |
| 220/230 kV | 132 | 130 | 89 | 42 | 98 | 3 |

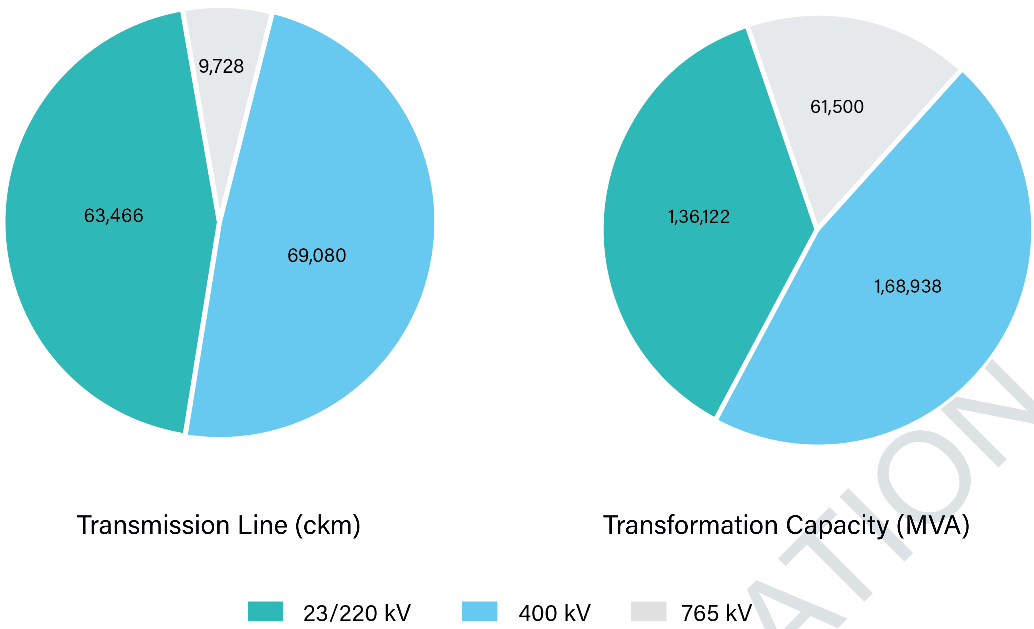



Figure 15: Southern region grid statistics by 2030

The generation capacity considered for year 2030 was 192 GW. Thermal generation has the highest share (64.2 GW), followed by solar (60.9 GW), wind (48.4 GW), hydro (8.3 GW), and nuclear (3.8 GW). Majority of the capacity addition, between 2022 and 2030, are solar (34.4 GW) and wind (18.3 GW) capacity.

In addition, based on CEA plans, we assumed that 6.5 GW of pumped-hydro capacity will become operational by 2030. Depending on scenario-wise load requirement and generation variation, pumped-hydro projects have been considered, either as generating mode or pumping mode. Full capacity of pumped-hydro generation is scheduled (we assume that sufficient water is available).

Power flow analysis was carried out for all the eight scenarios described in Section 5.2 of this report. The system loading, losses, and generation schedule for the scenarios considered for year 2030 are given in Table 19 (following page).

Table 19: Load generation balance for year 2030 (MW)

| Particulars (Total generation capacity) | Peak load | Off-peak load | Peak solar | Off-peak solar | Peak wind | Off-peak wind | Peak of solar + wind | Biggest drop in wind |
|---|---|---|---|---|---|---|---|---|
| Thermal (64,176) | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 |
| Nuclear (3,820) | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 |
| Hydro (8,264) | 366 | 300 | 644 | 271 | 271 | 382 | 164 | 380 |
| Pumped-Hydro as Gen. (6,506) | 6,006 | 6,506 | 0 | 0 | 0 | 6,506 | 0 | 0 |
| Solar (60,941) | 0 | 0 | 33,080 | 11,932 | 21,260 | 20,189 | 18,839 | 19,634 |
| Wind (48,402) | 12,650 | 2,893 | 1,082 | 45,052 | 45,706 | 160 | 39,980 | 6,804 |
| Import | 15,144 | 0 | 827 | 750 | 0 | 0 | 0 | 0 |
| Total power available | 72,518 | 48,051 | 73,986 | 96,357 | 1,05,590 | 65,590 | 97,336 | 65,171 |
| Load | 70,567 | 45,766 | 64,182 | 57,678 | 53,327 | 57,798 | 44,107 | 55,282 |
| Pumped-Hydro as Load | 0 | 0 | 6,506 | 0 | 0 | 0 | 0 | 0 |
| Loss | 1,251 | 626 | 948 | 1,777 | 1,698 | 780 | 1,457 | 687 |
| Export | 700 | 1,659 | 2,350 | 36,903 | 50,565 | 7,012 | 51,772 | 9,202 |
| **Total power consumed** | **72,518** | **48,051** | **73,986** | **96,358** | **105,590** | **65,590** | **97,336** | **65,172** |
| **Net power exchange*** | **+14,444** | **–1,659** | **–1,523** | **–36,153** | **–50,565** | **–7,012** | **–51,772** | **–9,202** |

* + for export, – for import.

From the table above, we observed that in all scenarios, except the peak-load scenario, the SR has excess generation, similar to what was observed in 2022. In off-peak load, peak solar, and biggest drop in wind scenarios, the excess power can be easily sent to other regions with the available transmission corridor. However, in peak wind, off-peak solar, and peak of solar + wind scenarios, SR has excess power of 50.6 GW, 36.2 GW, and 51.8 GW respectively. The projected load is almost completely and solely served through RE generation. The load and RE generation are depicted in Figure 16 (below).

**“In off-peak solar, peak wind, and peak of solar + wind scenarios, SR has excess power of 36 GW, 51 GW, and 52 GW respectively.”**

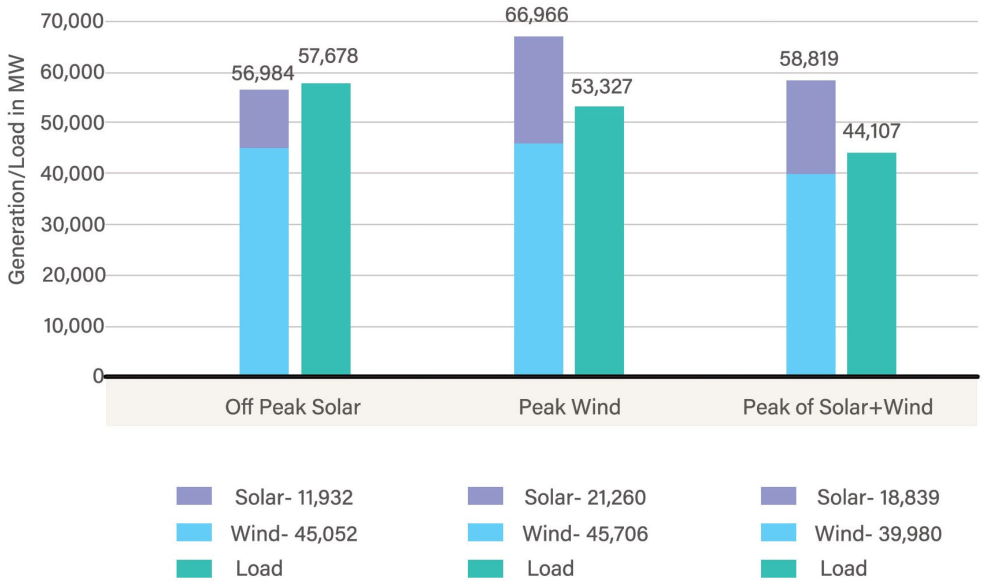



Figure 16: Load and RE generation of SR in off-peak solar, peak wind and peak of solar + wind scenarios (2030)

It is also interesting to note the behaviour of the demand and wind generation pattern from a day before till a day after the three aforementioned scenarios (refer Figure 17 on following page). It can be seen that the demand and the wind generation is almost a flat curve. The solar generation is similar to a bell curve, as expected. A similar pattern of generation from RE plants, as well as load, has been observed on the three days.

While the excess generation has promising possibilities, it is important to note that the current transmission corridors cannot accommodate evacuation of this power—the transmission capacity available from the SR to other regions is around 30,150 MW only. Thus, new inter-regional transmission corridors need to be added from the SR.

This analysis, for 2030, was conducted considering low hydro generation. A subsequent analysis was done considering average hydro generation to examine the effect of variation in hydro power generation on power flows. Table 19 (facing page) provides load generation balance for 2030 with low hydro. Table 20 (page 47) shows the variation in hydro power generation, along with change in import-export power.

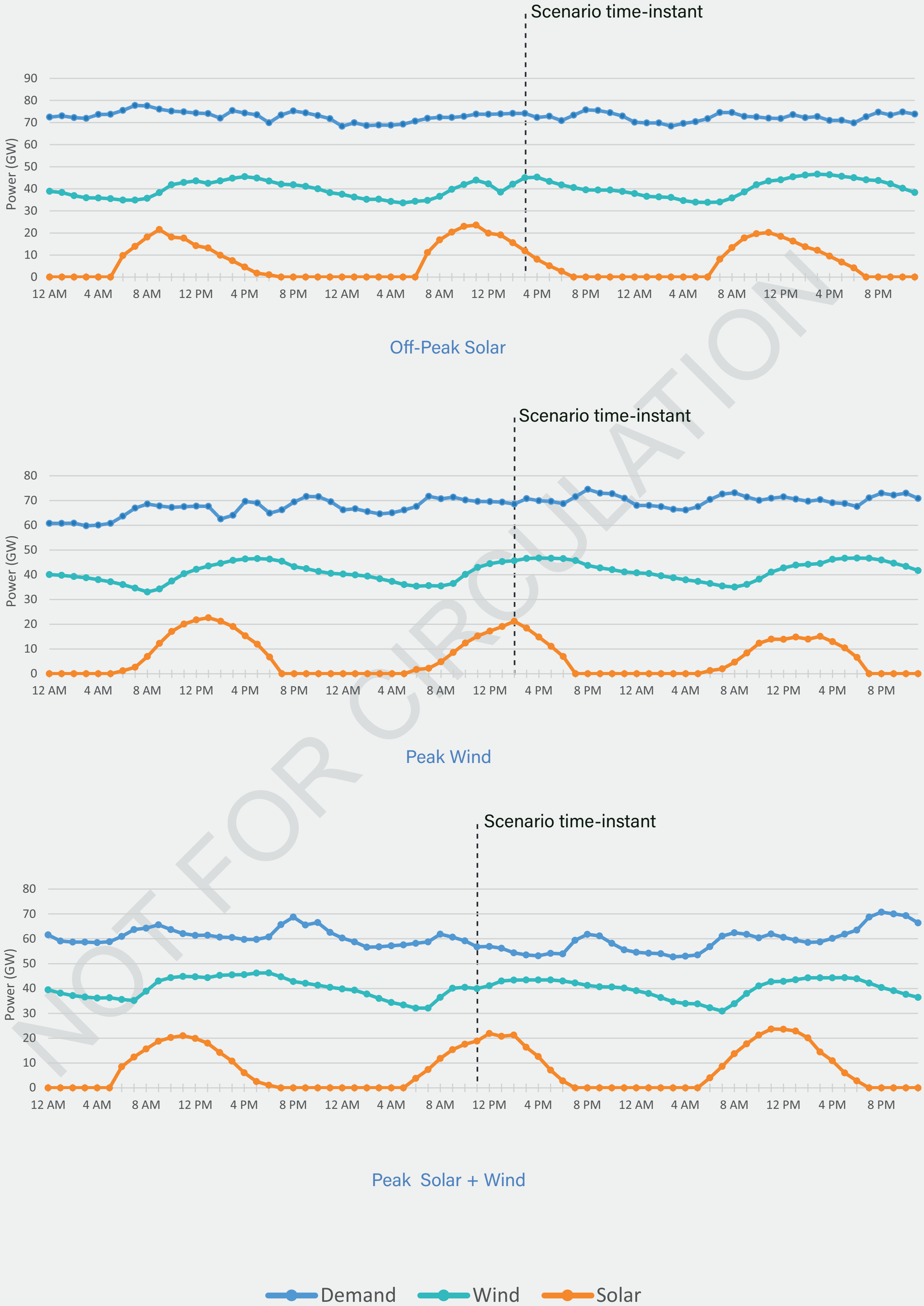



Figure 17: Generation and demand time profiles of select 2030 scenarios

Table 20: Load generation balance for year 2030 considering average hydro (MW)

| Particulars (Total generation capacity) | Peak load | Off-peak load | Peak solar | Off-peak solar | Peak wind | Off-peak wind | Peak of solar + wind | Biggest drop in wind |
|---|---|---|---|---|---|---|---|---|
| Hydro | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 | 35,297 |
| Net power exchange* | +12,238 ↓ | −3,082 ↑ | −3,276 ↑ | −37,432 ↑ | −52,199 ↑ | −9,035 ↑ | −53,055 ↑ | −11,703 ↑ |

* + for export, – for import. Arrows indicate change in magnitude with respect to net power exchange in Table 19 (page 44).

From the table above, it can be inferred that the generation rise from hydro will further increase the export power in all the scenarios except the peak-load scenario. In the peak load scenario, power import has been reduced due to the rise in hydro generation.

## *6.5.1 Case study with 75% PLF for Thermal Generation*

A separate case study has been analysed for the year 2030, assuming a higher load factor for thermal plants, to assess the additional renewable capacity requirement. An important motivation was to reduce the excess generation from RE during monsoon season scenarios. Here, the load factor for all the thermal power plants is assumed to be 75%. The resulting energy deficit, based on 19th EPS projections, was used to plan the additional renewable capacity required for 2030.

Table 21: RE capacity (GW) required for 2030 (with 75% PLF of thermal plants)

| State | Solar | Wind |
|---|---|---|
| Karnataka | 0 | 0 |
| Andhra Pradesh | 0 | 0 |
| Kerala | 2.2 | 3.6 |
| Tamil Nadu | 0 | 0 |
| Telangana | 2.8 | 4.7 |
| Puducherry | 0.2 | 0.3 |
| Total | 5.2 | 8.7 |

The capacity factors of solar and wind plants were based on historical data. We have considered solar and wind capacity ratio at 40:60, assuming that wind generation is easily controllable, compared to solar generation, in case of operational issues. The additional renewable capacity required to meet 2030 demand of the SR is around 13.9 GW, with 75% load factor of thermal power plants. State-wise break up of RE capacity requirement for 2030 is given in Table 21 (page 47).

Power flow studies have been performed for various scenarios, as described in Section 5.2, with 75% load factor of thermal generation. The load generation balance has been reported in Table 22 (below).

Table 22: Load generation balance for 2030 with 75% PLF of thermal plants (MW)

| Particulars (Total generation capacity) | Peak load | Off-peak load | Peak solar | Off-peak solar | Peak wind | Off-peak wind | Peak of solar + wind | Biggest drop in wind |
|---|---|---|---|---|---|---|---|---|
| Thermal (64,176) | 48,132 | 48,132 | 48,132 | 48,132 | 48,132 | 48,132 | 48,132 | 48,132 |
| Nuclear (3,820) | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 | 3,056 |
| Hydro (8,264) | 365 | 300 | 644 | 271 | 271 | 382 | 164 | 380 |
| Pumped-Hydro as Gen. (6,506) | 6,006 | 6,506 | 0 | 0 | 0 | 6,506 | 0 | 0 |
| Solar (31,740) | 0 | 0 | 18,162 | 5,990 | 10,796 | 10,858 | 10,248 | 9,788 |
| Wind (38,741) | 11,268 | 2,670 | 989 | 36,059 | 36,784 | 154 | 35,052 | 6,169 |
| Import | 3,133 | 0 | 2,700 | 750 | 0 | 0 | 0 | 0 |
| Total power available | 71,960 | 60,664 | 73,683 | 94,259 | 99,040 | 69,089 | 96,653 | 67,525 |
| Load | 70,567 | 45,766 | 64,182 | 57,678 | 53,327 | 57,798 | 44,107 | 55,282 |
| Pumped Hydro as Load | 0 | 0 | 6,506 | 0 | 0 | 0 | 0 | 0 |
| Loss | 1,394 | 913 | 1,092 | 1,689 | 1,626 | 1,018 | 1,489 | 868 |
| Export | 0 | 13,985 | 1,904 | 34,892 | 44,087 | 10,273 | 51,057 | 11,375 |
| **Total power consumed** | **71,960** | **60,664** | **73,683** | **94,259** | **99,040** | **69,089** | **96,653** | **67,525** |
| **Net power exchange*** | **+3,133** | **−13,985** | **+796** | **−34,142** | **−44,087** | **−10,273** | **−51,057** | **−11,375** |

* + for export, – for import.

Table 22 reveals that the SR will have excess power of 34.1 GW, 44.1 GW, and 51.1 GW during off-peak solar, peak wind, and peak of solar + wind scenarios, respectively. This is despite reducing the RE capacity addition for 2030 (to 13.9 GW), in this analysis. This could be attributed to MNRE's 2022 RE targets themselves being quite high (around 55 GW by 2022 in SR). Another reason for the excess generation could be due to low load in the monsoon season.

**“SR might face a peak excess power of around 50 GW despite reducing RE capacity addition to 13.9 GW, due to 2022 targets being quite high.”**

There are generally two options for dealing with the issue of excess power from RE: Keeping conventional generation idle or sending excess power to other regions. However, to send such large amounts of excess power (around 50 GW) from the SR, the first step is to identify power-deficit regions across India, and accordingly inter-regional transmission corridors have to be strengthened.

In this study, the reactive power requirements of RE plants on the grid was found to be manageable. Over-voltage conditions, which result from excess of reactive power, were resolved using suitable switching of reactors at appropriate places in the network model. Since, in this study, capacitor banks were not modelled (refer Section 5.1.1), certain localised effects of under-voltage may not have been captured.

# 07 | Findings

## 7.1 2022 Simulations

The key findings from the power flow analysis for 2022 under different scenarios are described in Table 23 below (peak load), Table 24 on the following page (off-peak solar, peak wind, and peak of solar + wind), and Table 25 on the following page (off-peak solar).

Table 23: Network elements overloaded in peak load scenario (2022)

| No. | State | Overloaded elements | Loading (%) | Reason for overloading |
|---|---|---|---|---|
| 1 | Tamil Nadu | 230 kV single circuit (SC) line from Tuticorin (NTPL) to TTPS auto substation | 104 | Supply of load near 230 kV substation from proposed 2×500 MW Tuticorin (NTPL) generation |
| 2 | Telangana | 220 kV SC line from Mamidipalli 400/220 kV SS to Sivarampalli 220/132 kV substation | 101 | More load growth near Sivarampalli substation |
| 3 | Tamil Nadu | 230 kV SC line from Pulianthope 400 kV substation to Vyasarpadi 230 kV substation | 105 | High load at Vyasarpadi and Basin Bridge area |
| 4 | Tamil Nadu | 100 MVA transformer at Athipet substation | 106 | More load growth in Athipet area |
| 5 | Telangana | 100 MVA transformer at Hayath-nagar substation | 106 | High load in Hayathnagar area |
| 6 | Andhra Pradesh | 2×100 MVA transformers of Tade-palli 220 kV substation | 102 | More load growth in Tadepalli area |
| 7 | Andhra Pradesh | 2×100 MVA transformers of Guntur 220 kV substation | 103 | High load in Guntur area |

Table 24: Network elements overloaded off-peak solar, peak wind & peak of solar+wind scenario (2022)

| No. | State | Overloaded elements | Loading (%) | Reason for overloading |
|---|---|---|---|---|
| 1 | Andhra Pradesh | 220 kV SC line from Regulapadu switching station to Gooty RS substation | 118 | Large number of wind plants near Regulapadu area |
| 2 | Karnataka/ Telangana | 220 kV SC line connecting Karnataka (Sedam) to Telangana (Tandur) | 165 | Large number of wind plants near Sedam area of Karnataka and the nearest load centre being Tandur (near Hyderabad) of Telangana |
| 3 | Andhra Pradesh | 3×315 MVA transformers of 400/220 kV Aspiri substation | 112 | Proposed 1000 MW Aspiri wind farm evacuated through this substation. |

Table 25: Network elements overloaded in off-peak solar scenario (2022)

| No. | State | Overloaded elements | Loading (%) | Reason for overloading |
|---|---|---|---|---|
| 1 | Tamil Nadu | 230 kV SC line from Pulianthope 400 kV substation to Vyasarpadi 230 kV substation | 105 | High load at Vyasarpadi and Basin Bridge area |
| 2 | Tamil Nadu | 230 kV SC line from Pasumalai 230 kV substation to Samayanallur 230 kV substation | 105 | More load growth is expected in Mondipatti area |

Network augmentation required to resolve the overloading issues, mentioned in Table 23 (page 51), Table 24 (above) & Table 25 (above), along with transmission lines required for new substations for 2022, is given in Appendix III.

Apart from the above-mentioned network element overloading, inter-regional transmission corridors require significant strengthening to export excess generation to other regions, during off-peak solar, peak wind, and peak of solar+wind scenarios.

## 7.2 2030 Simulations

The key findings from the power flow analysis for 2030, including the network element overloaded, overloaded percentage, and possible reason for overloading, has been provided in Table 26 (facing page):

Table 26: Network elements overloaded in all scenarios (2030)

| No. | State | Overloaded elements | Loading (%) | Reason for overloading |
|---|---|---|---|---|
| 1 | Tamil Nadu | 220 kV double circuit (DC) line connecting Pulianthope to Basin bridge LILOed at Vyasarpadi | 150 | More load growth at Vyasarpadi and B Bridge substations |
| 2 | Andhra Pradesh | 220 kV SC line connecting Nunna Vijayawada to Gunadala 220 kV substation | 150 | More load growth in Gunadala area |
| 3 | Telangana | Three 220 kV SC lines connecting Ramagundam generating station to Malayalapalli (NTPC) substation | 141 | More lift irrigation loads near Vemnur and Medaram area |
| 4 | Telangana | 220 kV SC line connecting Nagarjun Sagar generating station to Chellakurthi switching station | 153 | More load expected in and around Chellakurthi and Puliyathanda areas |
| 5 | Tamil Nadu | 220 kV SC line from Trichy substation to Alundur substation | 117 | High load at Trichy substation has to be served through one 220 kV line from Alundur |
| 6 | Andhra Pradesh | 220 kV SC line connecting Gazuaka PG 400 kV substation to Gazuaka 220 kV substation | 117 | To serve load of proposed Gopalapatnam 220 kV substation |
| 7 | Andhra Pradesh | 220 kV SC line from Gazuaka PG to Parwada substation | 110 | High load near Parwada area |
| 8 | Karnataka | 220 kV SC line connecting Yelahanka to Hebbal tap point | 113 | The new Yelahanka PG 400 kV substation will act as an additional source to supply the growing demand of Bangalore Metropolitan Area Network (BMAN), with more power flowing through Yelahanka to Hebbal tap line to serve BMAN load |
| 9 | Karnataka | 220 kV SC line from Yelahanka to Manyata substation | 110 | The new Yelahanka PG 400 kV substation will act as an additional source to supply growing demand of Bangalore Metropolitan Area Network (BMAN), with huge amount of power flowing through Yelahanka to Manyata line to serve BMAN load |
| 10 | Tamil Nadu | 230 kV SC line from Arasur 400 kV to Arasur 230 kV substation | 116 | More load growth near Arasur 230 kV substation area |
| 11 | Telangana | 220 kV DC line connecting Warangal/ Oglapuram 400 kV substation to Nagaram switching station | 113 | More load growth at Warangal 220 kV substation and Palakurthy 220 kV substation |
| 12 | Andhra Pradesh | 2×315 MVA transformers at 400 kV Tekkali substation | 133 | Supply projected load near Tekkali, Palakonda, and Garividi area |
| 13 | Andhra Pradesh | 220 kV DC line connecting Ghani 400 kV substation to Somayajalapalli substation | 103 | Around 1004 MW of solar plant capacity is connected to Ghani 400 kV substation |

| No. | State | Overloaded elements | Loading (%) | Reason for overloading |
|---|---|---|---|---|
| 14 | Andhra Pradesh | 220 kV DC line connecting Dhone switching station to Somayajulapalli | 132 | Large number of wind capacity connected in Dhone and Nansuralla area |
| 15 | Karnataka | 400 kV SC line connecting RTPS to Guddadahalli substation | 131.4 | High-solar capacity proposed at Guddadahalli area |
| 16 | Karnataka/ Telangana | 220 kV DC line connecting Sedam (Karnataka) to Tandur (Telangana) | 132.8 | Large amount of wind capacity is expected in Sedam region of Karnataka and Hyderabad (Telangana) is the nearest load centre for this generation |
| 17 | Tamil Nadu | 230 kV DC line connecting Madurai to Pasumalai substation | 111.6 | More wind plants around Madurai substation |
| 18 | Tamil Nadu | 230 kV SC line from Pasumalai to Konthagai substation | 110.8 | More wind plants around Madurai substation |

Network augmentation required to resolve overloading issues mentioned in Table 26 (page 53), along with the list of new substations/transmission lines required for 2030, is given in Appendix IV.

From the 2030 analysis, it is also observed that the excess power, of the order of 50 GW, needs to be exported from the Southern Region.

## 7.3 Illustrative Cost Analysis

As seen from the analyses, transmission network elements need to be strengthened and new substations/ transmission lines need to be set up to accommodate transfer of excess power from the SR to other states with lower generation. This requires some investment. We conducted an illustrative cost analysis, accounting for:

- The transmission network proposed by CSTEP to evacuate the additional RE plants required to meet 2030 demand

- Transmission strengthening required to resolve network constraints under various scenarios

Costs for these upgrades have been collected from various publicly available sources, as mentioned in Section 5.3. Table 27 (facing page) shows the total investment required for the new network elements proposed by CSTEP, for 2022 and 2030.

Table 27: Summary of investment required for 2022 & 2030

| Year | Particulars | Capacity addition proposed | | | Investment required in INR crores |
|---|---|---|---|---|---|
| | | 765 kV | 400 kV | 230/220 kV | |
| 2022 | Transmission lines (ckm) | 0 | 128 | 248 | 328 |
| | Transformation capacity (MVA) | 0 | 315 | 600 | 57 |
| 2030 | Transmission lines (ckm) | 130 | 3,277 | 1,859 | 6,303 |
| | Transformation capacity (MVA) | 3,000 | 1,200 | 1,7620 | 2,557 |
| **Total investment required by 2030** | | | | | **9,245** |

The table shows that the total investment required for network strengthening amounts to around INR 385 crores for year 2022 and INR 8,860 crores for year 2030, respectively. It is to be noted that these investment figures are for network strengthening, proposed by CSTEP only.

# POLICY RECOMMENDATIONS

The above study reveals that a significant amount of RE can be integrated into the grid. However, for the grid to be stable, several challenges must be addressed:

- Conventional generation will need to be backed down to accommodate increasing levels of RE in the coming years. Our study shows that there is excess power of the order of around 23 GW and 51 GW respectively for 2022 and 2030 for peak of solar + wind scenario instant. This is with all thermal generators operating at technical minimum, implying the need to shut down thermal plants for the duration of the RE influx.

- The investment required to strengthen intra-region transmission infrastructure is around INR 9,245 crores by 2030, in addition to the transmission network strengthening plans by CEA.

- To evacuate the proposed RE plant generation from the SR under the must-run condition, the inter-regional transmission infrastructure requires significant upgrades, to transfer excess power to other regions.

Resolving these can take India on to a path where RE is the mainstream electricity source. We propose the following policy measures to enable this transformation:

- Encourage thermal generators to schedule routine maintenance in the months of June, July, and August (monsoon season), in view of high renewable energy injections into the grid. Further, it is prudent to curtail wind generation instead of solar generation, due to the lower relative cost of the latter.

- Examine the case for a robust framework for renewable energy curtailment, especially since the SR is likely to generate excess energy during the monsoon season, according to studies for both 2022 & 2030 scenarios.

- Conduct grid balancing studies to examine the maximum limit of RE addition. This is necessary, considering that while SR states have enough RE potential to meet the energy requirement by 2030, RE generation is intermittent in nature.

- Identify energy-deficit regions to balance the excess generation, especially during the monsoon season; accordingly, propose suitable inter-regional transmission corridors. This requires a separate study.

# 08 | Conclusion

The power flow scenarios for the year 2022 and 2030 reveal difficult operational situations in the off-peak solar, peak wind, and peak of solar + wind scenarios.

While this opens up opportunities for exporting the entire excess power to other regions, it can be possible only if there is demand in the other regions. Assessing the absorption capacity of other regions and the availability of the transmission corridors were out of scope of this study. Considering that the other regions will also have a similar, if not the same thrust for development of renewable energy, similar situations of excess power may occur there as well. Hence, it is not appropriate to assume that the entire power generated can be exported from the SR to other regions.

We also observed that the conditions in these scenarios were not anomalous and were seen on preceding and subsequent days. Thus, such conditions are likely to be representative of these scenarios.

In a situation like this, the generation has to be reduced to balance the demand, in case the power cannot be exported (there is insufficient energy storage capacity to make a difference, as per projections). Looking at Table 19 (page 44), the only choice is between backing down thermal, solar, or wind.

These scenarios are possible when the same pattern of load growth, as we have assumed in the report, occurs across the region. Significant changes in spatial and temporal distribution of demand can result in different outcomes. Such variation in demand is difficult to predict at this stage. It is also worth repeating that while estimating the power injection from conventional generation, we assumed that no new projects are added. However, conventional generation projects that are under construction were assumed to be commissioned on time, as per the relevant sources (see Section 5.3 for details).

The study reveals that there is exceptionally large renewable energy potential in the southern region. With the achievement of MNRE's RE targets for the SR states by 2022, the region can act as a net exporter in all the scenario instants except peak load—provided the inter-regional transmission corridors from SR are strengthened to accommodate this excess power. Intra-regional transmission network strengthening is required as well, requiring an investment of around INR 385 crore.

SR needs an addition of 52.6 GW of renewable energy capacity to match the projected electrical energy demand in the southern region, by 2030 (as per 19th EPS projections). This level of RE injection could pose huge operational challenges on the transmission grid. The study projects that around INR 8,860 crore would be needed, after 2022, to strengthen and upgrade the transmission infrastructure.

**These upgrades are required over and above the network expansion plans already published by CEA.** This highlights the critical need for transparent, high-quality power flow studies to continue the seamless incorporation of greater RE into the Indian grid. However, detailed studies are required to verify and plan for higher RE penetration in the future. Specifically, production cost simulation studies are needed to understand the cost and emission implications of dispatching conventional generation around the must-run RE sources. Additionally, short-circuit and transient stability studies will be required before making large-scale changes to the grid.

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# Appendix I

Wastelands comprise the following categories:

- Salt-affected land: Land that has excessive salt in the soil with grasses grown in patch

- Gullied land: Land that results from terrain deformation due to localised surface run-off, resulting in the formation of perceptible channels causing undulating terrain.

- Scrubland: Land that has shallow and skeletal soil, chemically degraded slopes, severely eroded aridity with scrubs in the landscape

- Sandy area: Land in coastal, riverine or inland areas

- Desertic sand: Sand developed in situ or transported by Aeolian processes

- Coastal sand: Sand accumulated as a strip along the sea-coast

- Riverine sands: Accumulations in the flood plain as sheets due to river flooding

- Barren rocky/Stony waste: Land that has rock exposures often barren and devoid of soil and vegetation cover

# Appendix II

## 12.1. Solar Model (CSTEM PV)

CSTEP developed the CSTEM-PV (CSTEP's Solar Techno-Economic Model for Photovoltaics) web application to perform techno-economic assessments for proposing solar PV plants in India. The application uses publicly available data, typically found in equipment datasheets. Figure 17 (page 46) presents an overview of the model inputs and outputs in CSTEM-PV.

For comprehensive documentation of this web application, kindly refer (Sridhar & Thirumalai, 2018).

## 12.2. Wind Model (SAM)

The System Advisor Model (SAM) software was developed by the National Renewable Energy Laboratory (NREL), USA for techno-economic assessment in the development and integration of RE generator plants. SAM contains several performance and financial modules that can be combined to accurately model most RE generation projects.

The SAM software is available as a desktop application as well as a shared library with an API. This study utilised the API for plant-wise modelling of wind farms. For comprehensive documentation on the software, kindly refer (J. M. [National R. E. L. (NREL) Freeman Golden, CO (United States)] et al., 2018).

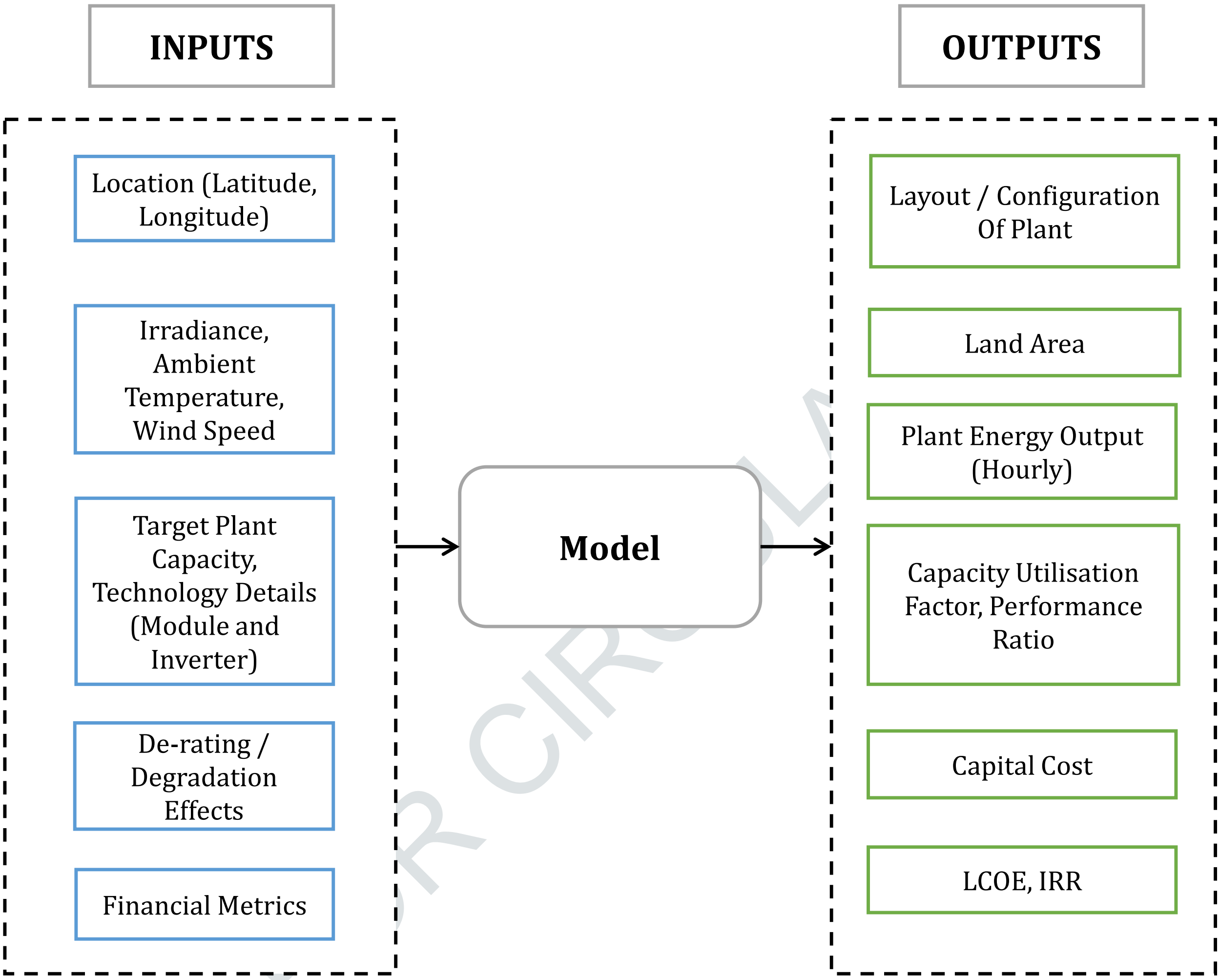


Figure 18: Inputs and outputs of the CSTEM-PV modelling framework

# Appendix III

Table 28: Substation augmentation proposed for 2022

| No. | Substation name | Voltage level (kV) | Transformation capacity (No. × Unit Capacity in MVA) | Cost in INR crores | State[1] |
|---|---|---|---|---|---|
| 1 | Athipet | 230/110 | 2×100 | 9.4 | TN |
| 2 | Hayatnagar | 220/33 | 1×100 | 11.0 | TS |
| 3 | Aspiri | 400/220 | 1×315 | 21.3 | AP |
| 4 | Tadepalli | 220/132 | 1×100 | 6.0 | AP |
| 5 | Guntur | 220/132 | 2×100 | 9.4 | AP |
| **Total** | | | | **57** | |

Table 29: Transmission lines proposed for 2022

| No. | From Substation | To Substation | Voltage level (kV) | No of circuits | Cost in INR crores | State[1] |
|---|---|---|---|---|---|---|
| 1 | Pulianthope | Vyasarpadi | 230 | 1 | 4.1 | TN |
| 2 | Vyasarpadi | Basin bridge | 230 | 1 | 4.1 | TN |
| 3 | Pasumalai | Samayanallur | 230 | 1 | 12.0 | TN |
| 4 | Samayanallur | Alagarkoil | 230 | 1 | 29.3 | TN |
| 5 | Tuticorn (NTPL) | TTPS auto | 230 | 1 | 10.8 | TN |
| 5 | Omega | Sholinganallur | 230 | 2 | 32.6 | TN |
| 7 | Thervaikandigai | Korattur | 400 | 2 | 78.1 | TN |
| 8 | Thervaikandigai | Manali | 400 | 2 | 62.4 | TN |
| 9 | Mamidipalli | Sivarampalli | 220 | 1 | 13.0 | TS |
| 10 | Sedam | Tandur | 220 | 1 | 37.4 | KA+TS |
| 11 | Regulapadu Switching Station | Gooty RS | 220 | 1 | 44.4 | AP |
| **Total** | | | | | **328** | |

[1] AP: Andhra Pradesh, TN: Tamil Nadu, KA: Karnataka, TS: Telangana

# Appendix IV

Table 30: Substations proposed for 2030

| No. | Substation name | Voltage level (kV) | Transformation capacity (No. × Unit Capacity in MVA) | Cost in INR crores | Type of proposal | State |
|---|---|---|---|---|---|---|
| 1 | Murari | 220/132 | 3×160 | 111.0 | New Substation | AP |
| 2 | Vinukonda | 220/132 | 3×160 | 111.0 | New Substation | AP |
| 3 | Gopalapatnam | 220/132 | 3×160 | 111.0 | New Substation | AP |
| 4 | Thullur | 220/132 | 3×160 | 111.0 | New Substation | AP |
| 5 | AP Carbides | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 6 | Bhimavaram | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 7 | Chinakampally | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 8 | Gangavram | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 9 | Gooty | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 10 | Gudivada | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 11 | Markapur | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 11 | Nagari | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 13 | Ongole | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 14 | Peddapuram | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 15 | Podili | 220/132 | 2×160 | 18.0 | Augmentation | AP |
| 16 | Rajampet | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 17 | Srisailam Rbph | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 18 | Tekkali | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 19 | VTS | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 20 | Eluru | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 21 | Cherivi | 220/132 | 1×160 | 9.0 | Augmentation | AP |
| 22 | Lingayapalem | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 23 | Appayadorapalem | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 24 | Kuppam | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 25 | Gannavaram | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 26 | Guntur | 220/132 | 2×100 | 11.9 | Augmentation | AP |
| 27 | Palakonda | 220/132 | 1×100 | 6.0 | Augmentation | AP |
| 28 | Moodabidre | 220/110 | 3×100 | 44.4 | New Substation | KA |
| 29 | MK Hubli | 220/110 | 1×100 | 5.9 | Augmentation | KA |
| 30 | Raichur | 220/110 | 1×100 | 5.9 | Augmentation | KA |
| 31 | Sirsi | 220/110 | 1×50 | 5.9 | Augmentation | KA |
| 32 | SRS Hubli | 220/110 | 1×100 | 5.9 | Augmentation | KA |
| 33 | T K halli | 220/110 | 1×100 | 5.9 | Augmentation | KA |

| No. | Substation name | Voltage level (kV) | Transformation capacity (No. × Unit Capacity in MVA) | Cost in INR crores | Type of proposal | State |
|---|---|---|---|---|---|---|
| 34 | Afzalpur (Ganagapura) | 220/110 | 1×100 | 5.9 | Augmentation | KA |
| 35 | Sindagi | 220/110 | 1×100 | 5.9 | Augmentation | KA |
| 36 | Nagarbhavi | 220/66 | 3×150 | 41.2 | New Substation | KA |
| 37 | Dasanakoppalu | 220/66 | 3×150 | 40.3 | New Substation | KA |
| 38 | HSR layout | 220/66 | 1×150 | 10.3 | Augmentation | KA |
| 39 | KIADB Doddaballapur | 220/66 | 1×50 | 9.3 | Augmentation | KA |
| 40 | Kolar | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 41 | Kushalnagar | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 42 | Madhuvanahally | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 43 | Malur | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 44 | Naganathapura | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 45 | Vajamangala | 220/66 | 2×100 | 23.0 | Augmentation | KA |
| 46 | Gollahalli | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 47 | Vrindavan alloy | 220/66 | 1×150 | 10.3 | Augmentation | KA |
| 48 | Exora | 220/66 | 1×150 | 10.3 | Augmentation | KA |
| 49 | Jigani | 220/66 | 1×150 | 10.3 | Augmentation | KA |
| 50 | Manyata | 220/66 | 1×150 | 10.3 | Augmentation | KA |
| 51 | Nagamangala | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 52 | Srinivasapura | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 53 | Kumbalgod | 220/66 | 2×150 | 20.6 | Augmentation | KA |
| 54 | Maddur | 220/66 | 1×100 | 11.5 | Augmentation | KA |
| 55 | Talaguppa | 765/400 | 2×1500 | 499.4 | New Substation | KA |
| 56 | Palakkad | 220/110 | 1×100 | 5.9 | Augmentation | KL |
| 57 | Taliparamba | 220/110 | 1×100 | 5.9 | Augmentation | KL |
| 58 | Trichur | 220/110 | 1×200 | 8.0 | Augmentation | KL |
| 59 | Vadakara (Orakattery) | 220/110 | 1×100 | 5.9 | Augmentation | KL |
| 60 | Avadi | 230/110 | 3×160 | 111.0 | New Substation | TN |
| 61 | Padapai | 230/110 | 3×160 | 111.0 | New Substation | TN |
| 62 | Basin Bridge | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 63 | Cuddalore | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 64 | Deviakurchi | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 65 | Eachengadu | 230/110 | 2×100 | 11.9 | Augmentation | TN |
| 66 | Guindy | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 67 | Gummidipoondi | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 68 | Kits Park | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 69 | Koyambadu cmrl | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 70 | Mambakkam | 230/110 | 2×100 | 11.9 | Augmentation | TN |
| 71 | Mylapur | 230/110 | 2×100 | 11.9 | Augmentation | TN |
| 72 | Oragadam | 230/110 | 1×100 | 5.9 | Augmentation | TN |

| No. | Substation name | Voltage level (kV) | Transformation capacity (No. × Unit Capacity in MVA) | Cost in INR crores | Type of proposal | State |
|---|---|---|---|---|---|---|
| 73 | Pudanchandi | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 74 | Pugulur | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 75 | Ranganathpuram | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 76 | SP Coil | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 77 | Tondiarpet | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 78 | Trichy | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 79 | Udayathur | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 80 | Unjanni | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 81 | Vinnamangalam | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 82 | Hosur | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 83 | Athipet | 230/110 | 2×100 | 11.9 | Augmentation | TN |
| 84 | Coimbatore | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 85 | Tiruverkadu | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 86 | Sankarapuram | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 87 | Savasapuram | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 88 | Valayapatty | 230/110 | 2×100 | 11.9 | Augmentation | TN |
| 89 | Vysarpadi | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 90 | CMRL Central Jail | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 91 | Mondipatty | 230/110 | 2×100 | 11.9 | Augmentation | TN |
| 92 | R A Puram | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 93 | Porur | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 94 | Tirupattur | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 95 | Singapuram | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 96 | Kurukkathi | 230/110 | 1×100 | 5.9 | Augmentation | TN |
| 97 | Salem TN | 400/110 | 1×200 | 11.1 | Augmentation | TN |
| 98 | Sriperumbudur | 400/110 | 1×200 | 11.1 | Augmentation | TN |
| 99 | Tharamani N | 400/110 | 1×200 | 11.1 | Augmentation | TN |
| 100 | Korattur N | 400/110 | 1×200 | 11.1 | Augmentation | TN |
| 101 | Sholinganallur | 400/110 | 2×200 | 22.2 | Augmentation | TN |
| 102 | B G Kothur LIS | 220/11 | 2×100 | 41.0 | New Substation | TS |
| 103 | V K Ramavaram LI | 220/11 | 2×100 | 41.0 | New Substation | TS |
| 104 | Mandaipalle | 220/132 | 3×160 | 111.0 | New Substation | TS |
| 105 | Nizampet | 220/132 | 3×160 | 111.0 | New Substation | TS |
| 106 | Adilabad | 220/132 | 3×160 | 111.0 | New Substation | TS |
| 107 | Bellampally | 220/132 | 2×100 | 11.9 | Augmentation | TS |
| 108 | Ghanapur | 220/132 | 1×160 | 9.0 | Augmentation | TS |
| 109 | KTPS | 220/132 | 1×50 | 6.0 | Augmentation | TS |
| 110 | Malayalapalli | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 111 | Sadashivpet | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 112 | Siddipet | 220/132 | 1×100 | 6.0 | Augmentation | TS |

| No. | Substation name | Voltage level (kV) | Transformation capacity (No. × Unit Capacity in MVA) | Cost in INR crores | Type of proposal | State |
|---|---|---|---|---|---|---|
| 113 | Huzurabad | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 114 | Mahabubabad | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 115 | Hayathnagar | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 116 | Miyapur | 220/132 | 1×160 | 9.0 | Augmentation | TS |
| 117 | Husnabad | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 118 | Choutuppal | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 119 | Thimmajjipet | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 120 | Nagarkurnool | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 121 | Narsapur | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| 122 | Manikonda | 220/132 | 1×100 | 6.0 | Augmentation | TS |
| **Total** | | | | **2557** | | |

Table 31: Transmission lines proposed for 2030

| No. | From Substation | To Substation | Voltage level (kV) | No of circuits | Cost in INR crores | State |
|---|---|---|---|---|---|---|
| 1 | Tadikonda | Nagarjuna university | 220 | 1 | 7.2 | AP |
| 2 | VTPS | Nagarjuna university | 220 | 1 | 7.2 | AP |
| 3 | Ankar | Achutapuram | 220 | 2 | 27.1 | AP |
| 4 | PD puram | Murari | 220 | 2 | 15.1 | AP |
| 5 | Bommur | Murari | 220 | 2 | 15.1 | AP |
| 6 | Narasaraopet | Vinukonda | 220 | 1 | 10.3 | AP |
| 7 | Podili | Vinukonda | 220 | 1 | 10.3 | AP |
| 8 | Gopalapatnam | Gazuwakka | 220 | 2 | 12.3 | AP |
| 9 | Thullur | Sattenpalle | 220 | 2 | 35.9 | AP |
| 10 | Upper Sileru PSP | Pendurthi | 220 | 1 | 119.4 | AP |
| 11 | Upper Sileru PSP | Donkarai | 220 | 1 | 23.8 | AP |
| 12 | Nunna Vijaywada | Gunadala | 220 | 1 | 18.1 | AP |
| 13 | Gazuwakka PG | Gazuwakka | 220 | 1 | 9.4 | AP |
| 14 | Gazuwakka | Parwada | 220 | 1 | 7.7 | AP |
| 15 | Ghani | Somayajulapalli | 220 | 1 | 15.9 | AP |
| 16 | Dhone | Somayajulapalli | 220 | 1 | 33.2 | AP |
| 17 | Kalpaka | Achutapuram | 400 | 1 | 13.1 | AP |
| 18 | Koriprolu | Achutapuram | 400 | 1 | 13.1 | AP |
| 19 | Upper Sileru PSP | Kalpakka | 400 | 2 | 239.8 | AP |
| 20 | SRS Peenya | Nagarbhavi | 220 | 3 | 241.1 | KA |
| 21 | Kadakola | Dasanakoppalu | 220 | 1 | 4.7 | KA |
| 22 | Basthipura | Dasanakoppalu | 220 | 1 | 4.7 | KA |
| 23 | UPCL | Moodabidre | 220 | 2 | 25.4 | KA |
| 24 | Hebbal | Yelahanka | 220 | 1 | 20.7 | KA |
| 25 | Manyata | Yelahanka | 220 | 1 | 27.1 | KA |

| No. | From Substation | To Substation | Voltage level (kV) | No of circuits | Cost in INR crores | State |
|---|---|---|---|---|---|---|
| 26 | Sedam | Tandur | 220 | 2 | 109.8 | KA |
| 27 | Sindhanoor | Raichur New | 400 | 4 | 433.6 | KA |
| 28 | Kudgi | Vijayapura PS | 400 | 2 | 168.8 | KA |
| 29 | Yalwar | Vijayapura PS | 400 | 2 | 180.8 | KA |
| 30 | Talaguppa | Sharavathy PSS | 400 | 4 | 299.2 | KA |
| 31 | RTPS | Guddadahalli | 400 | 1 | 280.7 | KA |
| 32 | Narendra (Kudgi) | Talaguppa | 765 | 1 | 187.0 | KA |
| 33 | Madhugiri (Tumkur) | Talaguppa | 765 | 1 | 187.0 | KA |
| 34 | Erode | Pugalur | 230 | 1 | 41.7 | TN |
| 35 | Erode | Pudanchandi | 230 | 1 | 65.9 | TN |
| 36 | Kalivelampatty | Rasipalyam | 230 | 2 | 19.4 | TN |
| 37 | Salem TN | Karuppur | 230 | 1 | 5.8 | TN |
| 38 | MTPS | Karuppur | 230 | 1 | 5.8 | TN |
| 39 | Singarpettai | Keezhakuppam | 230 | 1 | 7.2 | TN |
| 40 | Salem | Keezhakuppam | 230 | 1 | 7.2 | TN |
| 41 | Kongal nagaram | Udumalpet | 230 | 2 | 17.2 | TN |
| 42 | CMRL central jai | Membalam | 230 | 1 | 210.7 | TN |
| 43 | PP Nallur | Narimanam | 230 | 1 | 9.1 | TN |
| 44 | Thanjavur | Narimanam | 230 | 1 | 9.1 | TN |
| 45 | PP Nallur | Narimanam | 230 | 1 | 9.3 | TN |
| 46 | Thiruvarur | Narimanam | 230 | 1 | 9.3 | TN |
| 47 | Ponnapuram | Poolavady | 230 | 1 | 7.3 | TN |
| 48 | Mywady | Poolavady | 230 | 1 | 7.3 | TN |
| 49 | Sathumadurai | Arni | 230 | 2 | 27.3 | TN |
| 50 | Shenpagapudur | Kolapallur | 230 | 2 | 26.7 | TN |
| 51 | Thiruvanmiyur | Tharamani | 230 | 2 | 8.8 | TN |
| 52 | Rasipalyam | Tirupur | 230 | 1 | 9.6 | TN |
| 53 | Kurukkathi | Tirupur | 230 | 1 | 9.6 | TN |
| 54 | Theni | Usilampatty | 230 | 1 | 6.0 | TN |
| 55 | Madurai | Usilampatty | 230 | 1 | 6.0 | TN |
| 56 | Nemmalli Thippiyakudi | Vellalaviduthi | 230 | 1 | 35.6 | TN |
| 57 | Avadi | Korattur | 230 | 2 | 14.8 | TN |
| 58 | Padapai | S V Chatram | 230 | 2 | 19.4 | TN |
| 59 | Pulianthope | Vysarpadi | 230 | 1 | 7.7 | TN |
| 60 | Vysarpadi | Basin bridge | 230 | 1 | 7.7 | TN |
| 61 | Alundur | Trichy | 230 | 1 | 35.2 | TN |
| 62 | Arasur 400 | Arasur 230 | 230 | 1 | 14.5 | TN |
| 63 | Madurai | Pasumalai | 230 | 2 | 41.1 | TN |
| 64 | Pasumalai | Konthagai | 230 | 1 | 35.2 | TN |
| 65 | S V Chatram | Mamandur PS | 400 | 2 | 71.8 | TN |
| 66 | Guindy | Mamandur PS | 400 | 2 | 71.8 | TN |

| No. | From Substation | To Substation | Voltage level (kV) | No of circuits | Cost in INR crores | State |
|---|---|---|---|---|---|---|
| 67 | Sivaganga PS | Konthagai | 400 | 2 | 95.4 | TN |
| 68 | Sivaganga PS | Thennampatti | 400 | 2 | 151.9 | TN |
| 69 | Karambayam PS | Ariyalur (Villupuram) | 400 | 4 | 445.6 | TN |
| 70 | Sembatty PS | Madurai (Checkanurani) | 400 | 4 | 256.0 | TN |
| 71 | Karimangalam PS | Ramagundem | 400 | 2 | 382.4 | TN |
| 72 | Mandamarri PS | Ramagundem | 220 | 3 | 32.0 | TS |
| 73 | Jaipur | Ramagundem | 220 | 2 | 24.0 | TS |
| 74 | Khammam | Ayyagaripally | 220 | 1 | 7.0 | TS |
| 75 | W K palli | Ayyagaripally | 220 | 1 | 7.0 | TS |
| 76 | Medchal | Mandaipalle | 220 | 2 | 8.5 | TS |
| 77 | Malkaram | Mandaipalle | 220 | 2 | 8.5 | TS |
| 78 | Nizampet | Narsapur | 220 | 2 | 53.8 | TS |
| 79 | Adilabad | Nirmal | 220 | 2 | 61.4 | TS |
| 80 | Ramagundam | Malyalapalli | 220 | 3 | 24.2 | TS |
| 81 | Chellakurthy | Nagrjuna Sagar | 220 | 1 | 5.5 | TS |
| 82 | Tallapalli | Nagrjuna Sagar | 220 | 1 | 5.5 | TS |
| 83 | Ogalapuram | Nagaram | 220 | 2 | 34.4 | TS |
| 84 | Sadashivpet PS | Shankarpalli | 400 | 2 | 67.1 | TS |
| 85 | Wanaparthy PS | Yedula LIS | 400 | 2 | 92.0 | TS |
| 86 | Makthal PS | Veltoor | 400 | 2 | 128.0 | TS |
| 87 | Kamalapur PS | Warangal new | 400 | 2 | 64.0 | TS |
| 88 | Mathampalli PS | Suryapet | 400 | 2 | 140.0 | TS |
| 89 | Peddemul PS | Shankarapalli | 400 | 2 | 114.2 | TS |
| 90 | Maldakal PS | Uddandapur LIS | 400 | 2 | 68.0 | TS |
| 91 | Veltoor | Ghattu solar park | 400 | 2 | 170.7 | TS |
| 92 | Yedula LIS | Ghattu solar park | 400 | 2 | 170.7 | TS |
| **Total** | | | | | **6303** | |

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