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A 100% RENEWABLE POWER SYSTEM ACROSS INDIA BY 2050

White paper on power system optimisation

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India has committed in the 2015 Paris Agreement to reduce greenhouse gas (GHG) emissions intensity by 33–35% below 2005 levels and achieve 40% of installed electric power capacity from non-fossil sources by 2030[1]. In its efforts to further its global climate leadership, at the UN General Assembly in 2019 the country pledged a target of 450 GW of renewable energy (RE) to be achieved by 2030, which translates into about 60% of the power capacity being renewables[2]. India has taken remarkable strides forward in reforming its power sector in recent decades, with electricity shortages declining and connectivity approaching almost all households across the country.

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However, there is still a long way to go in terms of reaching developed-world standards. India's per capita electricity consumption is around 1150 kWh, against a global average of almost 3000 kWh[3]. Electricity generation is also the largest contributor to India's energy-related GHG emissions and a major contributor to the local air pollution predominant in the cities as well as to other environmental issues.

Historically, the power sector in India has relied on coal-based generation to satisfy the growing electricity demand across most states in the country. In recent times, significant growth in the share of installed capacity of renewables has been observed in some states and the country in general. States such as Gujarat, Rajasthan, Karnataka and Tamil Nadu are among the leading states in the country with respect to installed renewable capacities (see Figure 1). As indicated in Figure 1, coal still accounts for around 69% of the electricity generation; however, the capacity factors, or Full Load Hours (FLH), have been decreasing on a year-on-year basis. Several coal power plants are in financial distress [3], and air pollution has increasingly become a national problem causing adverse health impacts and negative economic consequences. The huge water requirements of coal power plants are causing increased levels of water stress and competing with irrigation demand for agriculture. These challenges indicate that the trend towards growing capacity addition of renewables is expected to continue and is required to be accelerated in order to meet India’s ambitious climate targets.

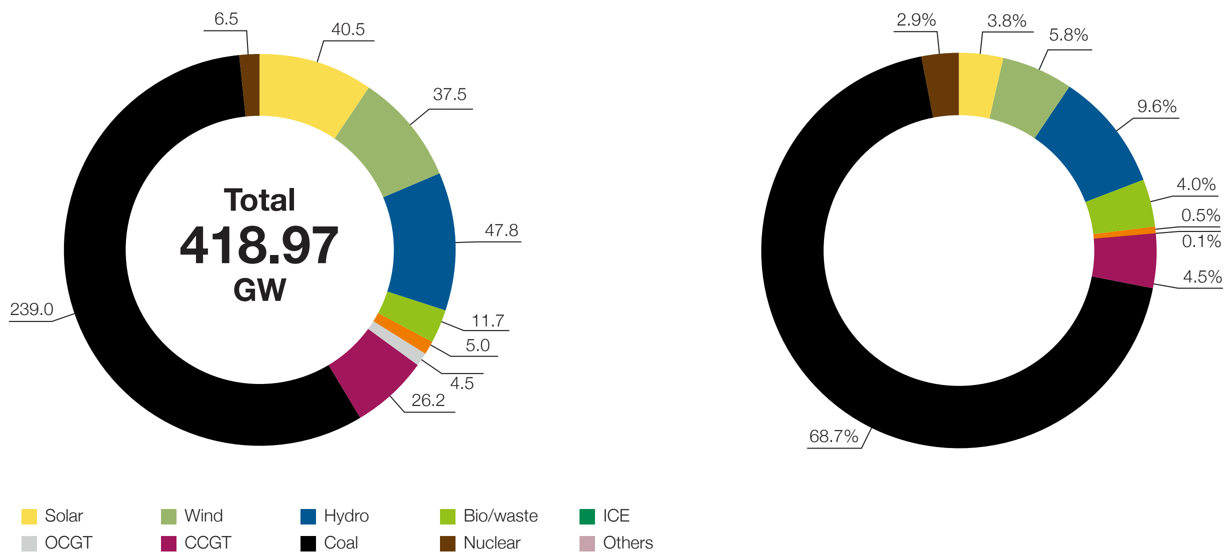

Figure 1: Resource-based electricity generation capacities (left) and generation share (right) across the Indian power sector in 2020. Abbreviations: Internal Combustion Engine (ICE), Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT).

India is currently faced with an energy trajectory that straddles multiple imperatives: sustainability, energy access across the country and energy self-sufficiency, while most importantly driving and sustaining rapid economic growth. In response, the Indian economy has embraced renewable energy at a scale and pace unprecedented in its history. Led by wind energy initially and more recently solar photovoltaic (PV), the country has already reached the halfway mark of its goal to achieve 175 GW installed renewable capacity by 2022. This joint research study by LUT University and Wärtsilä envisions an energy system transition pathway across the Indian power sector towards 100% renewables by 2050. It analyses the development of the power system in a Best Policy Scenario, in which GHG emissions from the power sector reach zero by 2050 with the comprehensive adoption of sustainable energy technologies.

II. TRANSITIONING TO A FULLY RENEWABLE POWERED ENERGY SYSTEM

Methods and influencing factors

The transition is modelled to a fully renewable powered system across India, which is comprised of four major regions as shown in Figure 2.

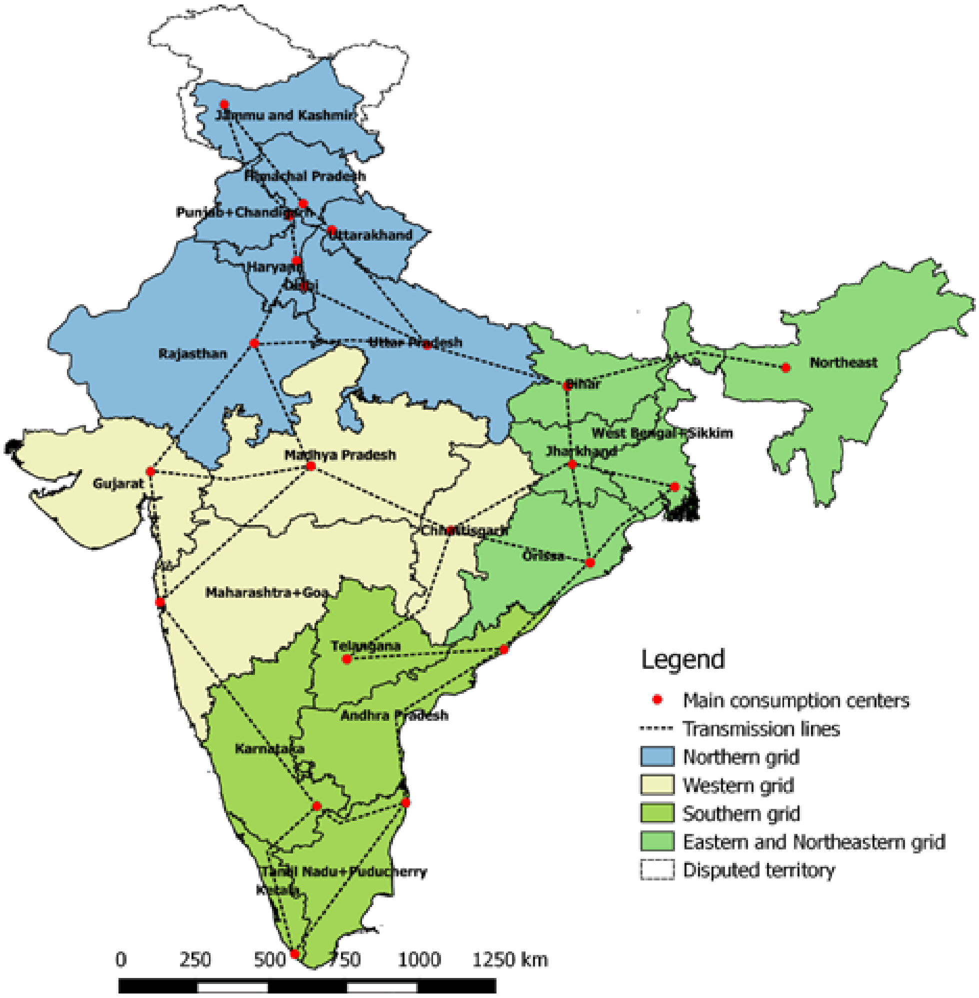

Figure 2: A map of India showing the four major power grid regions and their corresponding states/sub-regions.

The country is comprised of 22 states/sub-regions, which are grouped into four major regional grids (Northern, Western, Southern, Eastern and North-eastern). These grids are further interconnected to form a national transmission network, as highlighted in Figure 2. The individual states are interconnected with the regional grid plus the regional grids are interconnected with each other. Imports and exports between the states are considered as highlighted. It is assumed that the existing network of alternating current (AC) lines within the individual states will provide electricity to all consumers.

In addition, the energy transitions of the power sectors in the states of Gujarat, Telangana, Andhra Pradesh, Karnataka and Tamil Nadu have been modelled individually as isolated power systems, without taking into account interstate transmission. The results of individual states are available in the annex (A1 to A5) to this report.

LUT Energy System Transition Model

The LUT Energy System Transition modelling tool[4,5] simulates an energy system under given conditions, and this simulation is applied for five-year time periods from 2015 to 2050. For each period, the model defines a cost-optimal energy system structure and operation mode for the given set of constraints: power demand, available generation and storage technologies, financial and technical assumptions, and limits on installed capacity for all applied technologies. The model is based on linear optimisation and performed on an hourly resolution for entire years (further details on the workings of the model along with the respective mathematical representation of the target functions can be found in the methods section of the appendix). The model ensures high-precision computation and reliable results. The costs of the entire system are calculated as the sum of the annualised capital expenditures including the cost of capital, operational expenditures (including ramping costs), fuel costs and the cost of GHG emissions for all available technologies.

The energy system transition analyses also consist of distributed self-generation and consumption of residential, commercial and industrial PV prosumers, which are simulated with a different model describing the PV prosumer and battery capacity development. PV prosumers have the option to install their own rooftop PV systems, with or without lithium-ion batteries, and draw power from the grid in order to fulfil their demand[6,7], while also having the option to feed the surplus electricity into the grid. The target function for PV prosumers is the minimisation of the cost of consumed electricity, calculated as the sum of self-generation, annual costs and the cost of electricity consumed from the grid minus the cost of the electricity sold to the grid. The share of consumers opting to install their own generation and storage is projected to gradually increase from 3% in 2015[8,9] to 20% by 2050. The share of PV prosumers increases in accordance with the logistic function, in steps of 3, 9, 15, 18 and 20%. For a given year, if self-consumption of electricity becomes economically feasible then the share of prosumers for the following year increases, otherwise the share of potential prosumers remains the same. For some countries, such as Germany and Italy, the starting share of PV prosumers is 9% in 2015. The flow diagram of the LUT Energy System Transition Model including input and output data is presented in Figure 3. The technical and financial assumptions section of the appendix (Tables C1 to C5) provides the full set of technical and financial assumptions utilised in the modelling of the energy transition across India.

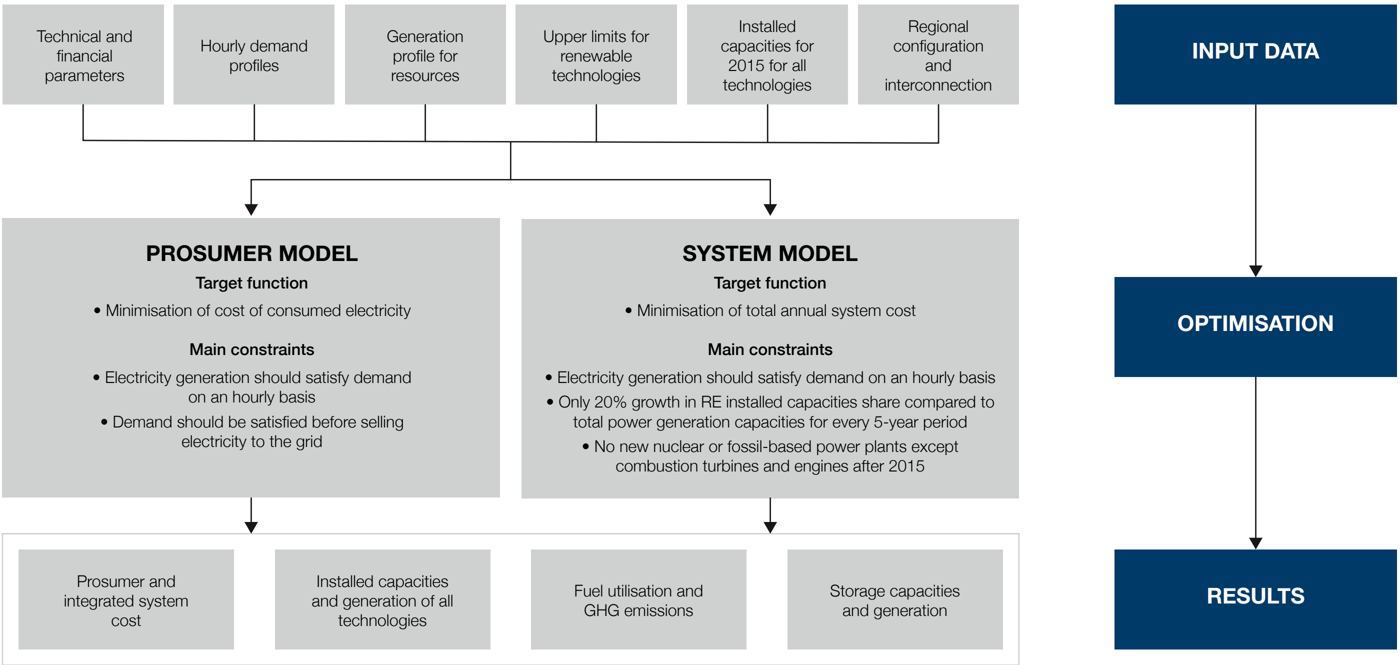

Figure 3: Key inputs and outputs of the LUT Energy System Transition Model [10].

Two crucial constraints are factored into the model in order to establish a sound basis for the energy system transition modelling:

1. New nuclear, coal and conventional fossil oil-based power plants are prohibited from being installed post-2015, mainly due to their inability to fulfil the high sustainability criteria set in the model, except the capacities which have been grid-connected by 2019.
2. The incremental increase in the share of installed capacities of renewable energy technologies is not permitted to exceed 4% per annum in congruence with empirical data[11]. Additionally, this increase in share is further limited to 3% between 2015 and 2020.

The applied strong sustainability requirements do not allow new investments in nuclear power plants, as mentioned, but the utilisation of the existing capacity continues until the end of individual technical lifetimes to facilitate a gradual phase out. This leads to 0.3% of nuclear generation in 2050, which is obviously negligible, but as a consequence of the applied rule. The total system cost would not be affected even if this tiny generation share were substituted by renewable energy and respective storage capacities. Coal-fired power plants are also not permitted to receive new allocations; however, the existing capacities have to be amortised until the end of their technical lifetimes. Their utilisation is cost optimised so that, in later periods of some states, full load hours decline to zero. Even though the capacities are no longer producing electricity, they have to be amortised to represent the sunken costs of the investments. Consequently, these power plants form a cold reserve (also called a security reserve)[12]. Gas turbines and engines are permitted to be installed beyond 2015 due to their lower carbon emissions and the possibility to accommodate synthetic natural gas (SNG) or bio-methane into the system[13]. Gas-fired power plants are more flexible, not only in their ramping rates but also in terms of their ability to accommodate different fuels as fossil gas is gradually phased out and incrementally substituted with bio-methane and synthetic gas via power-to-gas technologies.

Renewable electricity generation technologies and resources

The model has integrated all crucial aspects of power systems: power generation, storage and transmission. The technologies introduced to the model are classified into the following categories:

- Technologies for electricity generation: Renewable Energy (RE), fossil and nuclear technologies
- Energy storage technologies
- Electricity transmission technologies

Figure 4 displays the schematic representation of the LUT Energy System Transition Model and all the power sector technologies considered for simulating the energy transition[14].

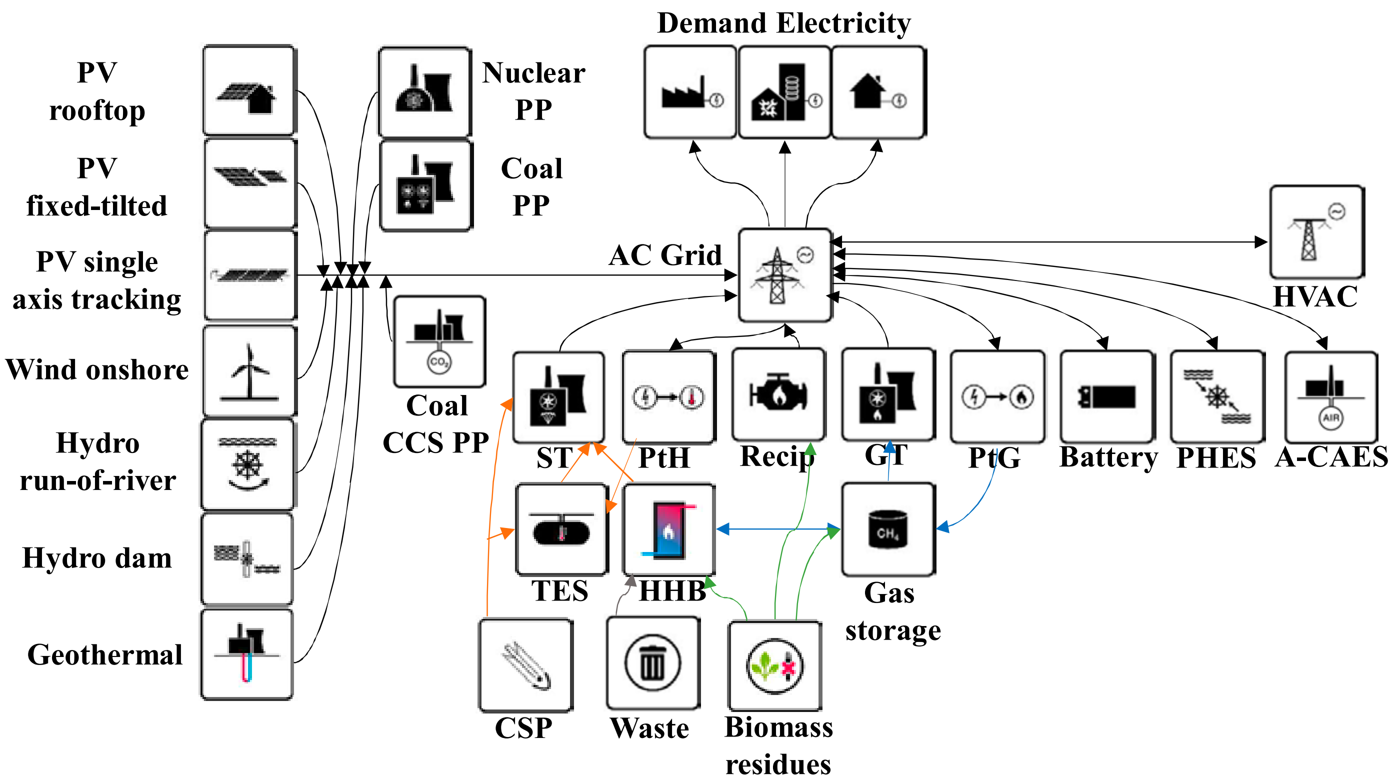

Figure 4: A schematic representation of the LUT Energy System Transition Model for the power sector representing the various RE sources for power generation as well as transmission options, storage technologies and power demand sectors.

RE technologies are solar PV (optimally fixed-tilted, single-axis north-south tracking and rooftop PV), concentrating solar thermal power (CSP), wind turbines (onshore and offshore), hydropower (run-of-river and dam), geothermal and bioenergy (solid biomass, biogas and waste-to-energy power plants). The fossil fuel-based generation technologies considered are coal-fired power plants, reciprocating combustion engines (gas), open cycle gas turbines (OCGT), heavy duty open cycle gas turbines (OCGT HD) and combined cycle gas turbines (CCGT).

Storage technologies are further classified into the following categories:

- Short-term: Li-ion batteries and pumped hydro energy storage (PHES)
- Medium-term: adiabatic compressed air energy storage (A-CAES) and thermal energy storage (TES)
- Long-term: gas storage including power-to-gas technology, which allows production of synthetic methane for the energy system.

The energy transition simulation takes into account the existing power grid and its development with corresponding electricity transmission and distribution losses [15]. All states within India can be interconnected with high voltage direct current (HVDC) or high voltage alternating current (HVAC) power lines, therefore increasing local flexibility while reducing overall national system costs.

Financial and technical assumptions

The financial and technical assumptions are mostly taken from various sources (CEA[16,17], CERC[18,19], Pleßmann et al.[20,] European Commission[21], TIP-PV[22], Vartiainen et al.[23], Fraunhofer ISE 2015[24], Neij 2008[25], Haysom et al.[26], Kutscher et al.[27], Sigfusson and Uihlein[28], Agora Energiewende[29], Breyer et al.[30], IEA[31], McDonald and Schrattenholzer[32] and Urban et al.[33]); all these assumptions and corresponding references can be found in the technical and financial assumptions section of the annex (Table 2.2 to 2.5). Assumptions are considered for five-year time periods from 2015 to 2050. The weighted average cost of capital (WACC) starts from 11% in 2015 and declines to 7% in 2050 (Annex, Table C3), but in the case of residential solar PV prosumers, WACC is set to 4% due to lower financial return requirements. Electricity prices for residential, commercial and industrial consumers were taken from Tariff Order for individual states and extended to 2050 based on the methods of Breyer and Gerlach [34]. Excess electricity generated by PV prosumers is limited to 100% of their own demand, the surplus is fed into the national grid, and is assumed to be incentivised for a transfer price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before feeding it to the grid. The costs for biomass are calculated using data from the IEA[35] and the Intergovernmental Panel on Climate Change (IPCC)[36]. Solid wastes gate fees are 50€/ton in 2015, 53€/ton in 2020, 59€/ton in 2025, 68€/ton in 2030, 80€/ton in 2035, 95€/ton in 2040 and 100€/ton in 2045 and 2050; the assumption is based global gate fees gradually increasing, reaching 100€/ton by 2050 as is the case in most developed countries.

Resource potential for renewable energy technologies

The generation profiles for optimally fixed-tilted PV, solar Concentrating Solar Power (CSP) and wind energy are calculated according to Bogdanov and Breyer [5] and for single-axis tracking PV according to Afanasyeva et al.[37]. The hydropower feed-in profiles are computed based on daily resolved water flow data for the year 2005[38]. The raw data on the biomass and waste resources were obtained from the Food and Agricultural Organisation (FAO) of the United Nations. The potentials were calculated according to the methodology described in Mensah et al.[39]. These potentials were further classified into categories of solid wastes, solid residues and biogas. Only 40% of the biomass resource potential was utilised, which is an assumption made for the power sector as there would be much higher biomass demand from other sectors.

Geothermal energy potential is estimated according to the method described in Aghahosseini et al.[40]. The regional distribution of full load hours (annual generation) of solar PV (single-axis tracking) and wind onshore (at 150 m hub-height), which are the two most vital sources of electricity in the energy transition across India, are shown in Figure 5. It can be observed that almost all states across the country have great potential for solar all year round, while the southern and western regions have exceptional wind potential. Offshore wind potential is the highest off the coasts of Tamil Nadu in the south and Gujarat in the west.

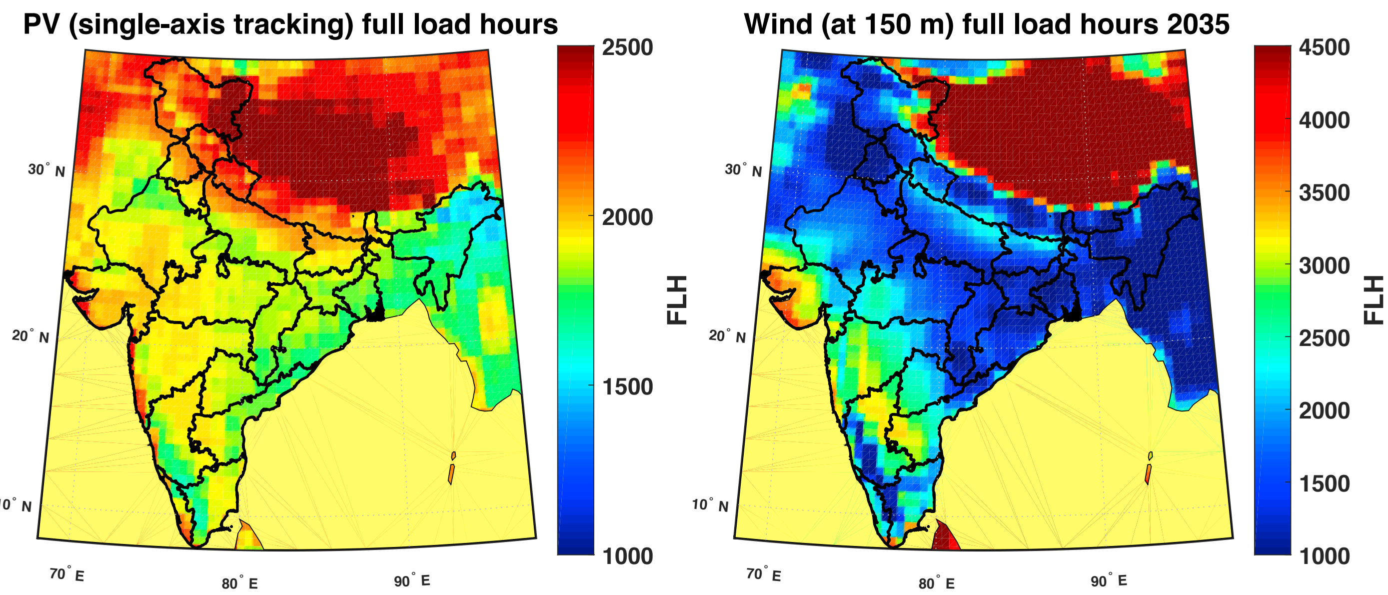

Figure 5: Indian mapping of annual full load hours for solar PV with single-axis tracking (left) and onshore wind at 150 m hub height (right).

Capacity factors for wind-energy generation potential are taken from Bloomberg projections for the whole of India, which increase from 29% in 2020 to 36% in 2035. The best sites have a maximum capacity factor of above 60% (approx. 5256 FLH) in 2035. Beyond 2035, the same capacity factor is assumed until 2050.

The annual variation in the hourly generation profiles of solar PV and wind are shown in Figure 6.

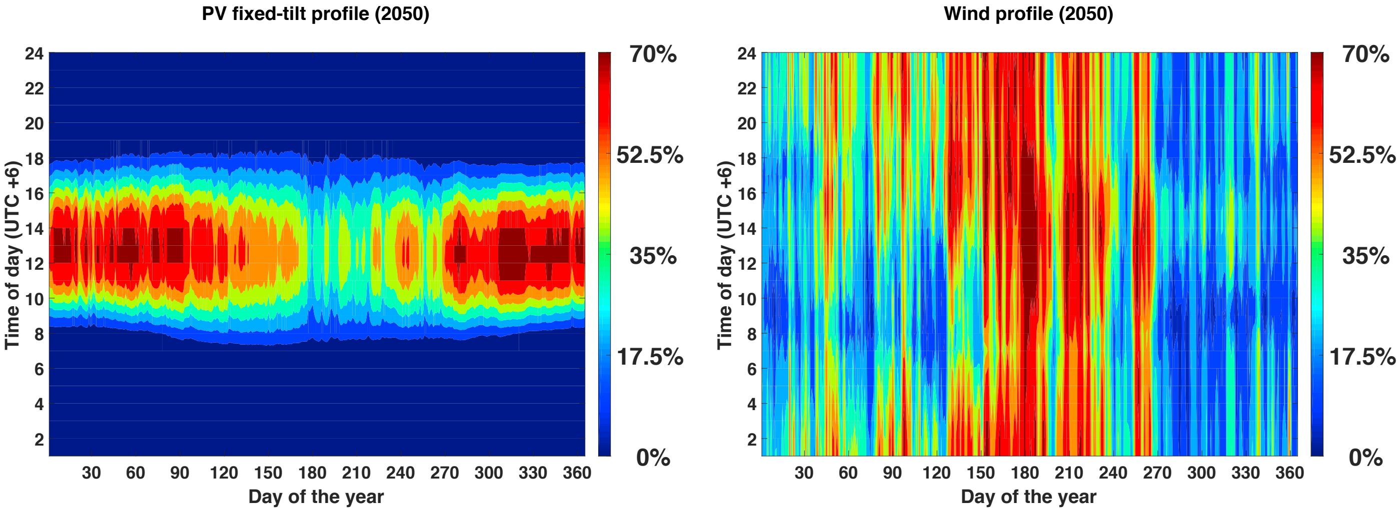

Figure 6: Annual distribution of the hourly generation profile for solar PV (left) and wind energy (right) across India.

Wind energy generation is predominant in the monsoon months and overcomes the solar resource unavailability and provides the perfect complement during periods of low solar radiation. Solar PV on the other hand is more evenly distributed across the year, as shown in Figure 6.

The monthly averaged resource availability through the year for solar PV and wind across India is highlighted in Figure 7. The seasonal complementary nature of solar PV and wind energy is clearly evident and ensures the electricity demand is satisfied, which is rather stable through the year. Monthly values are normalised to the highest monthly value throughout the year.

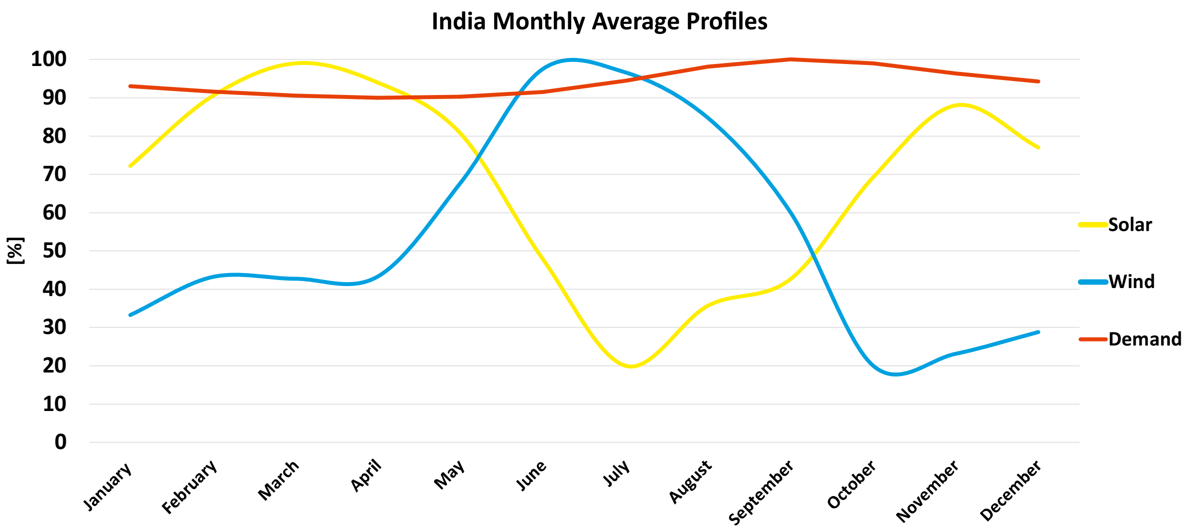

Figure 7: Annual distribution of the monthly average electricity generation profiles for solar PV and wind energy, and the demand profile across India in 2050.

Development of electricity demand

The electricity demand of the Indian power sector is estimated to increase from 1345 TWh in 2020 to about 5921 TWh by 2050, which represents a cumulative average annual growth rate of around 4.9% in the energy transition period. Electrification of other energy sectors (such as heat, transport and industry) has not been considered in this research, but could lead to enhanced demand for electricity in the future. The population of India is expected to grow from nearly 1.3 billion people in 2015 to around 1.7 billion people by 2050, while the average per capita electricity demand rises from 1 MWh in 2015 to 3.5 MWh in 2050 as highlighted in Figure 8.

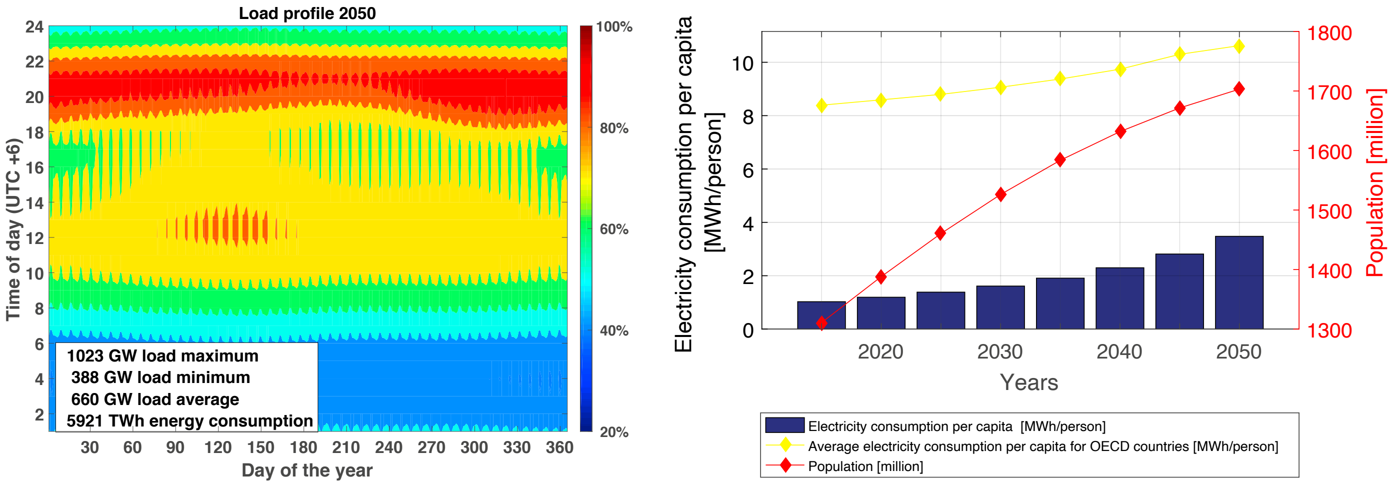

Figure 8: Development of average electricity consumption per capita in India and in OECD countries, growth in population from 2015 to 2050 (left) and the synthetic load profile in 2050 (right) 41.

The synthetic electricity demand profiles from 2015 until 2050 are generated based on the methods of Toktarova et al.[41]. Figure 8 shows the synthetic load profile of India in 2050, with a synthetic peak load of 1923 GW. The load profile will be different for the centralised system due to partial load covering by prosumers. For the modelling of individual states and regions, their corresponding load profiles are used as highlighted in section A of the annex.

III. RESULTS: ENERGY TRANSITION ACROSS THE INDIAN POWER SECTOR

Electricity

The electricity generation capacity satisfies demand from the power sector across India. The total installed capacity grows massively from about 400 GW in 2020 to around 4000 GW by 2050, an increase of 10 times in the next three decades as shown in Figure 9. In the initial period of the transition, a larger share of wind capacities is installed up to 2025, but in the later part of the transition solar PV dominates the shares of installed capacities, reaching almost 3000 GW by 2050. On the other hand, the share of fossil fuels and nuclear declines through the transition, with installed capacities of coal at risk of becoming stranded assets and having very low full load hours during the transition years as the share of renewables increases. Reciprocating gas engines are installed from 2025 onwards to provide flexibility to the system, which is already over 55% renewable based.

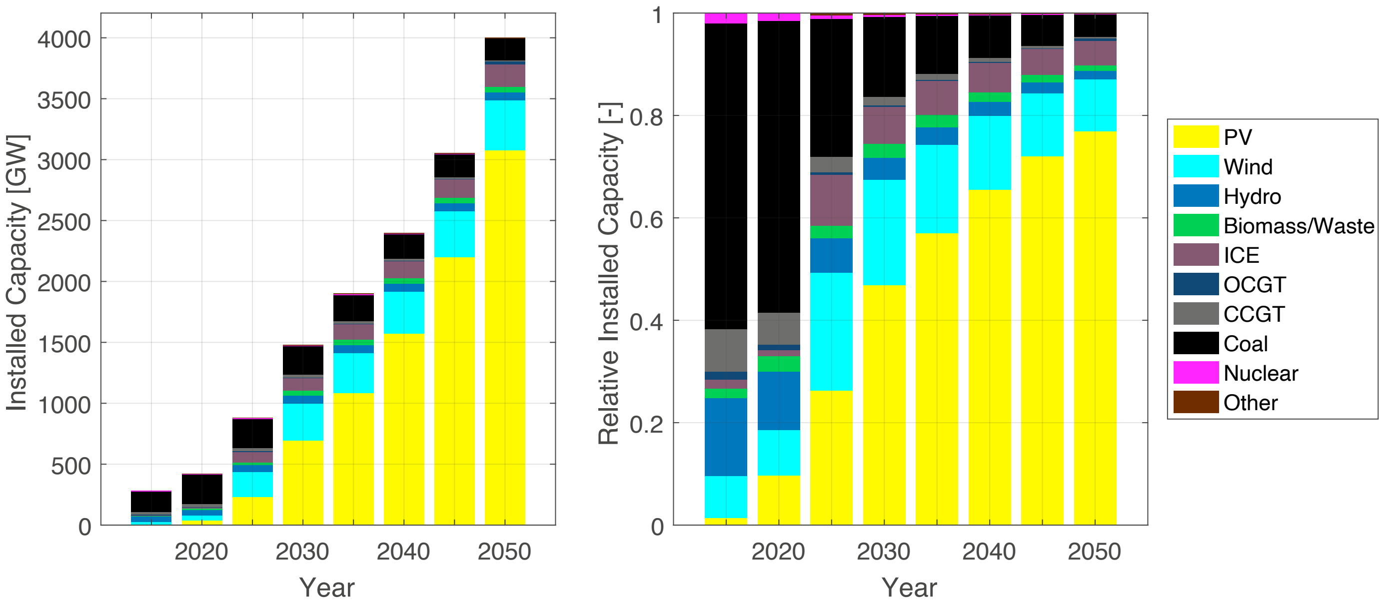

Figure 9: Installed capacities by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 across India.

The share of coal in electricity generation declines from a dominating 69% in 2020 to zero by 2050, as shown in Figure 10. Beyond 2015, the share of coal continues to drop as the shares of wind energy (27%) in 2025 and then solar PV (43%) in 2030 increase in the total electricity generation as they become more cost competitive (see Figure 10). Reciprocating gas engines have a share of 1.1% in electricity generation in 2050, mainly driven by their higher efficiency and lower cost, while having FLH of over 800, mainly utilised for peak supply and balancing. The fuel mix for reciprocating gas engines develops from 100% fossil gas in 2020 to 85% SNG and 15% biomethane in 2050.

It is quite evident that the Indian power sector undergoes a rapid transition away from coal towards solar PV as the prime source of electricity generation, as electricity from solar PV has the lowest cost throughout the transition. The trend during the last few years of record low tariffs across the country are already disrupting the economics of the power sector, and with the introduction of low-cost storage solutions this trend is expected to be further amplified.

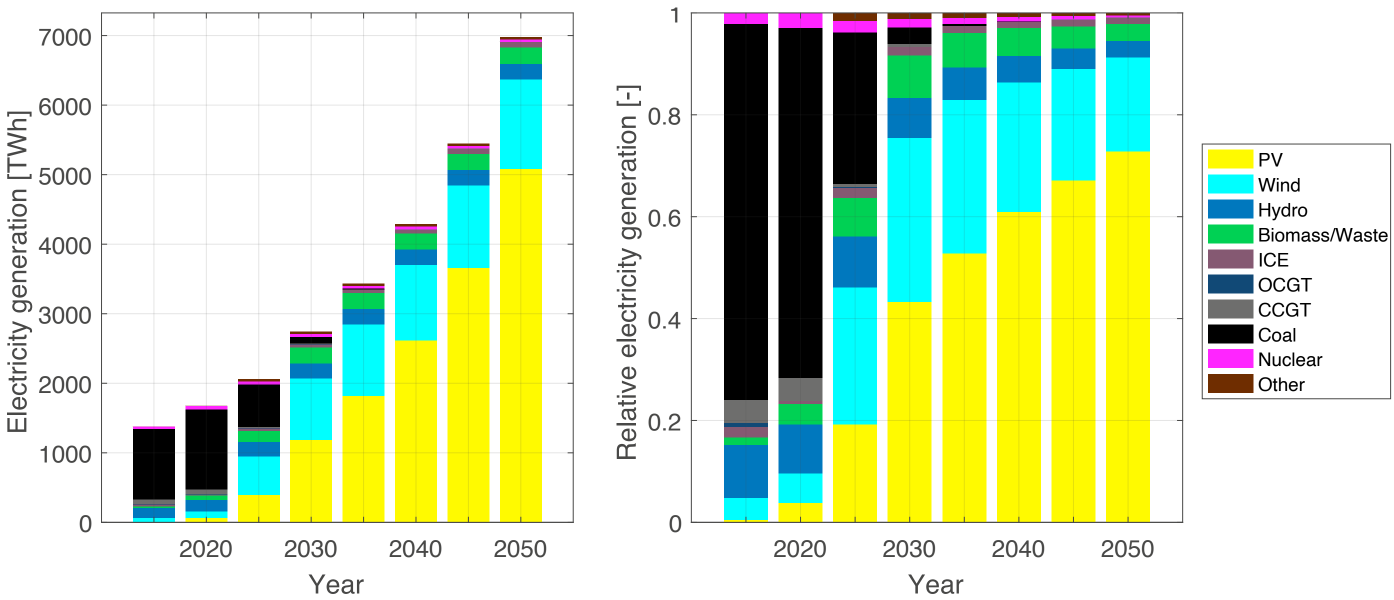

Figure 10: Electricity generation by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 across India.

Storage

Energy storage technologies play a critical role in enabling a secure energy supply in the power sector across India, which is fully based on renewable energy by 2050. Storage kicks in predominantly around 2030 as high shares of renewable energy contribute to the energy mix. The installed electricity storage capacity increases from about 22 TWh in 2030 to around 95 TWh by 2050, as shown in Figure 11. Utility-scale and prosumer batteries with major shares of gas storage are installed during the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with more than 98% by 2050, as highlighted by Figure 11.

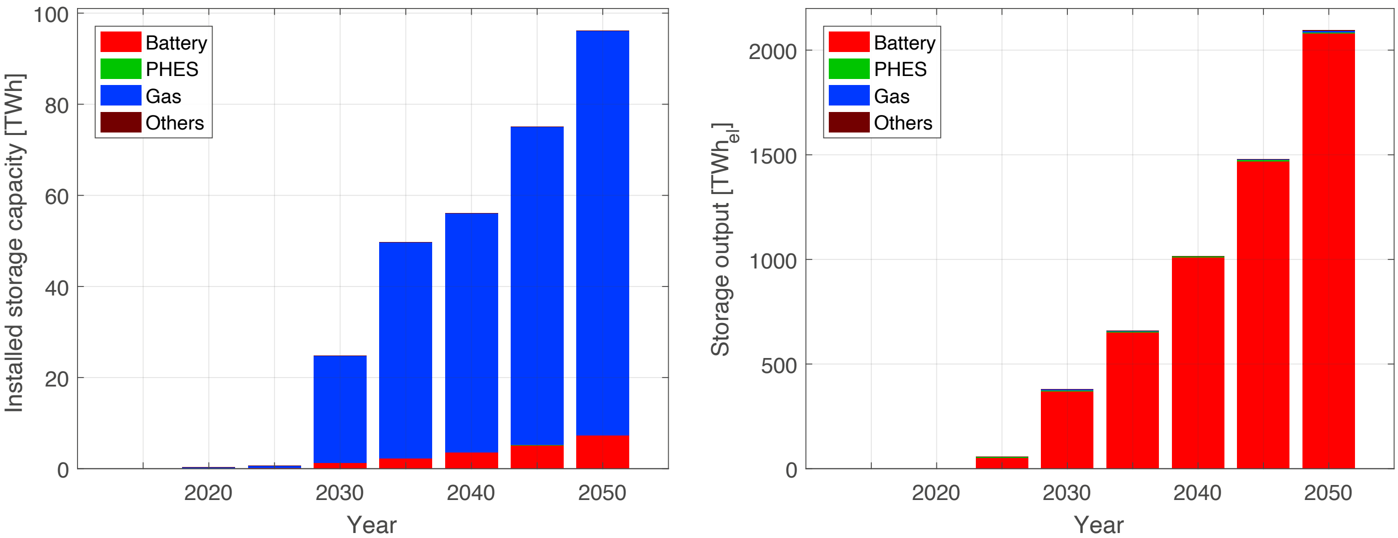

Figure 11: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2015 to 2050 across India.

Gas storage, which is synthetic natural gas produced through the power-to-gas process, has large capacities and fewer operating hours as it contributes vital seasonal storage during the transition. Battery storage on the other hand mainly plays a role in providing diurnal energy storage, as indicated in Figure 12. Gas storage mainly plays a role in providing seasonal storage, particularly needed in the monsoon season, when the solar resource is at its lowest. The gas storage discharges slowly over the monsoon period and is completely discharged by the end of winter as can be observed in Figure 12. Some hydropower reservoirs provide complementarity with solar and wind but are used mainly for seasonal balancing.

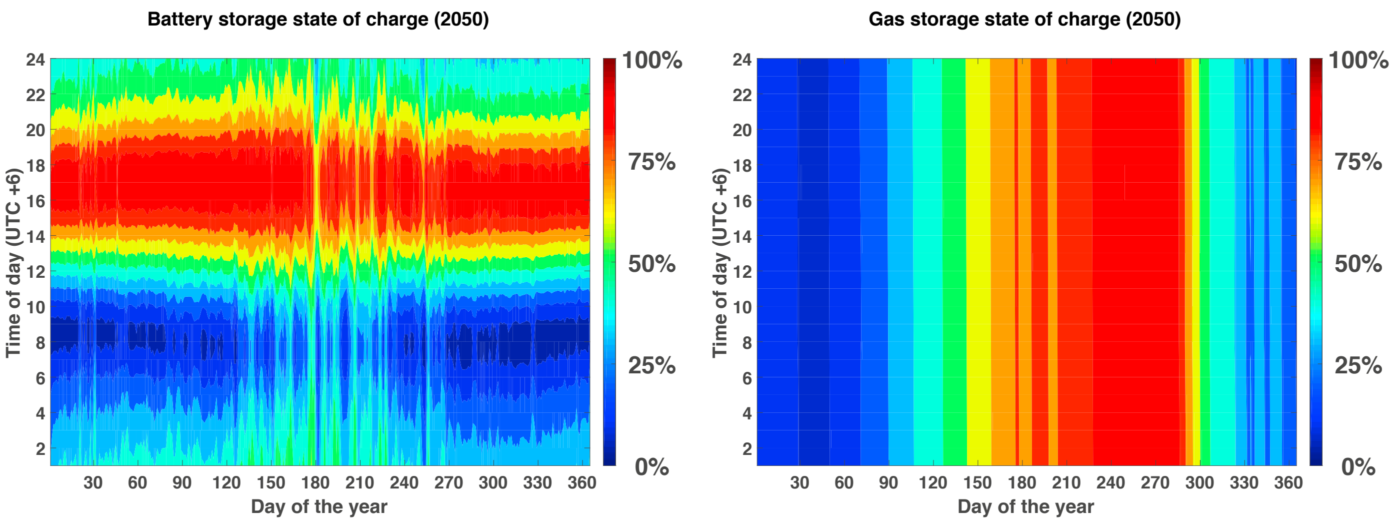

Figure 12: State of charge for battery storage (left) and gas storage (right) in 2050 across India.

System outlook

The power system of India undergoes a massive transformation from its fossil fuel-dominated structure in 2020 to a fully renewable-dominated structure by 2050, which is highlighted by Figures 13 and 14.

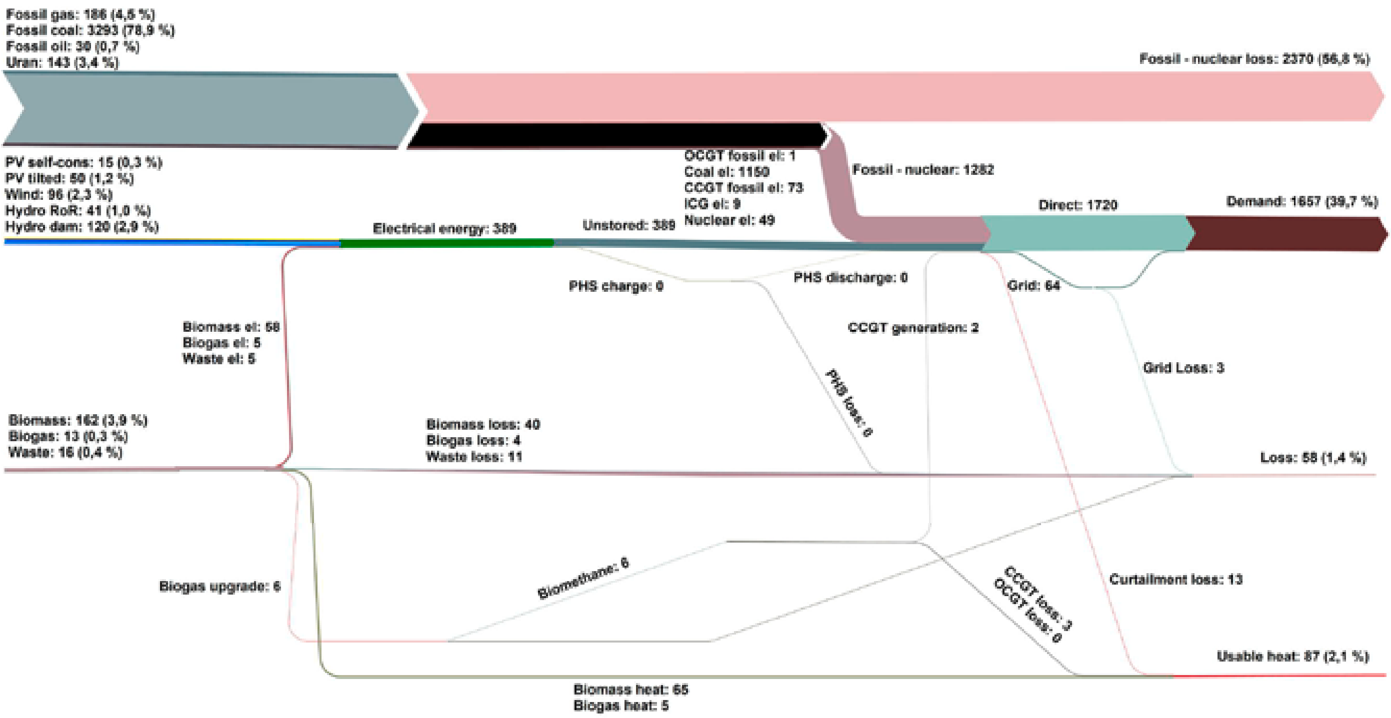

Figure 13: Energy flows of the Indian power system in 2020.

The energy flows in 2020, which are based on a fossil fuel-dominated power system, reflect a loss of around 57%, indicating a highly inefficient system in terms of resource conversion (see Figure 13).

On the other hand, energy flows in 2050, which are based on a 100% renewable power system, reflect a loss of just 9.3% and a curtailment of 257 TWh, which can be used for other applications; future sector coupling with other energy sectors (heat, transport and industry) will reduce this even further, indicating a highly efficient system in terms of resource conversion. This is highlighted by the energy flows as depicted in Figure 14.

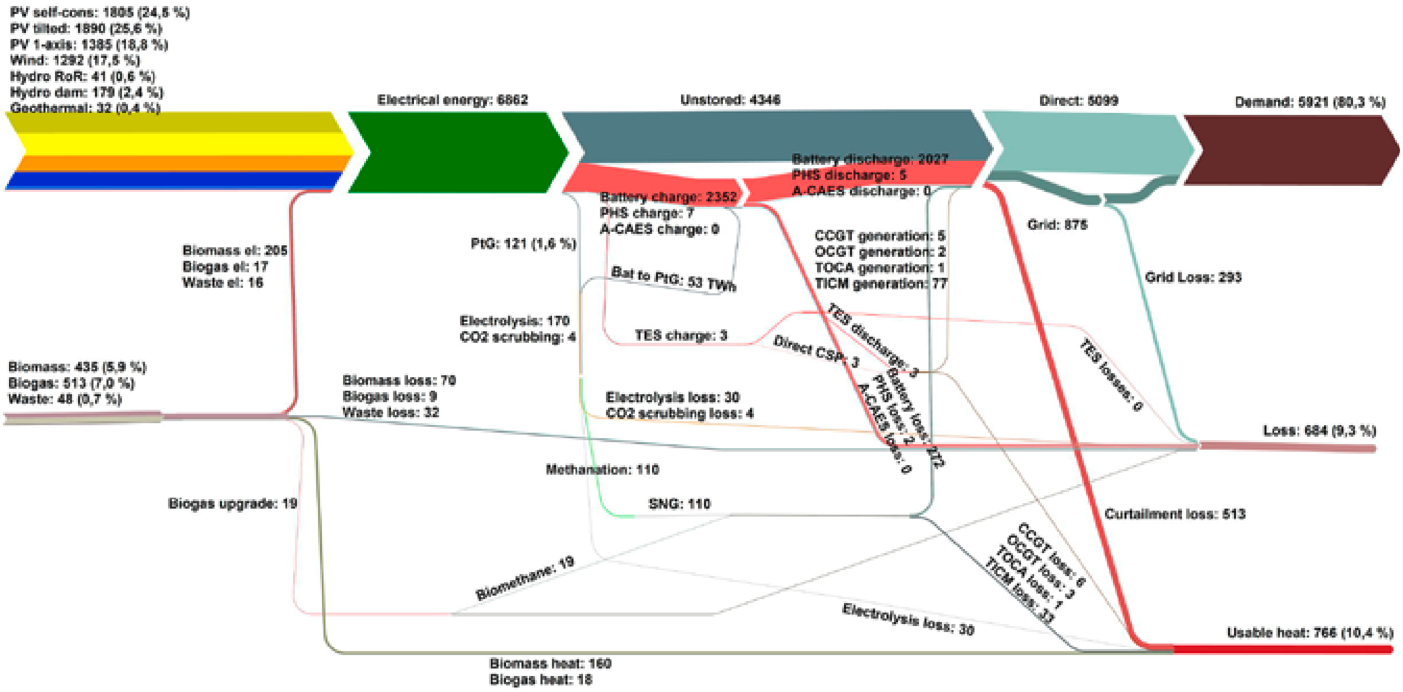

Figure 14: Energy flows of the Indian power system in 2050.

The power system across India has distinctive operational characteristics, which vary according to regional and seasonal patterns. The aggregated seasonal impact is highlighted by a pan-India best solar week in 2050 (see Figure 15) and a pan-India worst solar week in 2050 (see Figure 16).

During the summer period, solar PV and complementary wind energy are the main electricity generation sources. Batteries are used daily, charging during the day and discharging during the evening and night-time hours to meet peak consumption, as highlighted in Figure 15. Additionally, there is some excess electricity, which can be utilised in the case of an integrated energy system with coupling of the heat, transport and industrial sectors.

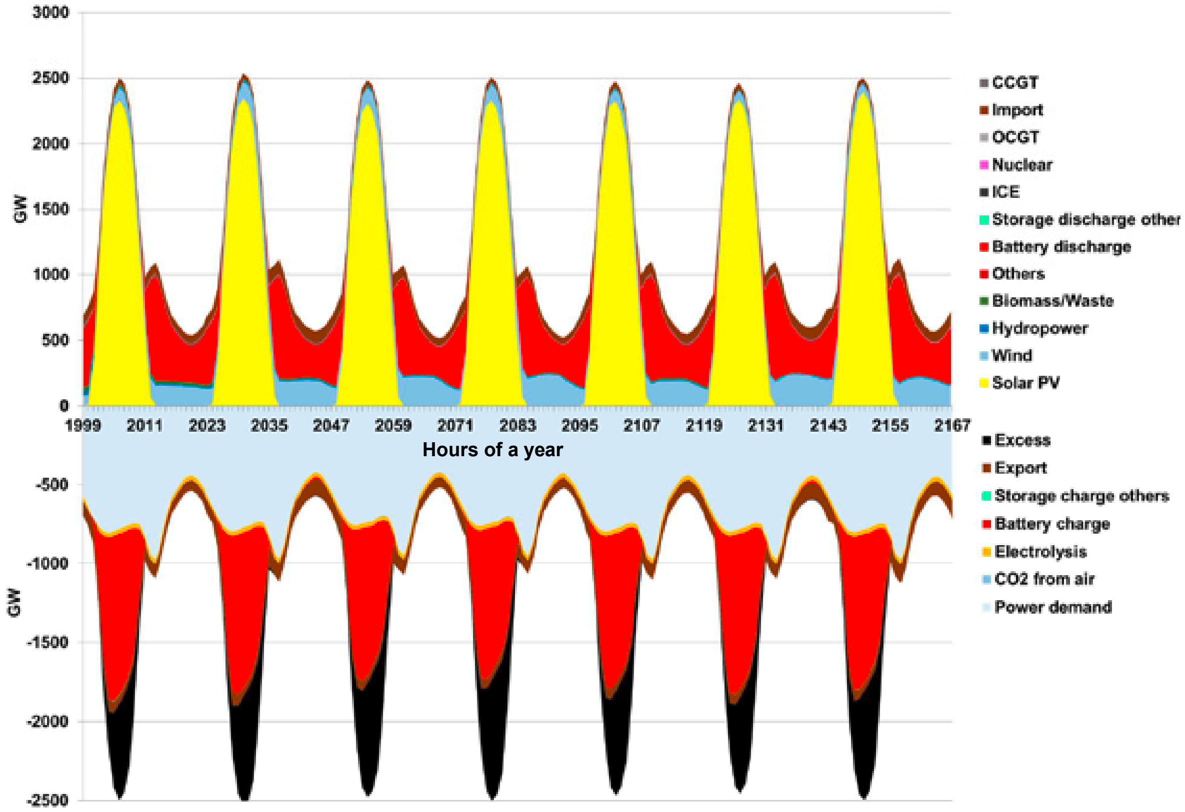

Figure 15: Time series of the Indian power system during a best solar week in 2050.

During the monsoon period, solar PV generation decreases, while wind generation increases and becomes the main source of electricity generation. A share of dispatchable bioenergy compensates for the lack of solar PV and wind generation. Reciprocating gas engines are utilised in periods of low generation, especially in the beginning of the week when wind generation is low and when solar generation is also low in the middle and at the end of the week, as show in Figure 16.

Import and export of electricity between the states and regions of the country play a vital role in the monsoon season but are somewhat limited in summer. The amount of excess electricity is lower in the monsoon season as compared to the summer season.

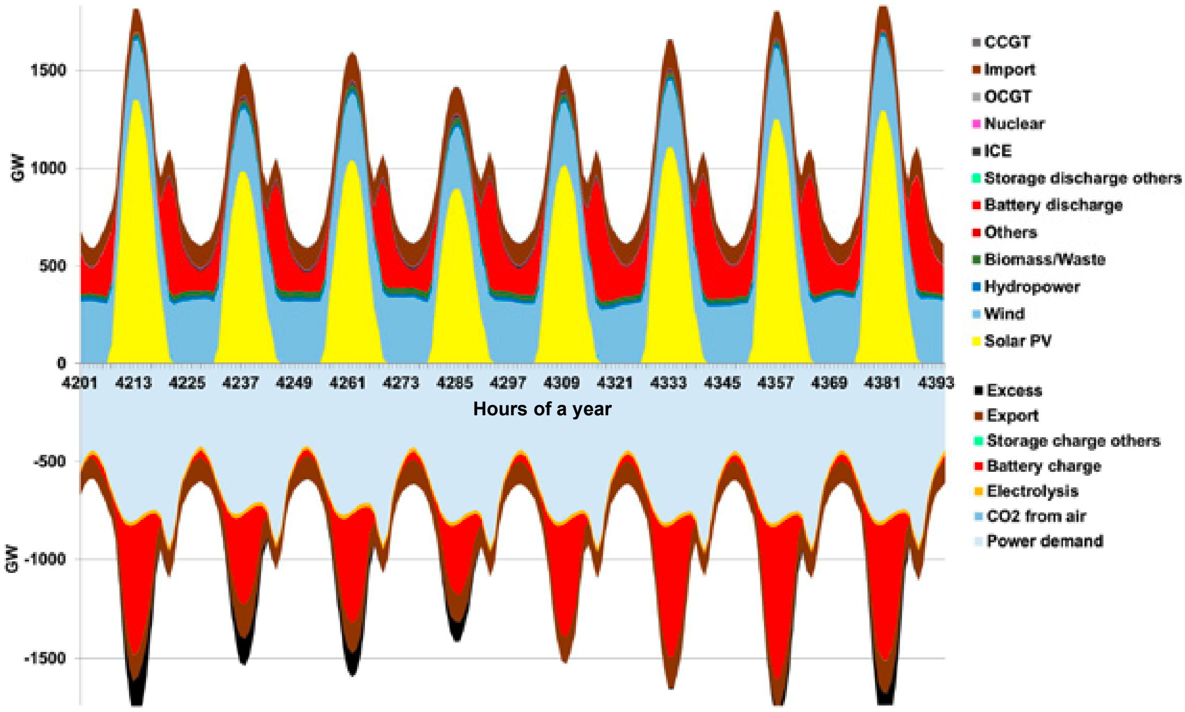

Figure 16: Time series of the Indian power system during a worst solar week in 2050.

Costs and investments

As indicated in Figure 17, capital expenditures increase through the transition, initially with wind and reciprocating gas engines, and later with solar and batteries being dominant.

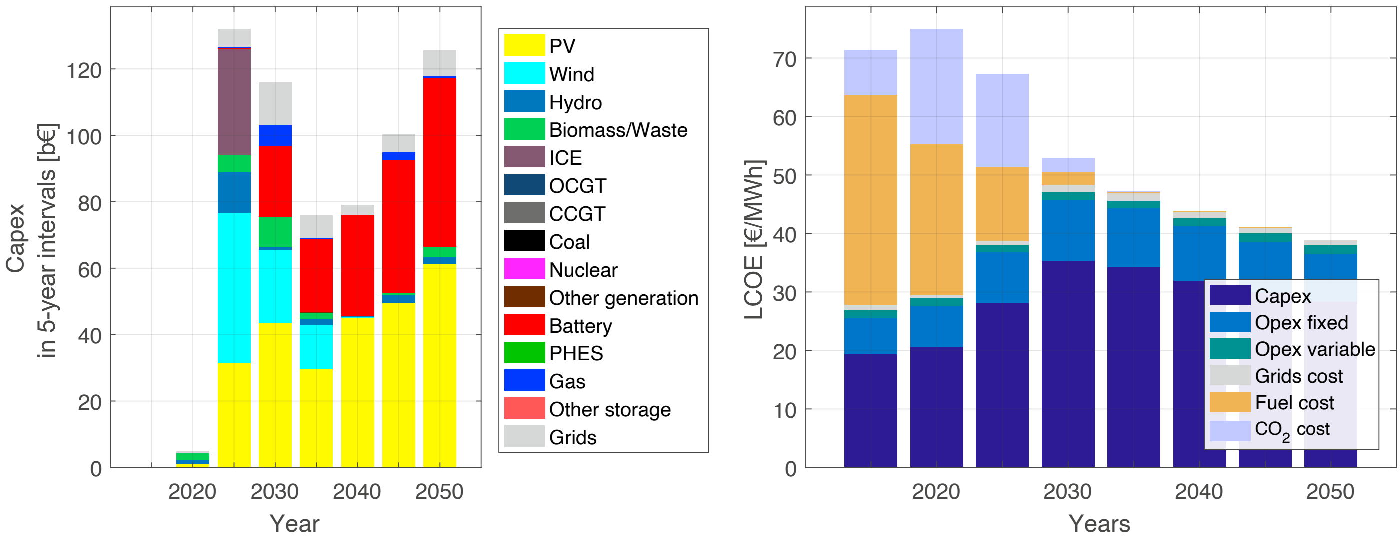

Figure 17: Capital expenditures for five-year intervals (left) and levelised cost of electricity (right) during the energy transition from 2015 to 2050 across India.

The levelised cost of electricity declines from around 75 €/MWh in 2020 (including GHG emissions costs) to around 38 €/MWh by 2050 (see Figure 17) and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which for India could mean increased self-reliance in terms of energy by 2050. Capital costs are distributed across a range of technologies, with major investments in solar PV, wind energy, reciprocating gas engines, batteries and other storage up to 2050, as shown in Figure 17.

The steady increase in capex-related energy system costs indicates that fuel imports from other states across the country and the respective negative impacts on trade balances will fade during the transition.

Greenhouse gas (GHG) emissions

The results of the power system transition across India indicate that GHG emissions can be reduced from nearly 1166 $MtCO_{2eq}$ in 2020 to zero by 2050 across the power sector, as shown in Figure 18. The CO_{2eq} intensity of electricity generation rapidly declines during the transition, enabled by the phasing out of fossil-based power plants, mainly coal, which indicates a deep defossilisation by 2030 (see Figure 18).

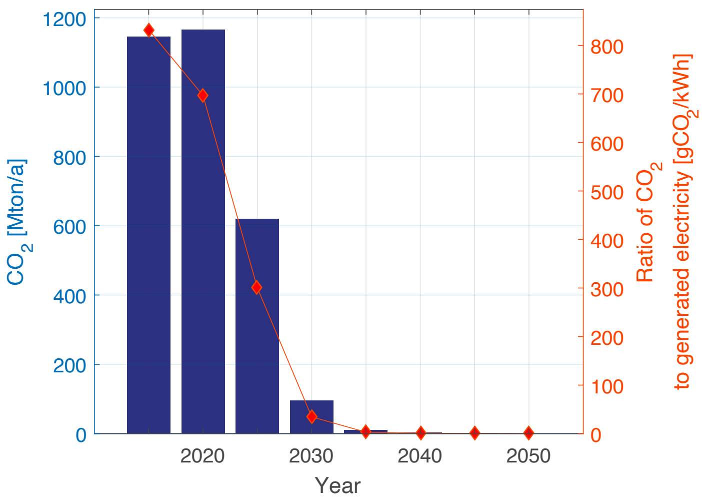

Figure 18: GHG emissions from the power sector across India during the energy transition from 2020 to 2050.

The presented best-policy scenario with 100% renewable energy by 2050 for the Indian power sector is compatible with the goals of the Paris Agreement and will enable India to meet its commitments and take a leadership role globally. A deep defossilisation of the power sector is possible by 2030 and a steady decline of emissions is possible beyond 2030 up to 2050.

Regional outlook

Electricity generation capacities are installed across India to satisfy the demand for power up to 2050. Solar PV capacities are predominant across all states/ sub-regions of India that have excellent solar resources throughout the year, while bioenergy capacities are mainly in the northern and eastern agrarian states (see Figure 19). Hydropower is predominant in states that have major rivers flowing through them and therefore have much better hydropower conditions, as shown in Figure 19. Overall, solar PV and wind capacities along with some hydropower capacities constitute the majority of the installed capacity across India in 2050. Similarly, higher shares of solar PV generation are present across all the states/ sub-regions, as highlighted in Figure 19. This could enhance the complementarity of solar PV and battery storage in an interconnected Indian power system and also neutralise the effects of the monsoon season across the region, as highlighted in detail in Gulagi et al.[42].

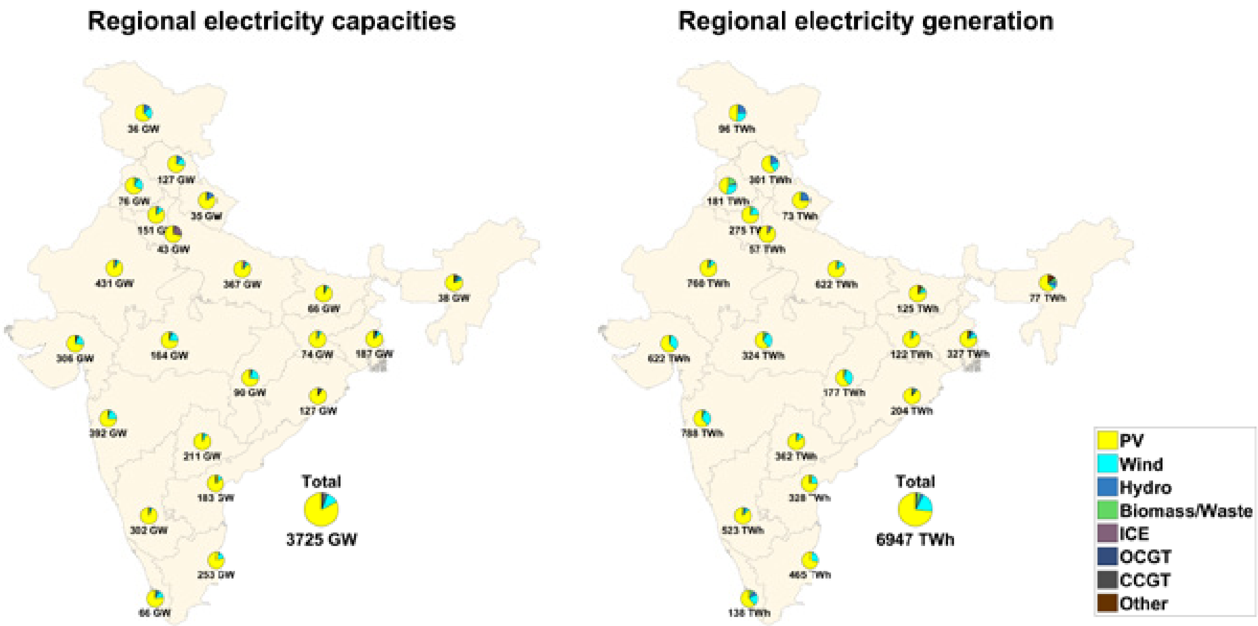

Figure 19: Regional electricity generation capacities (left) and electricity generation (right) across India in 2050.

Storage capacities are well distributed across the states/sub-regions of India, mainly to complement higher shares of installed solar PV capacities. The installed storage capacities are dominated by gas storage, which exists mainly to provide seasonal storage (see Figure 20).

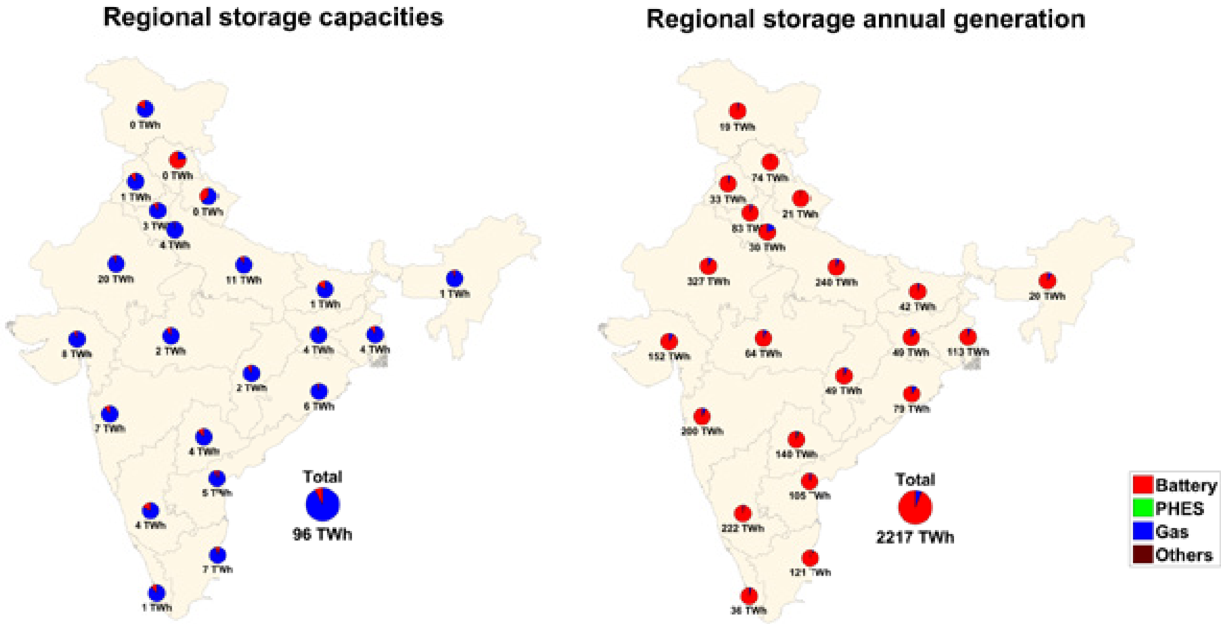

Figure 20: Regional variations in electricity storage capacities (left) and storage output (right) across India in 2050.

Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050, as shown in Figure 20. A-CAES contributes complementary shares of electricity storage output during the transition across the different states/sub-regions of India, with higher shares in Rajasthan, Maharashtra and Karnataka.

National installed capacity of solar PV reaches 3076 GW across the country in 2050 as shown in Figure 21. The state of Rajasthan with its excellent solar resources has the highest installed capacity of 388 GW in 2050. Solar PV emerges as the prime source of electricity generation across India and supplies an average of nearly 73% of electricity generation across the country as shown in Figure 21. Delhi having the highest share of 90% and Punjab with the lowest share of 47% of solar PV generation in 2050.

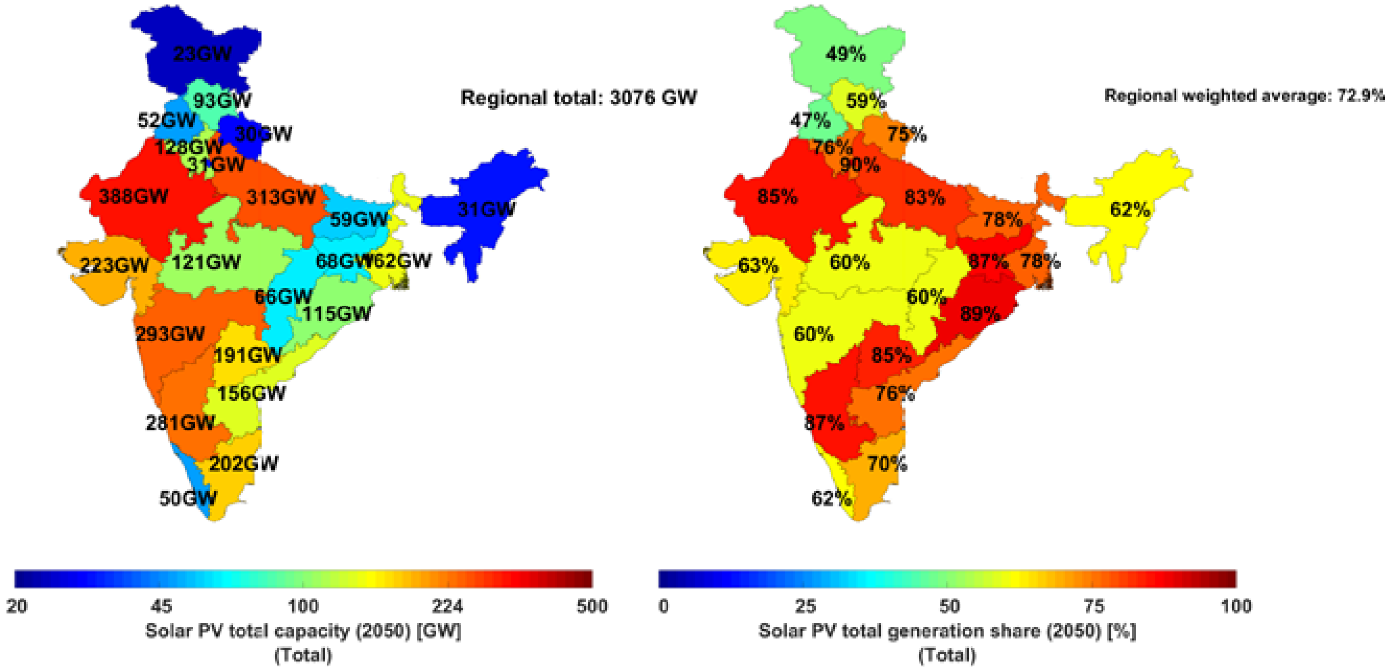

Figure 21: Regional solar PV capacities (left) and shares of solar PV generation (right) across North India in 2050.

The storage output for the entire Indian power sector is predominantly from batteries (both utility-scale and prosumers) at a national average of over 35% of electricity generation in 2050, as shown in Figure 22. Electrolysers play a vital role in terms of the production of hydrogen in the transition of the energy system across North India and reach a regional installed capacity of 407 GW_{el} in 2050. The major capacities are in the solar-rich states of Rajasthan, Karnataka and Uttar Pradesh with minor capacities in the rest of the states across the country, as shown in Figure 22. Electrolysers not only produce hydrogen, which is a fuel as well as feedstock for production of electricity-based synthetic fuels, but also provides crucial flexibility to the power system during the transition.

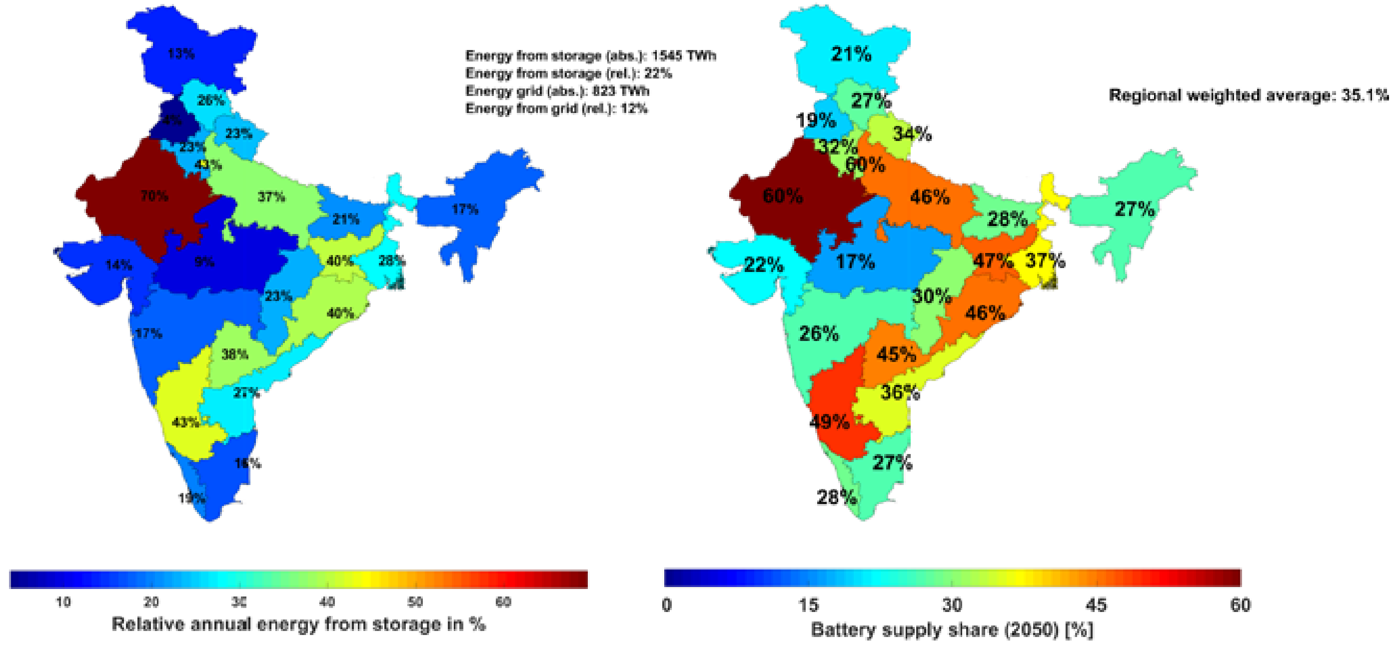

Figure 22: Regional variation of storage supply shares (left) and battery supply shares (right) across India in 2050.

Role of transmission

Transmission infrastructure is extremely vital for the regional and national integration of the power system and enables the transition across the country towards 100% renewables in a cost-effective manner. The power transmission capacity increases by more than six times from 2020 to 2050, as shown in Figure 23. The cross-state electricity transmitted reaches close to 12% of the electricity generated in 2050, as highlighted in Figure 23. This indicated that a strong regional and national grid is vital for India to benefit from the low-cost renewable resources distributed across the various states.

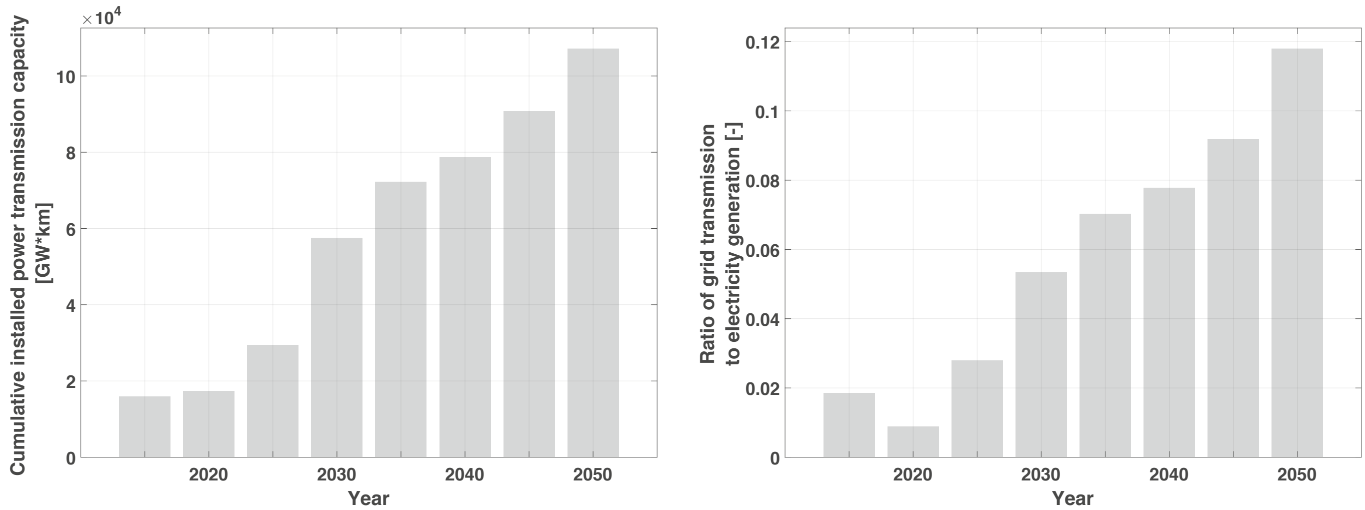

Figure 23: Installed grid capacity (left) and share of grid electricity supply (right) across India during the transition from 2015 to 2050.

The grid utilisation across India is shown in Figure 24. The maximum grid utilisation is during the monsoon season, while during regular days the lowest grid transmission capacity is needed, which is explained by direct use of solar PV electricity. About 22% of all electricity demand is directly covered by storage discharge, mainly during the night hours (see Figure 24). Storage and grids provide complementary flexibility in the system, as storage provides flexibility on a temporal scale (shifting electricity at the same location, but available at different times), while grids provide flexibility on a geographical scale (shifting electricity at the same time, but from one location to another).

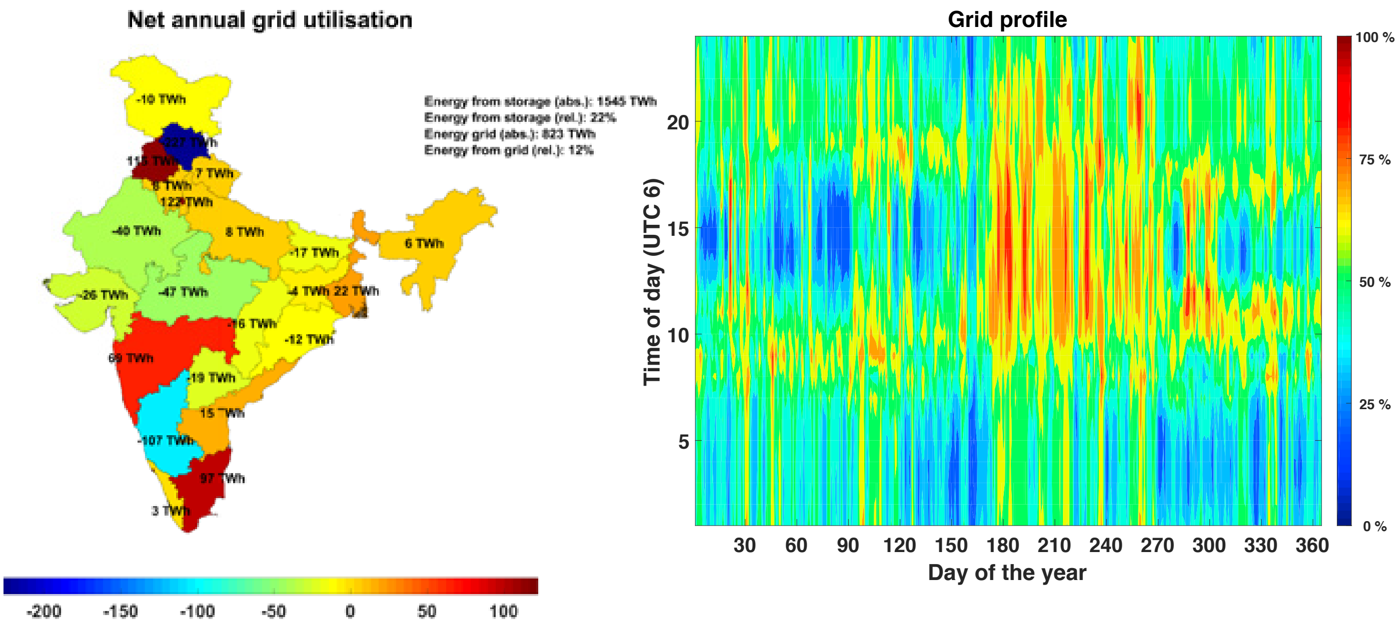

Figure 24: Regional variation (left) and temporal variation (right) in grid utilisation across India in 2050.

A strong regional grid is vital for all states in the region to benefit from the low-cost renewable resources in the entire region. The annual net grid utilisation across the country is around 823 TWh, which is 12% of the electricity generated in 2050 as shown in Figure 25.

Annual imported and exported electricity (TWh)

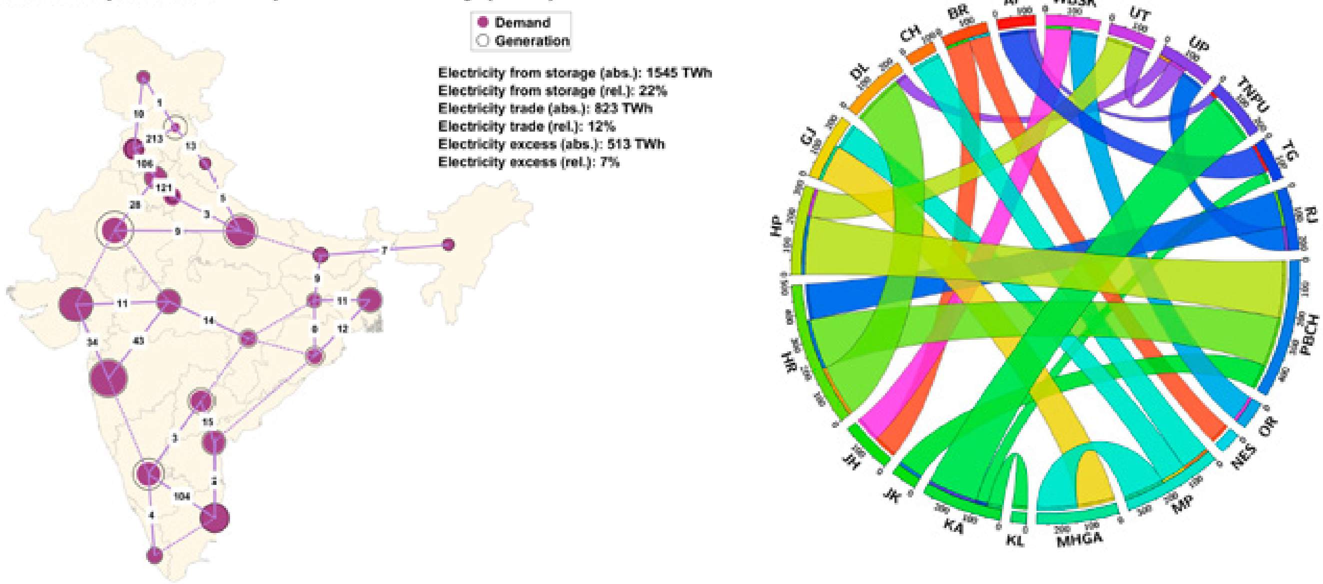

Figure 25: Regional electricity exports and imports (left) and interregional exchange of electricity (right) across India in 2050.

In a cost-optimised energy system across the Indian grid, transmission and distribution play a vital role in ensuring all the states/sub-regions benefit and reduce their overall energy costs. This setup is extremely important for city states like Delhi, which imports most of its electricity. On the other hand, states such as Himachal Pradesh, Rajasthan and Karnataka emerge as huge exporters of low-cost renewable electricity (see Figure 25), which provides these states with an economic boost and creates much-needed jobs.

Power sector transition in states

As part of this research, power system transition pathways for five individual states – Gujarat, Telangana, Andhra Pradesh, Karnataka and Tamil Nadu – were modelled without considering respective interstate transmission. While the results indicate that the states can easily satisfy future power demands, as highlighted in the annex, the power system is somewhat over capacity and expensive compared to a nationally integrated power system. The states benefit from the interconnections with other states and across the country as this reduces both the total capacity requirement and the overall system cost. The utilisation of storage capacities is also considerably reduced when the states are interconnected as the states utilise low-cost renewable electricity from neighbouring regions rather than having to add their own storage capacities. Therefore, wider and more expansive transmission along with grid interconnections reduce the need to build excess capacities and reduce curtailment. Furthermore, with the consideration of more energy sectors and trends such as sector coupling and integrated energy systems, the overall efficiency of the system could be increased while decreasing costs and curtailment.

IV. ANNEX

A. RESULTS

Below are the detailed results for each of the states modelled individually.

A1. GUJARAT

The state of Gujarat, which is part of the western grid in the Indian power system (see Figure A1.1), is one of the most industrialised states in the country and has a growing energy demand. It is modelled to be self-sufficient in terms of meeting its future power demand as part of this research. Furthermore, no imports or exports with other neighbouring states are considered. It is also assumed that the existing network of AC lines, mainly for distribution of electricity within Gujarat, will provide electricity to all consumers in the future.

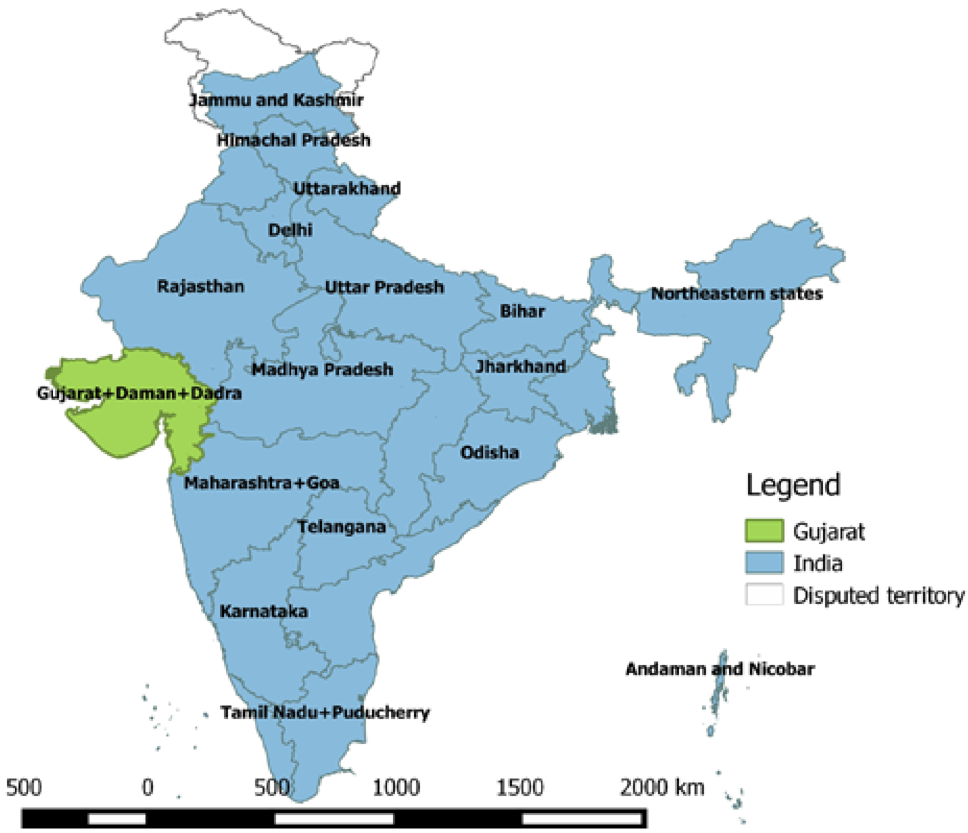

Figure A1.1: Gujarat within the regional setup of India.

Historically, the power sector in Gujarat has relied on coal-based generation to satisfy the growing electricity demand across the state. In recent times significant growth in the share of installed capacity of renewables has been observed, and Gujarat is now among the leading states in the country in terms of renewables (see Figure A1.2). As indicated in Figure A1.2, coal still accounts for around 78% of the electricity; however the capacity factors, or alternately the Full Load Hours (FLH), of coal power plants across the country have been decreasing on a year-on-year basis. In addition, several of these plants are in financial distress. Air pollution has increasingly become a national problem causing adverse health impacts and negative economic consequences. The huge water requirements of coal power plants are causing increased levels of water stress and competing with irrigation demand for agriculture. These challenges indicate that the trend of growing the capacity addition of renewables is expected to continue and is required to be accelerated to meet India's ambitious climate targets.

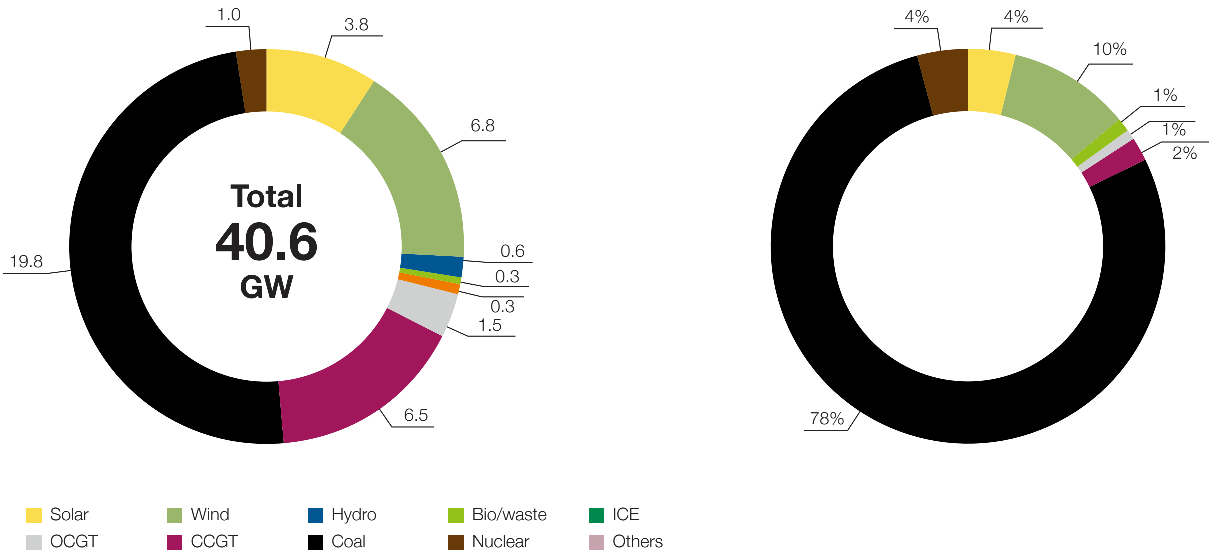

Figure A1.2: Resource-based electricity generation capacities (left) and generation share (right) of the Gujarat power sector in 2020.

Demand

The cumulative average annual growth rate of electricity consumption is about 4.9% during the energy transition period from 2015 to 2050 compared to the 7% average growth rate of electricity demand across the country in recent times. The population of Gujarat is expected to grow from about 66 million in 2020 to 86 million by 2050, while the average per capita electricity demand rises from 2.1 in 2020 to 7.1 MWh by 2050, as indicated in Figure A1.3.

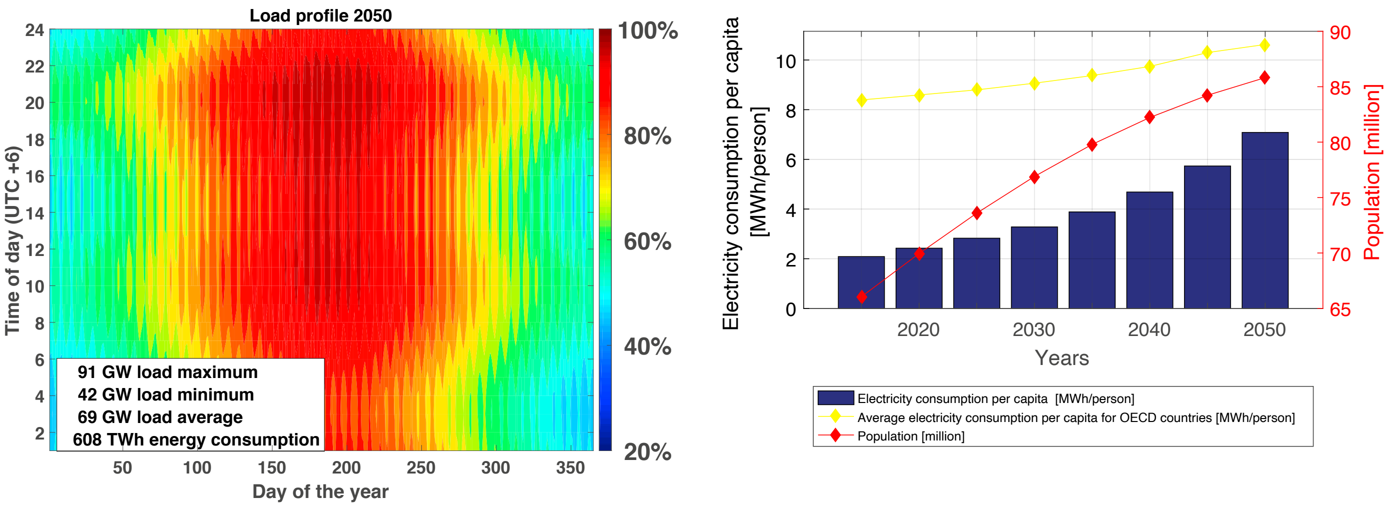

Figure A1.3: Annual distribution of the hourly load profile in 2050 (left) and development of the per capita electricity consumption (right) during the energy transition from 2015 to 2050 in Gujarat.

The electricity demand is assumed to increase from 138 TWh in 2015 to around 609 TWh in 2050. The load profile in 2050 will be different for the centralised system due to partial load covering by prosumers, as shown in Figure A1.3. However, the seasonal variations in demand in Gujarat are quite evident, with peaks in the summer and pre-monsoon seasons.

Resource

The resource of solar PV and wind, which are the most relevant sources in the energy transition, are highlighted in Figure A1.4. Solar PV is more evenly distributed throughout the state, with high potential in the western regions of Kutch, while the wind potential is mainly concentrated in the western parts of the state and indicates high offshore wind potential in the region, as highlighted in Figure A1.4.

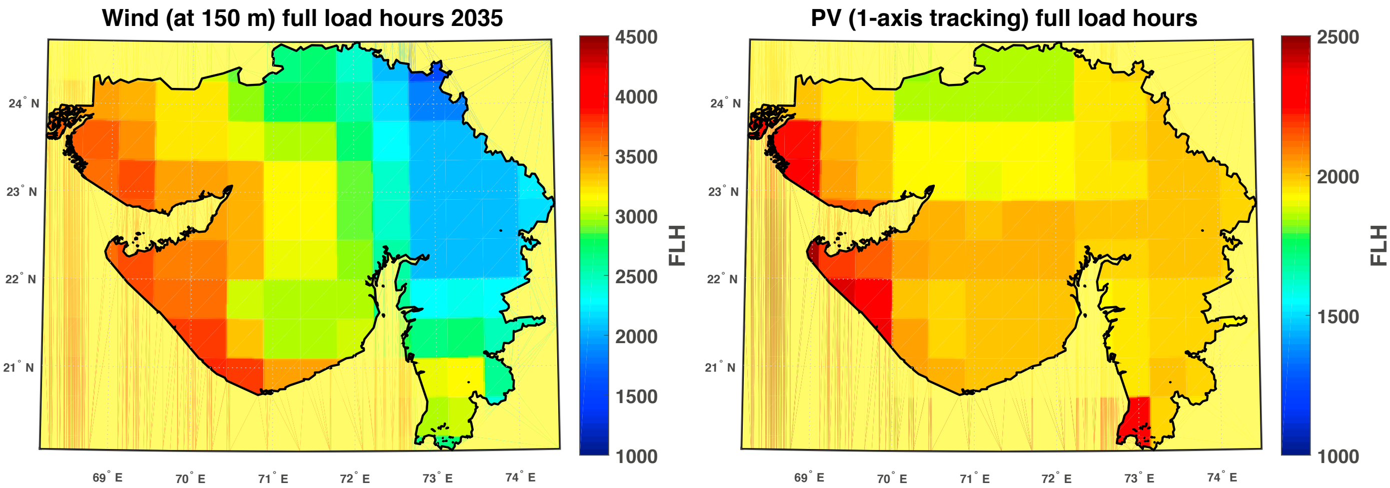

Figure A1.4: Regional distribution of capacity factors/full load hours for solar PV (left) and wind energy (right) across Gujarat. The wind capacity factor/full load hours shown are for 2035 and beyond.

The capacity factors for the wind energy generation potential are taken from Bloomberg projections for the whole of India; they increase from 29% in 2020 to 36% in 2035. The best sites have maximum capacity factors of 48% (about 4200 FLH) in 2035. Beyond 2035, the same capacity factor/FLH is assumed until 2050.

The annual variations in aggregated hourly generation profiles of solar PV and wind are shown in Figure A1.5. Wind energy generation is predominant in the monsoon months and overcomes the solar resource unavailability and complements perfectly in periods of low solar radiation; solar PV on the other hand is more evenly distributed through the year, as shown in Figure A1.5.

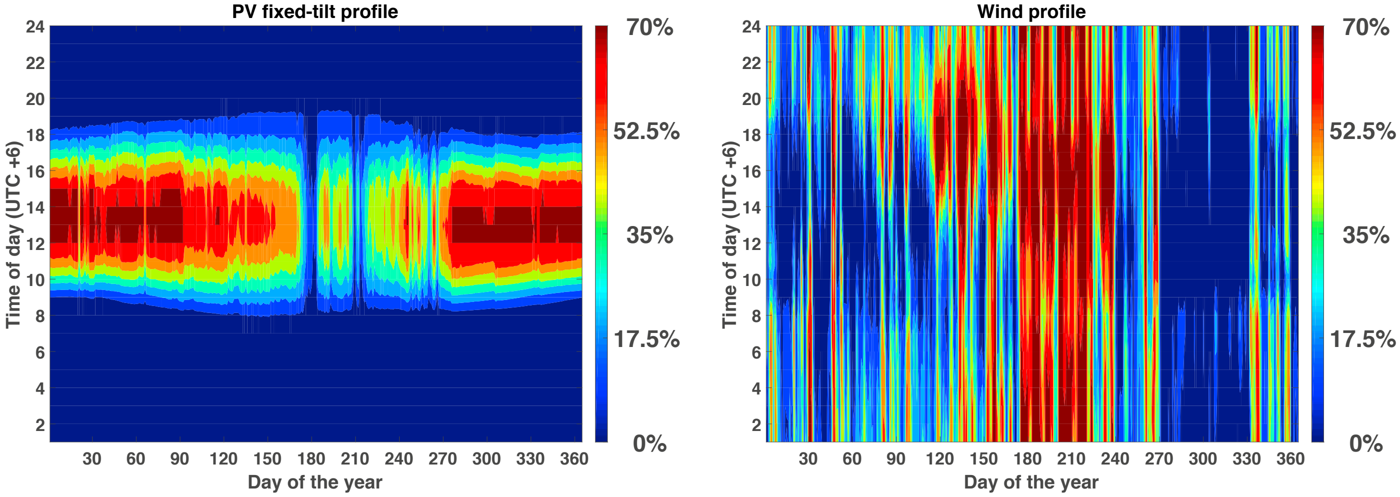

Figure A1.5: Annual distribution of the hourly generation profile for solar PV (left) and wind energy (right) in Gujarat.

The monthly averaged resource availability throughout the year for solar PV and wind is highlighted in Figure A1.6. The seasonal complementary nature of solar PV and wind energy is clearly evident and ensures that demand, which is rather stable through the year, is satisfied. Monthly values are normalised to the highest monthly value throughout the year.

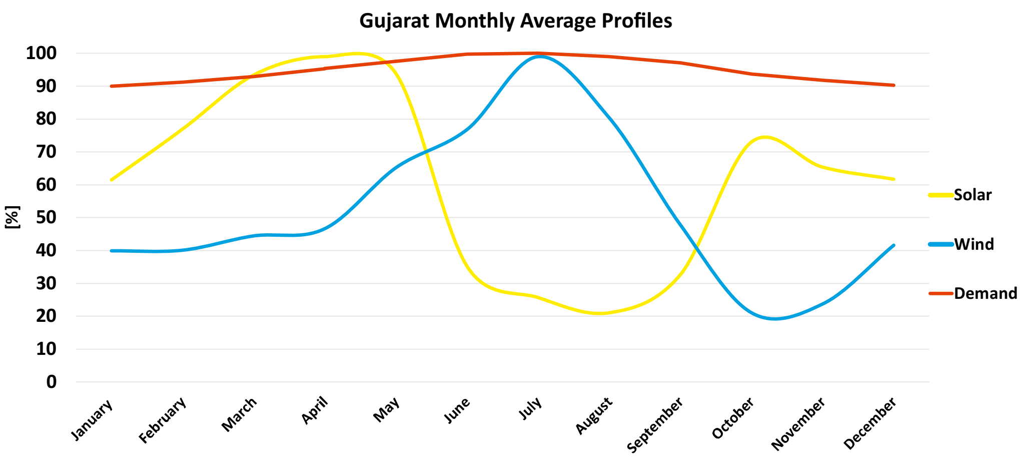

Figure A1.6: Annual distribution of the monthly average electricity generation profiles for solar PV and wind energy, and the demand profile in Gujarat in 2050.

Electricity

The electricity generation capacity in Gujarat satisfies demand from the power sector. The total installed capacity grows massively from about 40 GW in 2020 to around 380 GW by 2050, as shown in Figure A1.7. In the initial period of the transition, a larger share of wind capacities is installed up to 2025, but in the later part of the transition solar PV dominates the shares of installed capacities, reaching almost 270 GW by 2050. On the other hand, the share of fossil fuels and nuclear energy declines during the transition, with installed capacities of coal at risk of becoming stranded assets and having very low full load hours during the transition years as the share of renewables increases. Reciprocating gas engines are increasingly installed from 2030 onwards to provide flexibility to the system, which is already 50% renewable based.

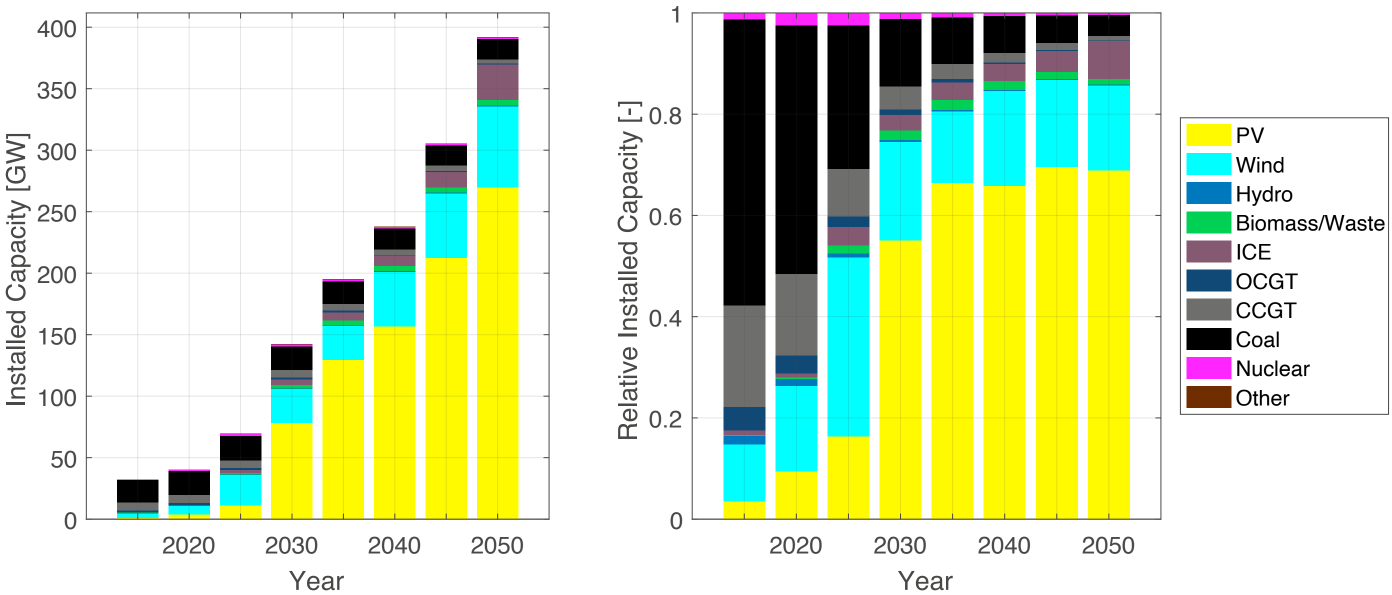

Figure A1.7: Installed capacities by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Gujarat.

As shown in Figure A1.8, the share of coal in electricity generation increases in 2020 to provide the electricity needed to meet the increasing power demand, as coal is cheaper than gas and oil. Beyond 2020, the share of coal continues to drop as the share of wind energy (32%) in 2025 and then solar PV (53%) in 2030 increase in the total electricity generation as they become more cost competitive (see Figure A1.8). Reciprocating gas engines have a share of 3.3% in electricity generation in 2050, mainly driven by their higher efficiency and lower cost, while having FLH of over 800, mainly utilised for peak supply and balancing. The fuel mix for reciprocating gas engines develops from 100% fossil gas in 2020 to 98% synthetic natural gas and 2% biomethane in 2050.

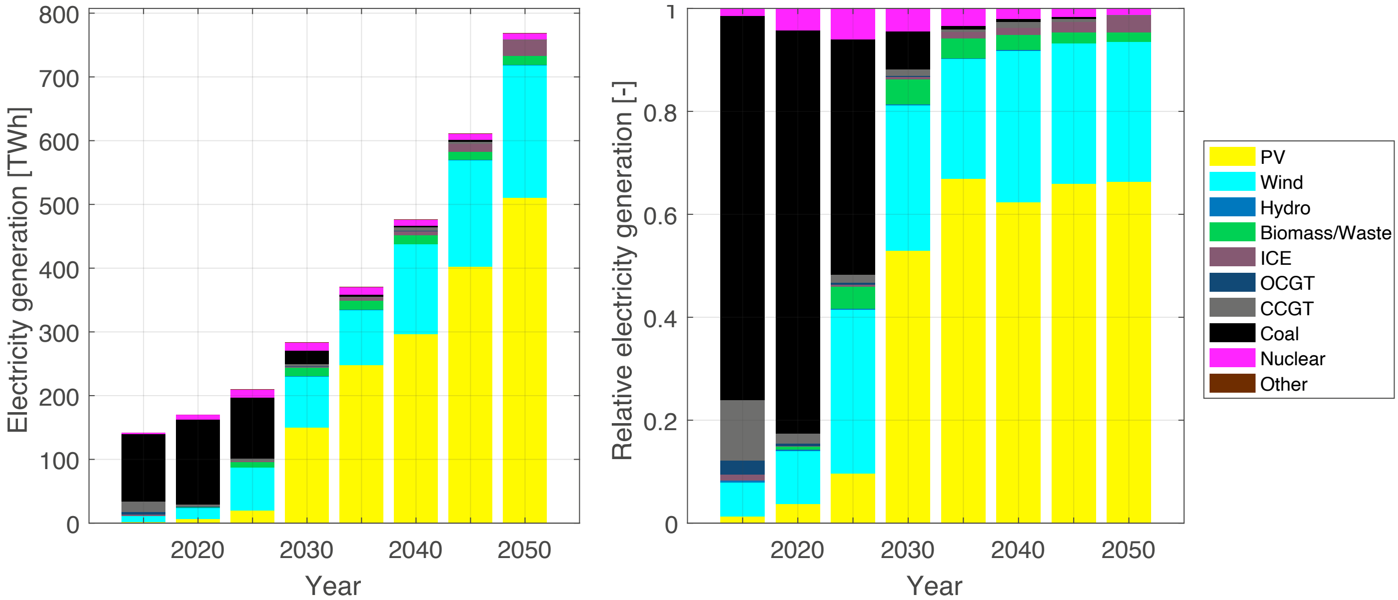

Figure A1.8: Electricity generation by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Gujarat.

Storage

Energy storage technologies play a critical role in enabling a secure energy supply in the power sector of Gujarat, which by 2050 is fully based on renewable energy. The installed electricity storage capacity increases from just 0.5 TWh in 2030 to around 28 TWh by 2050, as shown in Figure A1.9. Utility-scale and prosumer batteries, with major shares of gas storage, are installed during the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with more than 99% by 2050, as highlighted by Figure A1.9.

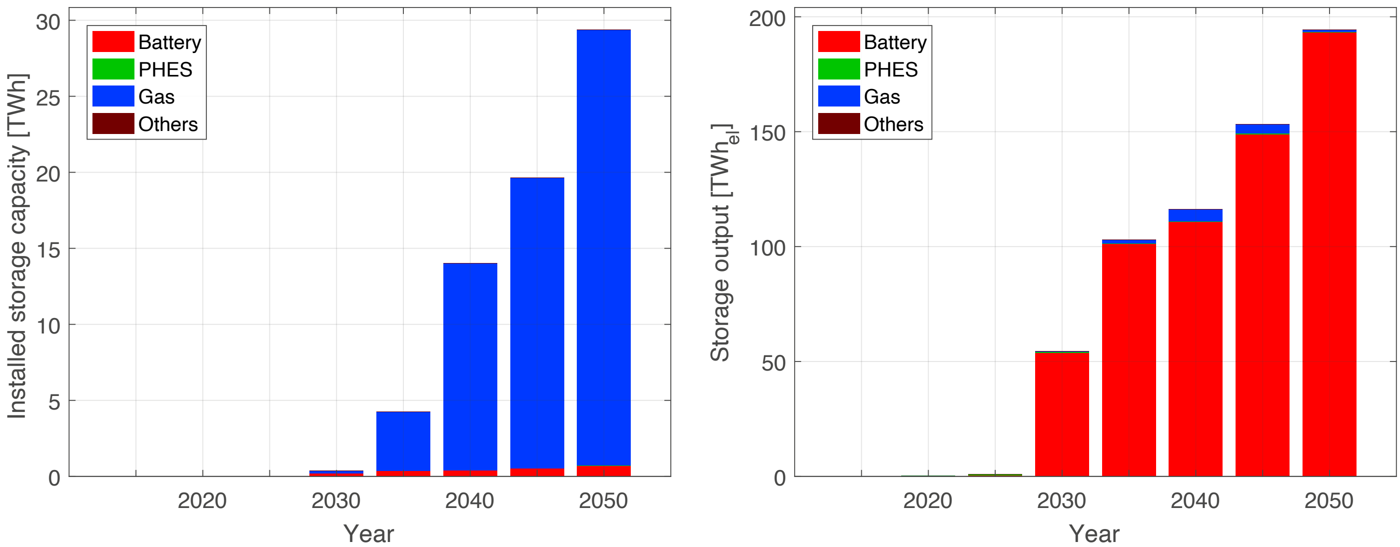

Figure A1.9: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Gujarat.

Gas storage, which is synthetic natural gas produced through the power-to-gas process, has large capacities and fewer operating hours as it contributes vital seasonal storage during the transition. Battery storage mainly plays a role in providing diurnal storage, as indicated in Figure A1.10.

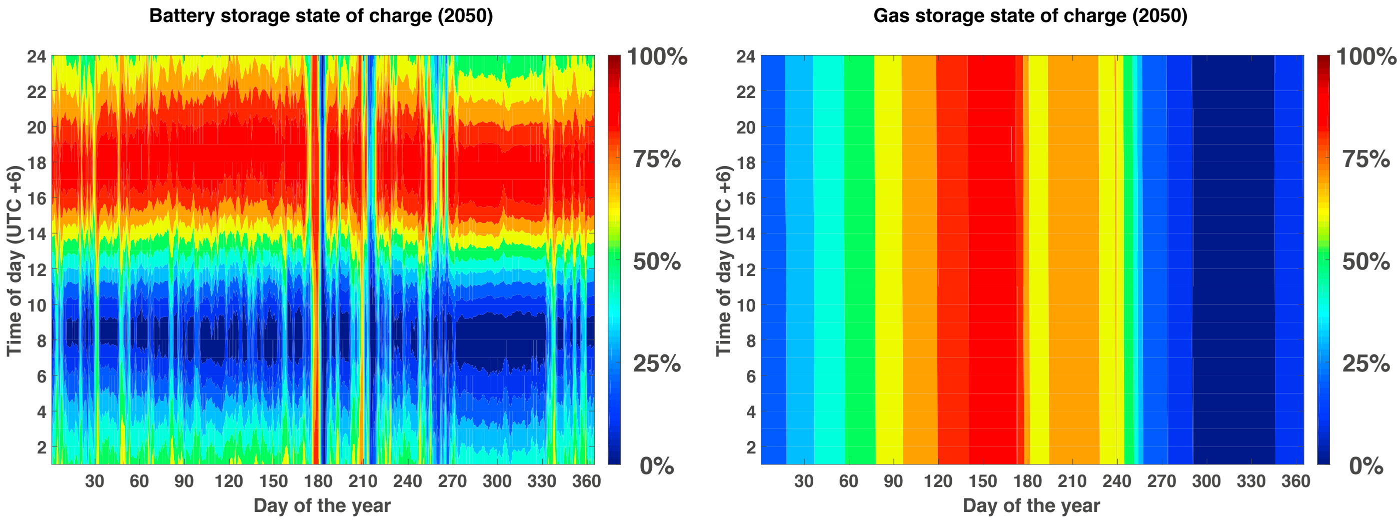

Figure A1.10: State of charge for battery storage (left) and gas storage (right) in 2050 for Gujarat.

Gas storage mainly plays a role in providing seasonal storage, which is especially needed in the monsoon season when the solar resource is at its lowest. The gas storage discharges slowly over the monsoon period and is completely discharged by the end of winter, as can be observed in Figure A1.10. Some hydropower reservoirs provide complementarity with solar and wind but are used mainly for seasonal balancing.

System outlook

The power system in Gujarat has distinctive operational characteristics, which vary according to the seasonal pattern. This is highlighted by a summer week in 2050 (see Figure A1.11) and monsoon week in 2050 (see Figure A1.12). During the summer period, solar PV and complementary wind energy are the main electricity generation sources. Batteries are used daily, charging during the day and discharging during the evening and night to meet peak consumption, as highlighted in Figure A1.12.

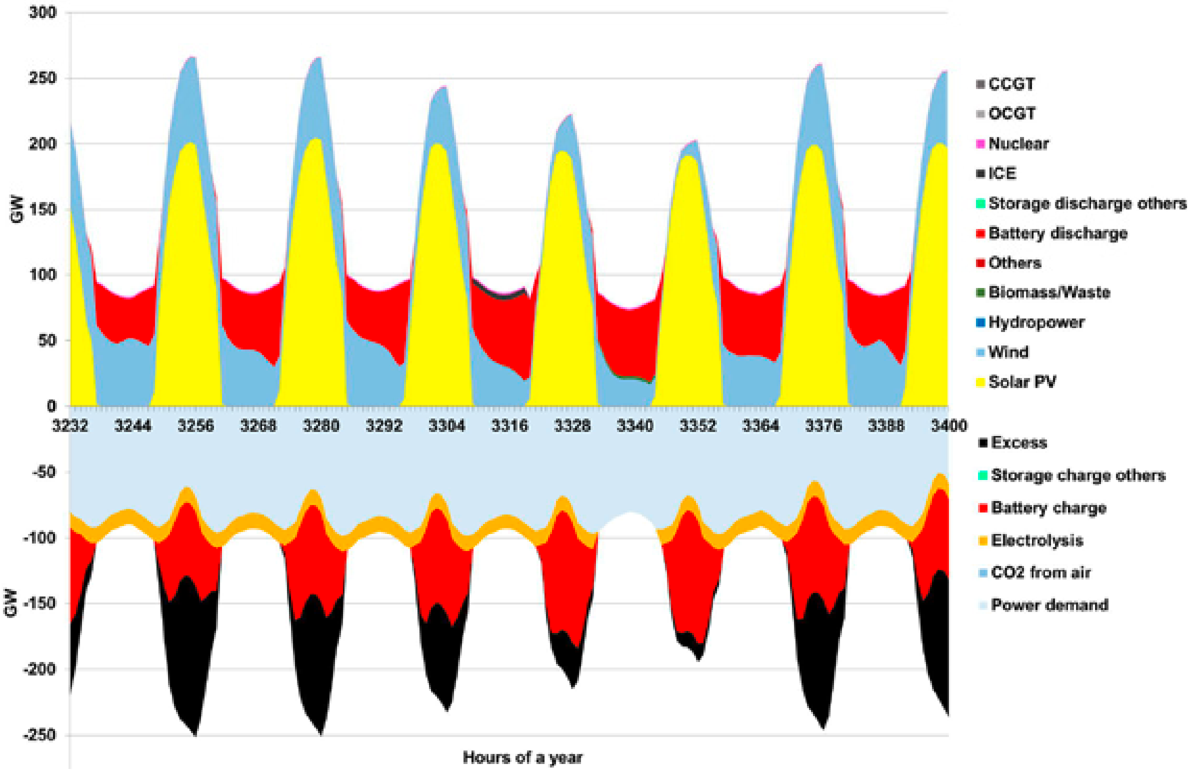

Figure A1.11: Time series of the power system in Gujarat during a best solar week in 2050.

During the monsoon period, solar PV generation decreases while wind generation increases and becomes the main source of electricity generation. A share of dispatchable bioenergy compensates for the lack of solar PV and wind generation. Reciprocating gas engines are utilised in periods of low generation, especially in the beginning of the week when wind generation is low and when solar generation is also low during the middle and end of the week, as shown in Figure A1.12.

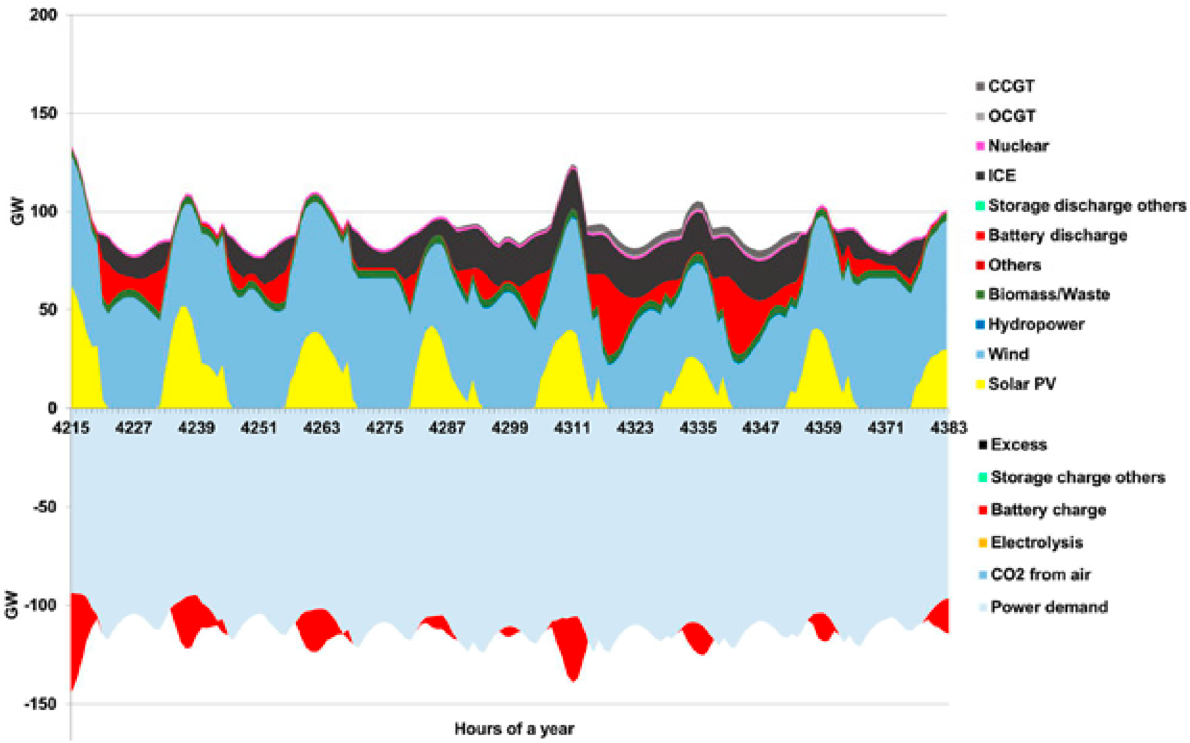

Figure A1.12: Time series of the power system in Gujarat during a worst solar week in 2050.

Costs and investments

As indicated in Figure A1.13, capex increases during the transition, with wind initially and later solar and batteries being dominant.

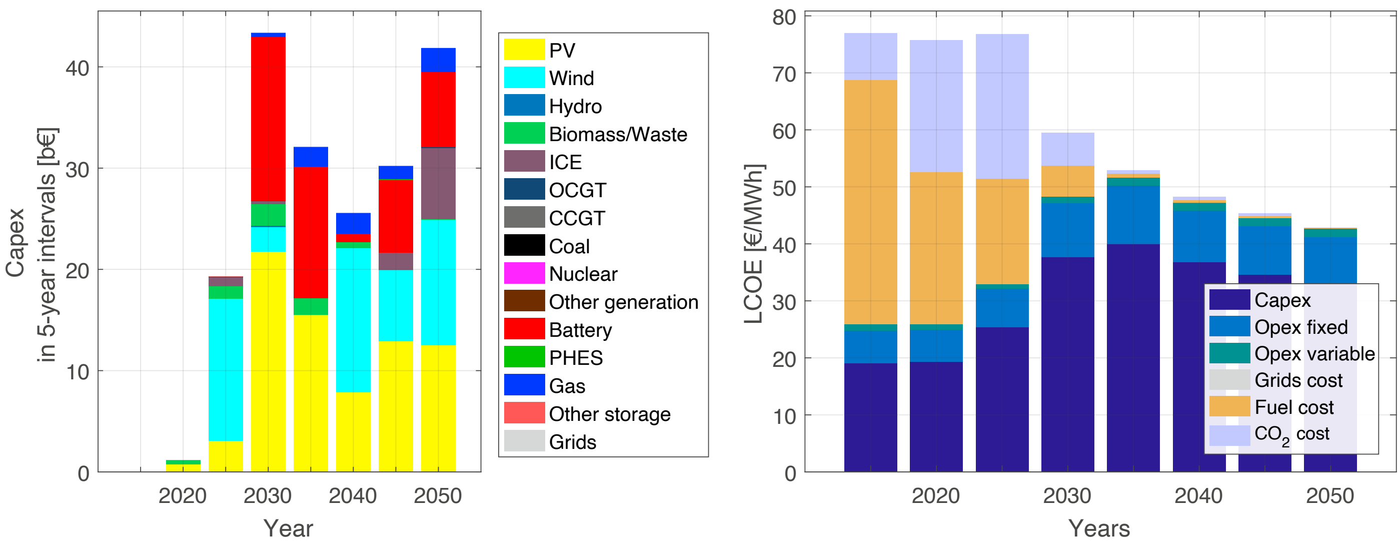

Figure A1.13: Capital expenditures for five-year intervals (left) and levelised cost of electricity (right) during the energy transition from 2015 to 2050 in Gujarat.

The levelised cost of electricity declines from around 77 €/MWh in 2020 to around 43 €/MWh by 2050 (see Figure A1.13) and is increasingly dominated by capital costs as fuel costs continue to decline during the transition period, which could mean increased self-reliance in terms of energy for Gujarat by 2050. Capital costs are divided across a range of technologies, with major investments in solar PV, wind energy, batteries and gas storage up to 2050, as shown in Figure A1.13.

The steady increase in capex-related energy system costs indicates that fuel imports from other states across the country and the respective negative impacts on trade balances will fade during the transition.

Greenhouse gas (GHG) emissions

The results of the power system transition in Gujarat indicate that GHG emissions can be reduced from 140 $MtCO_{2eq}$ in 2020 to zero by 2050 across the power sector, as shown in Figure A1.14. The CO_{2eq} intensity of electricity generation rapidly declines during the transition, enabled by the phase-out of fossil-based power plants, which indicates a deep defossilisation by 2035 (see Figure A1.14).

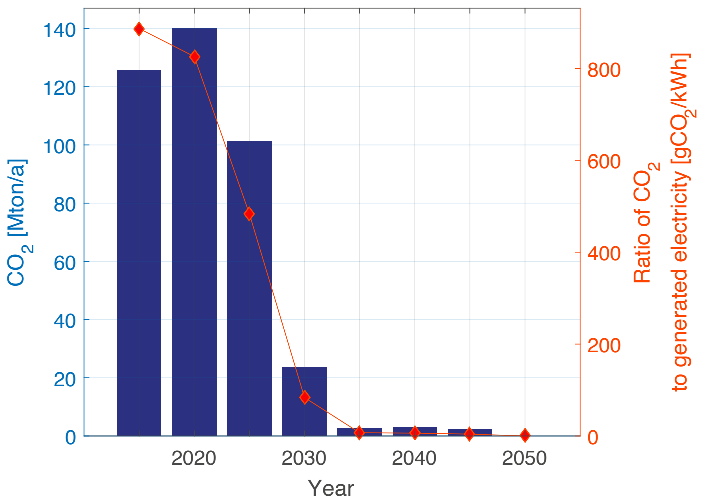

Figure A1.14: GHG emissions from the power sector during the energy transition from 2020 to 2050 in Gujarat.

The presented 100% RE scenario for the power sector of Gujarat is compatible with the goals of the Paris Agreement and will enable India to meet its commitments and take a leadership role. A deep defossilisation of the power sector is possible by 2030, and a steady decline in emissions is possible beyond 2030 up to 2050.

A2. TELANGANA

The recently formed state of Telangana is part of the southern grid in the Indian power system (see Figure A2.1). It is one of the rapidly developing information technology hubs in the country and has a growing energy demand. It is modelled to be self-sufficient in terms of meeting its future power demand as part of this research. Furthermore, no imports or exports with other neighbouring states are considered. It is also assumed that the existing network of AC lines, mainly for distribution of electricity within Telangana, will provide electricity to all consumers in the future.

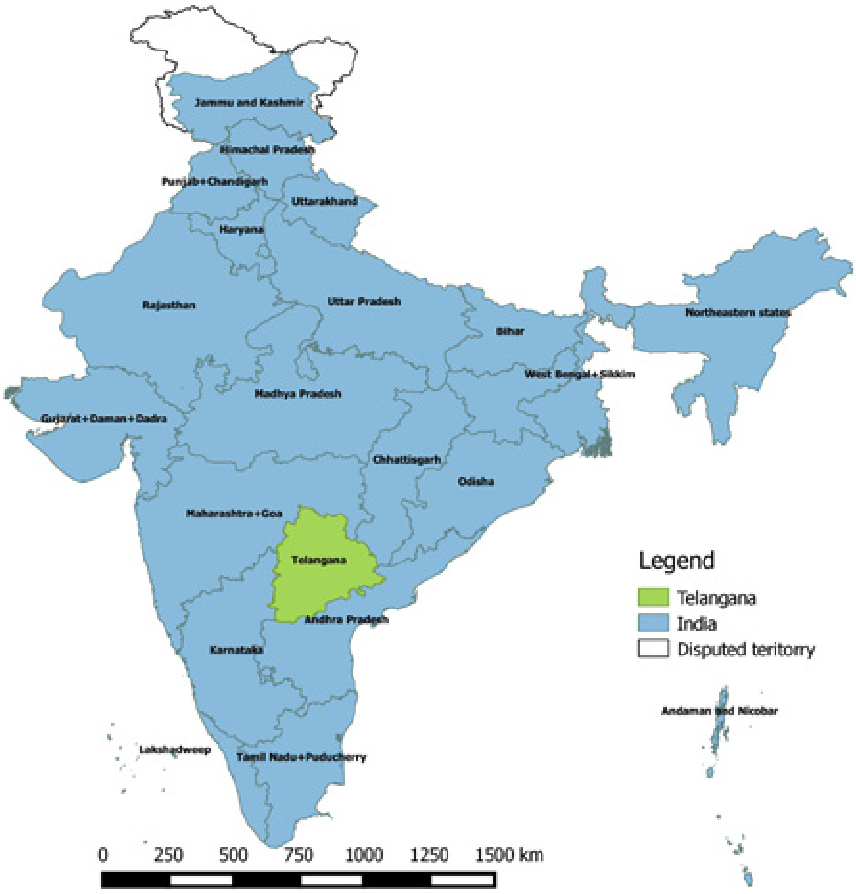

Figure A2.1: Telangana within the regional setup of India.

The power sector in Telangana is quite heavily relied on coal-based generation to satisfy the growing electricity demand across the state. In recent times significant growth in the share of installed capacity of renewables has been observed, predominantly in the form of solar PV capacities (see Figure A2.2). As indicated in Figure A2.2, coal still accounts for around 82% of the electricity in 2020; however the capacity factors, or alternately the Full Load Hours (FLH), of coal power plants across the country have been decreasing on a year-on-year basis. In addition, several of these plants are in financial distress. Air pollution has increasingly become a national problem causing adverse health impacts and negative economic consequences. The huge water requirements for coal power plants are causing increased levels of water stress and competing with irrigation demand for agriculture. These challenges indicate that the trend of growing the capacity addition of renewables is expected to continue and is required to be accelerated to meet India's ambitious climate targets.

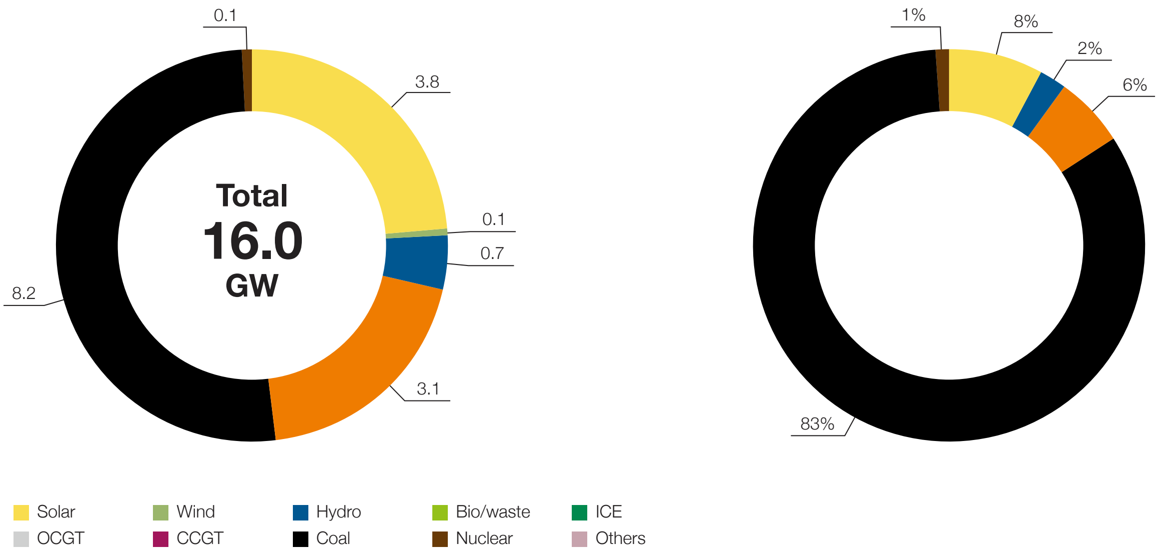

Figure A2.2: Resource-based electricity generation capacities (left) and generation share (right) of the Telangana power sector in 2020.

Demand

The cumulative average annual growth rate of electricity consumption is about 4.9% during the energy transition period from 2015 to 2050, comparable to a 7% average growth rate of electricity demand across the country in recent times. The population of Telangana is expected to grow from about 40 million in 2020 to nearly 50 million by 2050, while the average per capita electricity demand rises from 1.8 MWh in 2020 to 5.8 MWh by 2050, as indicated in Figure A2.3.

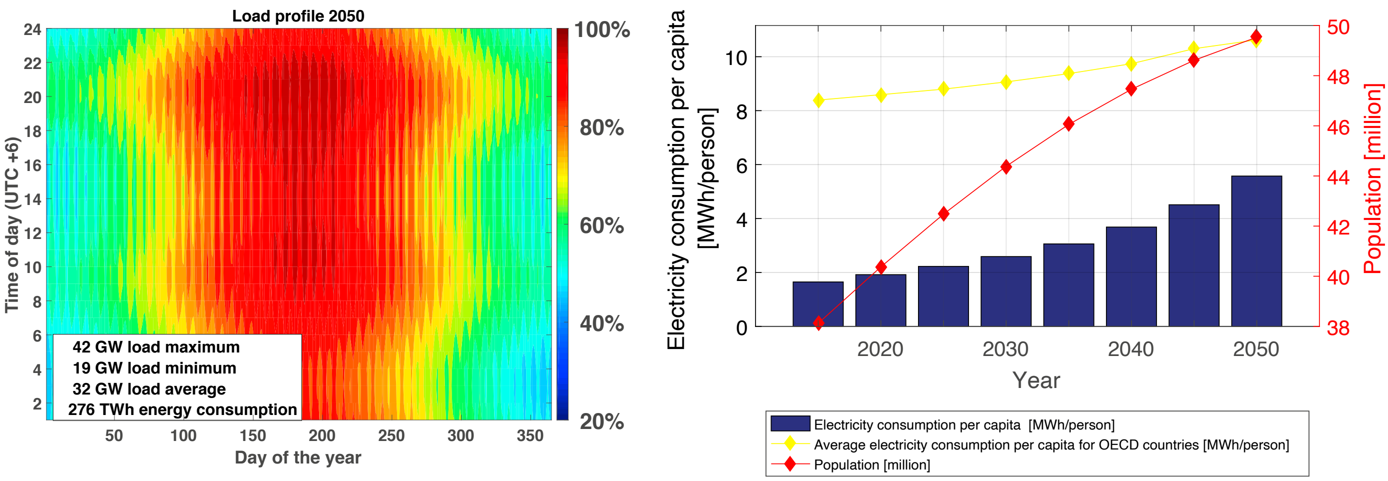

Figure A2.3: Annual distribution of the hourly load profile in 2050 (left) and development of the per capita electricity consumption (right) during the energy transition from 2015 to 2050 in Telangana.

The electricity demand is assumed to increase from 138 TWh in 2015 to around 609 TWh by 2050. The load profile in 2050 will be different for the centralised system due to partial load covering by prosumers, as shown in Figure A2.3. However, the seasonal variations in demand in Telangana are clearly evident, with peaks in summer and the pre-monsoon season.

Resource

The resource of solar PV and wind, which are the most relevant sources in the energy transition across Telangana, are highlighted in Figure A2.4. Solar PV is more evenly distributed throughout the state, with high potential in the southern and western regions, whereas the wind potential is mainly concentrated in the southwestern part of the state and indicates high concentration in the region, as highlighted in Figure A2.4.

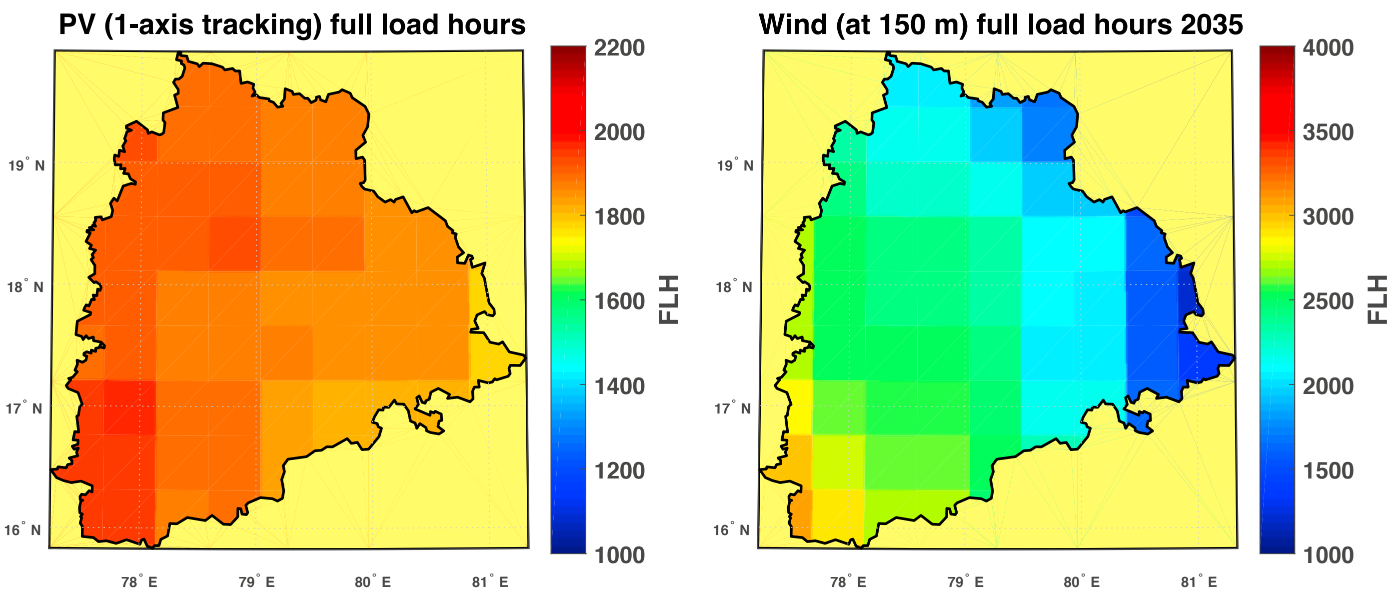

Figure A2.4: Regional distribution of capacity factors/full load hours for solar PV (left) and wind energy (right) across Telangana. The wind capacity factor/full load hours shown are for 2035 and beyond.

Capacity factors for the wind energy generation potential are taken from Bloomberg projections for the whole of India, which increase from 29% in 2020 to 36% in 2035. The best sites have maximum capacity factors of 48% (about 4200 FLH) in 2035. Beyond 2035, the same capacity factor/FLH is assumed until 2050.

The annual variations in aggregated hourly generation profiles of solar PV and wind are shown in Figure A2.5. Wind energy generation is predominant in the monsoon months and compensates for the lack of solar resource availability and complements perfectly in periods of low solar radiation; solar PV on the other hand is more evenly distributed through the year, as shown in Figure A2.5. Grids will play a key role in the state of Telangana as the wind potential is more concentrated in the southwestern region and solar is well distributed across the state; well-planned transmission can therefore enhance the complementarity of these resources.

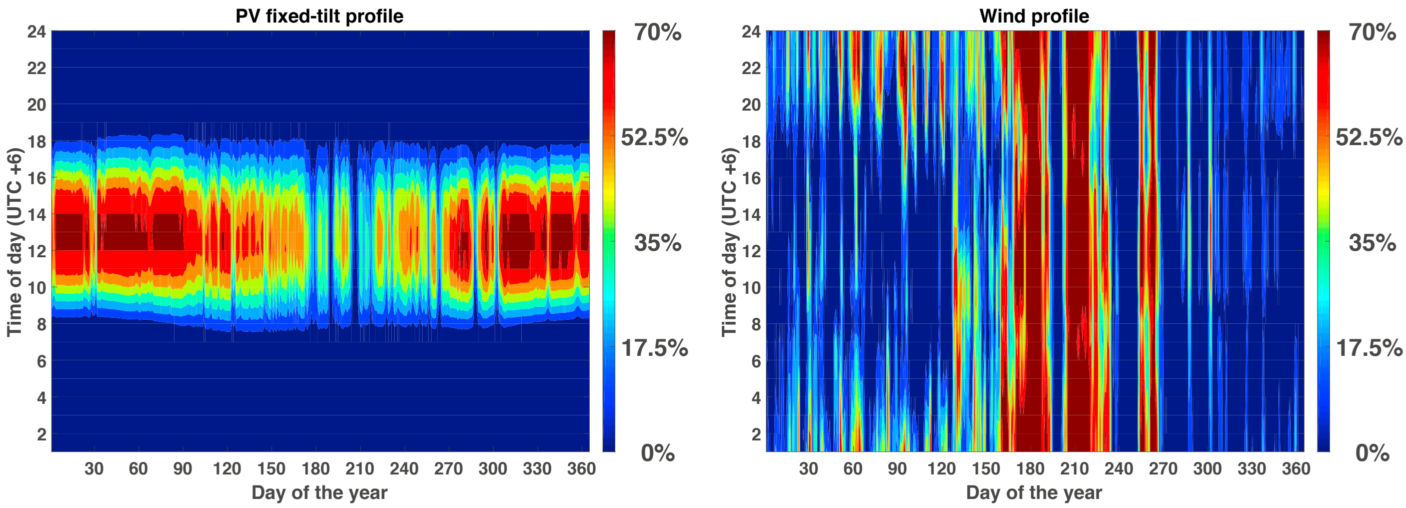

Figure A2.5: Annual distribution of the hourly generation profile for solar PV (left) and wind energy (right) in Telangana.

The monthly averaged resource availability throughout the year for solar PV and wind is highlighted in Figure A2.6. The seasonal complementary nature of solar PV and wind energy is clearly evident and ensures demand, which is rather stable through the year, is satisfied. Monthly values are normalised to the highest monthly value throughout the year.

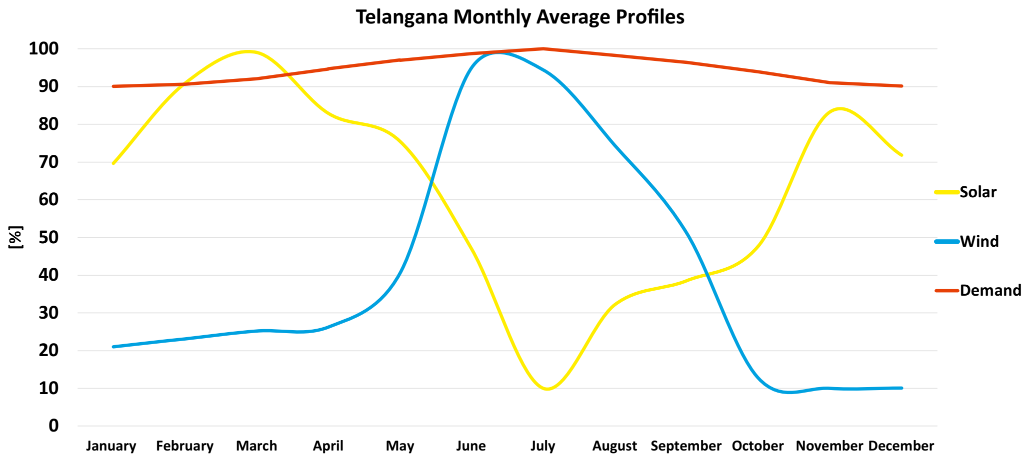

Figure A2.6: Annual distribution of the monthly average electricity generation profiles for solar PV and wind energy, and the demand profile in Telangana in 2050.

Electricity

The electricity generation capacity in Telangana satisfies demand from the power sector during the transition. The total installed capacity grows massively from about 16 GW in 2020 to around 240 GW by 2050 as shown in Figure A2.7. Solar PV dominates the shares of installed capacities from 2020 onwards, reaching almost 180 GW by 2050. Wind capacities complement solar PV with some shares from 2025 during the transition. On the other hand, the shares of fossil fuels decline through the transition, with installed capacities of coal at risk of becoming stranded assets and having very low full load hours during the transition years as the share of renewables increases. Reciprocating gas engines are installed increasingly from 2025 onwards to provide flexibility to the system, which is already 50% renewable based.

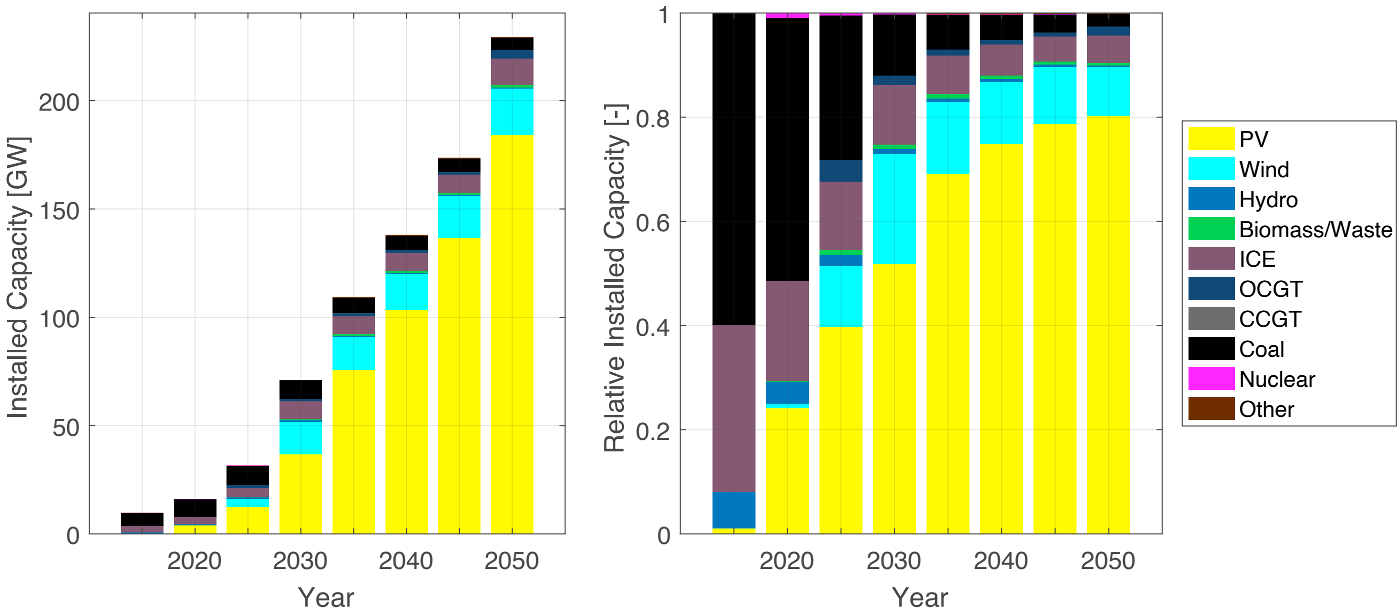

Figure A2.7: Installed capacities by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Telangana.

As shown in Figure A2.8, the share of coal in electricity generation increases in 2020 to provide electricity needed to meet the increasing power demand, as coal is cheaper than gas and oil. Beyond 2020, the share of coal continues to drop as the share of solar PV (22%) in 2025 and wind energy (26%) in 2030 increase in the total electricity generation as they become more cost competitive (see Figure A2.8). Reciprocating gas engines have a share of 2.8 % in electricity generation in 2050, mainly driven by their higher efficiency and lower cost, while having FLH of over 1350, mainly utilised for peak supply and balancing. The fuel mix for reciprocating gas engines develops from 100% fossil gas in 2020 to 99% synthetic natural gas and 1% biomethane in 2050.

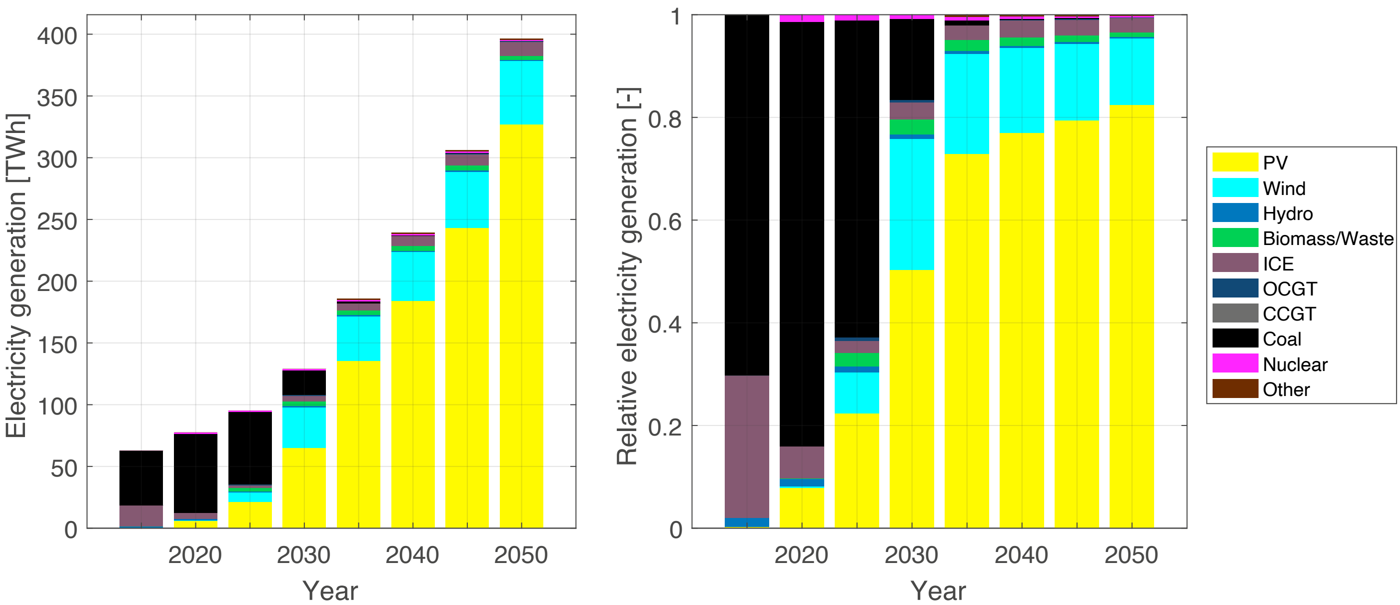

Figure A2.8: Electricity generation by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Telangana.

Storage

Energy storage technologies play a critical role in enabling a secure energy supply in the power sector of Telangana, which by 2050 fully based on renewable energy. The installed electricity storage capacity increases from just 0.5 TWh in 2030 to around 13 TWh by 2050, as shown in Figure A2.9. Utility-scale and prosumer batteries, with major shares of gas storage, are installed during the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with more than 99% by 2050, as highlighted by Figure A2.9. Storage output covers 42% of electricity demand across Telangana by 2050.

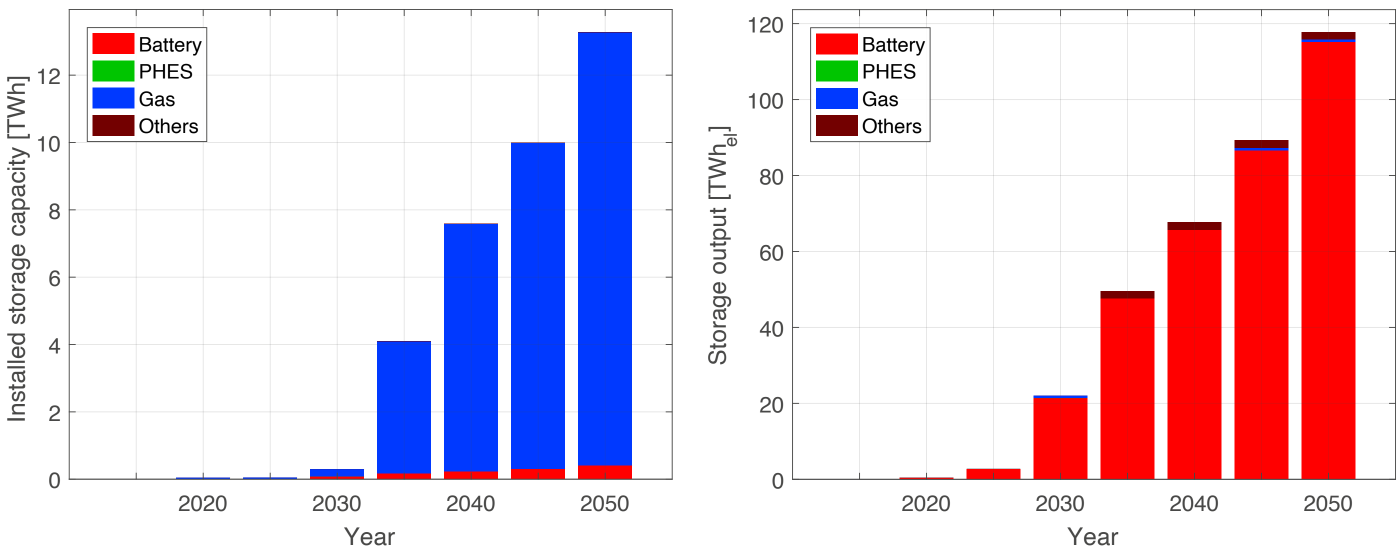

Figure A2.9: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Telangana.

Gas storage, which is synthetic natural gas produced through the power-to-gas process, has large capacities and fewer operating hours as it contributes vital seasonal storage during the transition. Battery storage mainly plays a role in providing diurnal storage, as indicated in Figure A2.10.

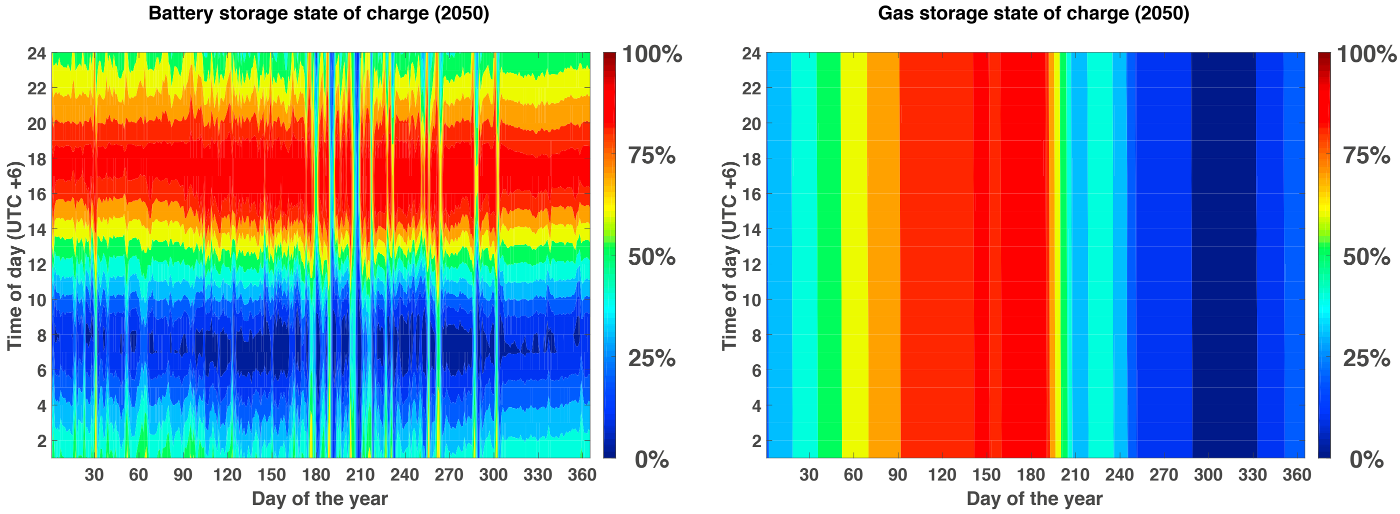

Figure A2.10: State of charge for battery storage (left) and gas storage (right) in 2050 for Telangana.

Gas storage mainly plays a role in providing seasonal storage, which is especially needed in the monsoon season when the solar resource is at its lowest. The gas storage discharges slowly over the monsoon period and is completely discharged by the end of winter, as can be observed in Figure A2.10. Some hydropower reservoirs provide complementarity with solar and wind but are used mainly for seasonal balancing.

System outlook

The power system in Telangana has distinctive operational characteristics, which vary according to the seasonal pattern. This is highlighted by a summer week in 2050 (see Figure A2.11) and a monsoon week in 2050 (see Figure A2.12).

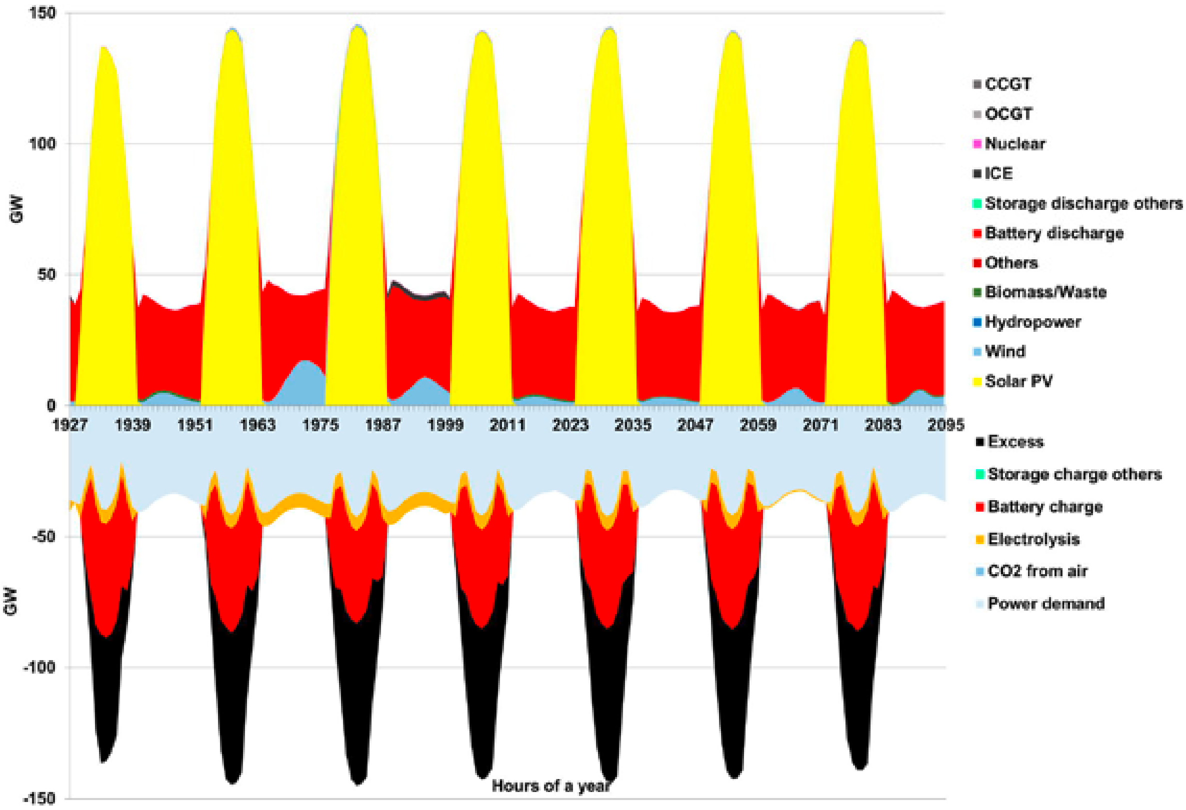

Figure A2.11: Time series of the power system in Telangana during a best solar week in 2050.

During the summer period, solar PV and very low shares of complementary wind energy are the main electricity generation sources. Batteries are used daily, charging during the day and discharging during the evening and night to meet peak consumption, as highlighted in Figure A2.11.

During the monsoon period, solar PV generation decreases while wind generation increases and becomes the main source of electricity generation. Some shares of dispatchable bioenergy compensate for the lack of solar PV and wind generation. Reciprocating gas engines are utilised in periods of low generation, especially in the beginning of the week when wind generation is low and when solar generation is also low during the middle and end of the week, as shown in Figure A2.12.

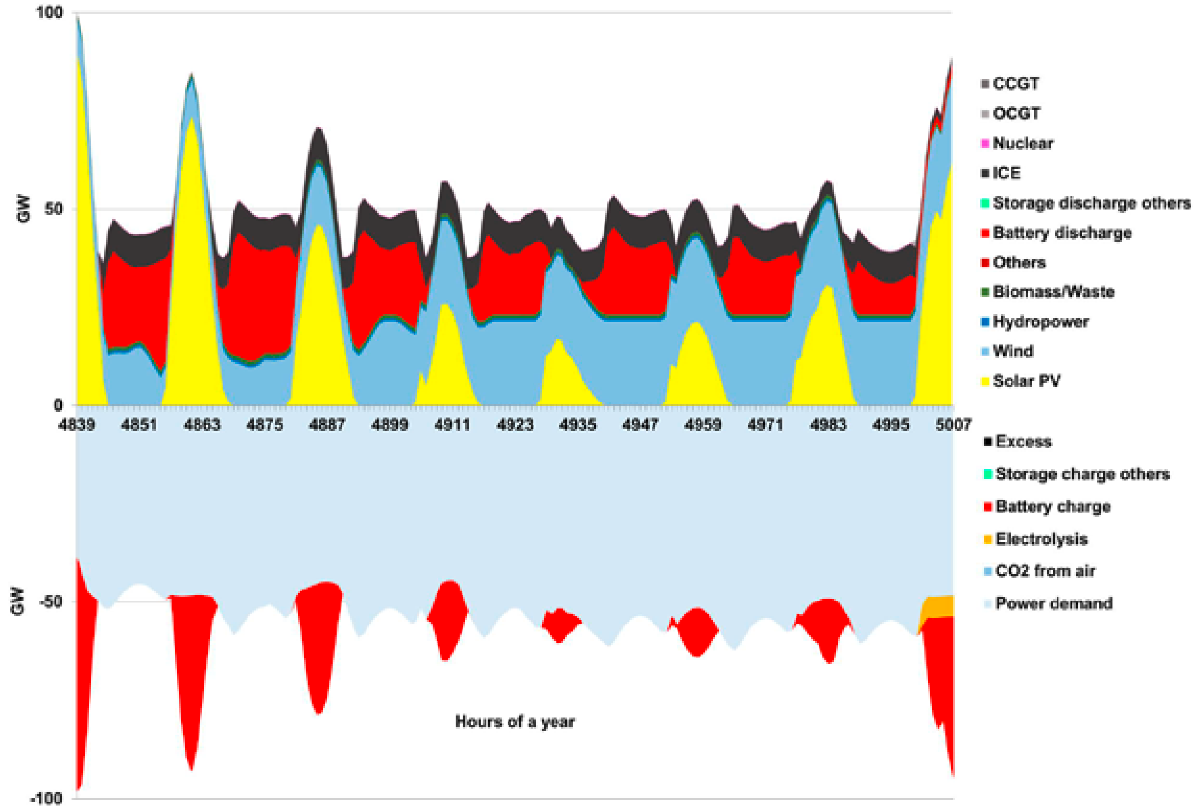

Figure A2.12: Time series of the power system in Telangana during a worst solar week in 2050.

Costs and investments

As indicated in Figure A2.13, capex increases during the transition, with wind initially and later solar and batteries being dominant.

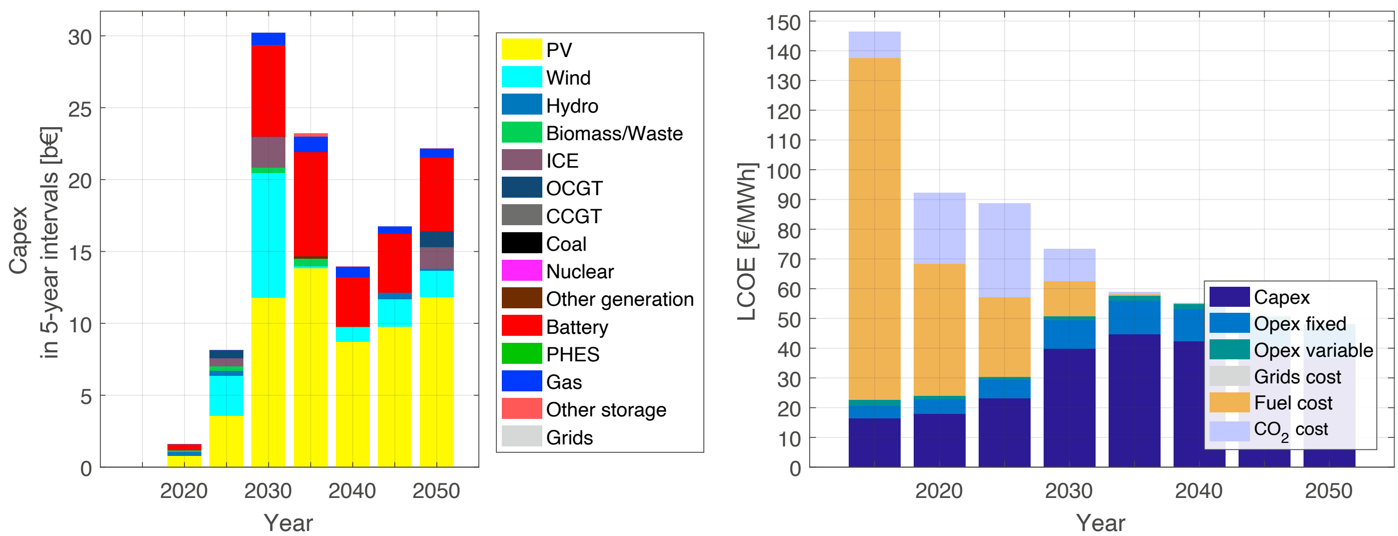

Figure A2.13: Capital expenditures for five-year intervals (left) and levelised cost of electricity (right) during the energy transition from 2015 to 2050 in Telangana.

The levelised cost of electricity declines from around 90 €/MWh in 2020 to around 48 €/MWh by 2050 (see Figure A2.13) and is increasingly dominated by capital costs as fuel costs continue to decline during the transition period, which could mean increased self-reliance in terms of energy for Telangana by 2050. Capital costs are divided across a range of technologies, with major investments in solar PV, wind energy, batteries and gas storage up to 2050, as shown in Figure A2.13.

The steady increase in capex-related energy system costs indicates that fuel imports from other states across the country and the respective negative impacts on trade balances will fade during the transition.

GHG emissions

The results of the power system transition in Telangana indicate that GHG emissions can be reduced from over 65 $MtCO_{2eq}$ in 2020 to zero by 2050 across the power sector, as shown in Figure A2.14. The CO_{2eq} intensity of electricity generation rapidly declines during the transition, enabled by the phase-out of fossil-based power plants, which indicates a deep defossilisation by 2035 (see Figure A2.14).

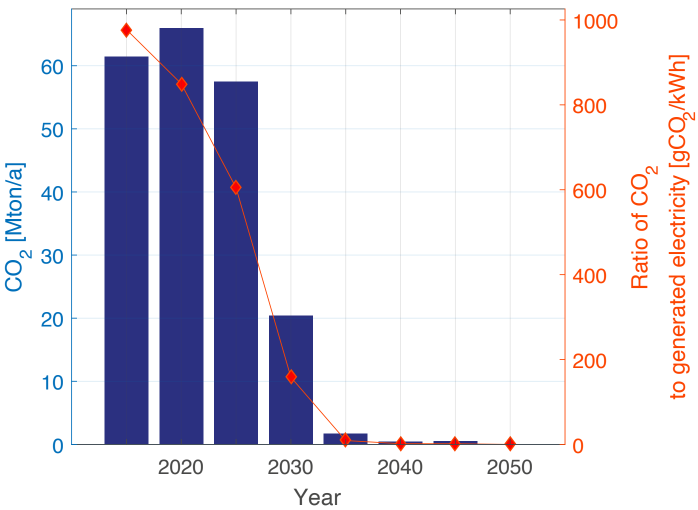

Figure A2.14: GHG emissions from the power sector during the energy transition from 2020 to 2050 in Telangana.

The presented 100% RE scenario for the power sector of Telangana is compatible with the goals of the Paris Agreement and will enable India to meet its commitments and take a leadership role. A deep defossilisation of the power sector is possible by 2035, and a steady decline of emissions is possible beyond 2035 up to 2050.

A3. ANDHRA PRADESH

The recently bifurcated state of Andhra Pradesh is part of the southern grid in the Indian power system (see Figure A3.1). Although it is one of the country's largely agrarian states, the energy demand is growing rapidly as a result of increasing industrialisation and urbanisation. It is modelled to be self-sufficient in terms of meeting its future power demand as part of this research. Furthermore, no imports or exports with other neighbouring states are considered. It is also assumed that the existing network of AC lines, mainly for distribution of electricity within Andhra Pradesh, will provide electricity to all consumers in the future.

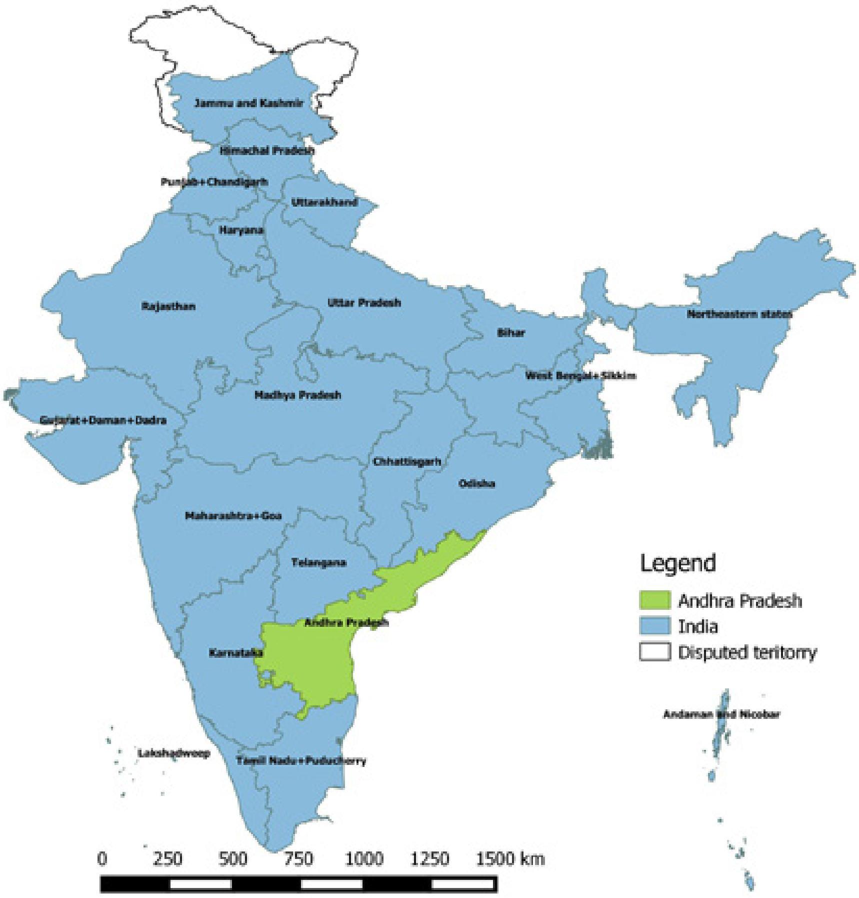

Figure A3.1: Andhra Pradesh within the regional setup of India.

Historically, the power sector in Andhra Pradesh has relied on coal-based generation to satisfy the growing electricity demand across the state. In recent times significant growth in the share of installed capacity of renewables has been observed, and Andhra Pradesh is now among the leading states in the country in terms of renewables (see Figure A3.2). As indicated in Figure A3.2, coal still accounts for around 62% of the electricity; however the capacity factor or alternately the Full Load Hours (FLH), of coal power plants across the country have been decreasing on a year-on-year basis. In addition, several of these plants are in financial distress. Air pollution has increasingly become a national problem causing adverse health impacts and negative economic consequences. The huge water requirements of coal power plants are causing increased levels of water stress and competing with irrigation demand for agriculture. These challenges indicate that the trend of growing the capacity addition of renewables is expected to continue and is required to be accelerated to meet India's ambitious climate targets.

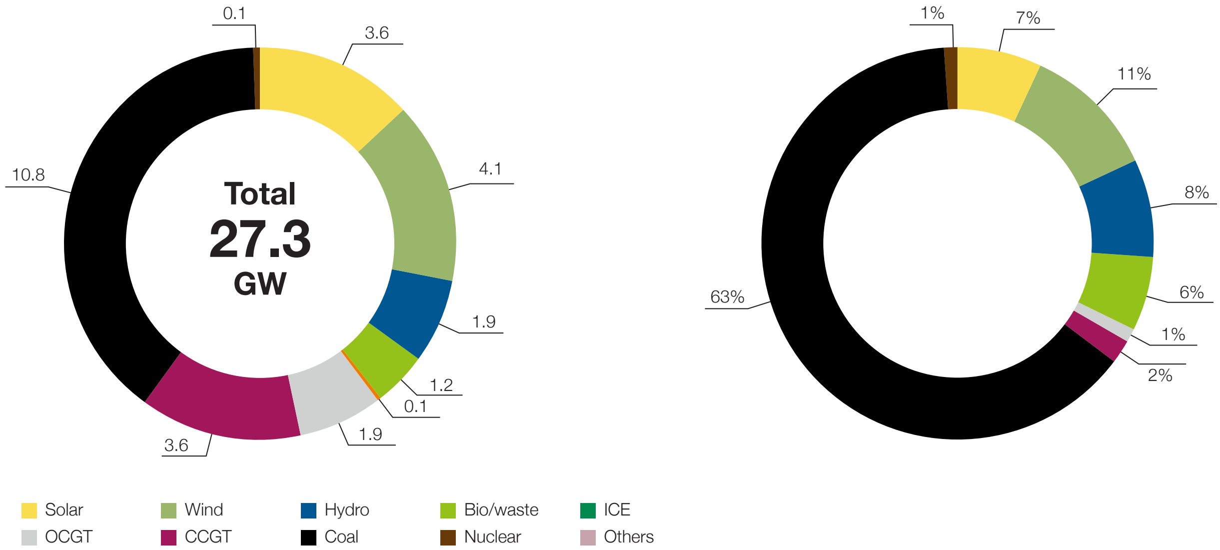

Figure A3.2: Resource-based electricity generation capacities (left) and generation share (right) of the Andhra Pradesh power sector in 2020.

Demand

The cumulative average annual growth rate of electricity consumption is about 4.9% during the energy transition period from 2015 to 2050 compared to a 7% average growth rate of electricity demand across the country in recent times. The population of Andhra Pradesh is expected to grow from 58 million in 2020 to 72 million in 2050, while the average per capita electricity demand rises from 1.4 MWh in 2020 to 4.1 MWh by 2050, as indicated in Figure A3.3.

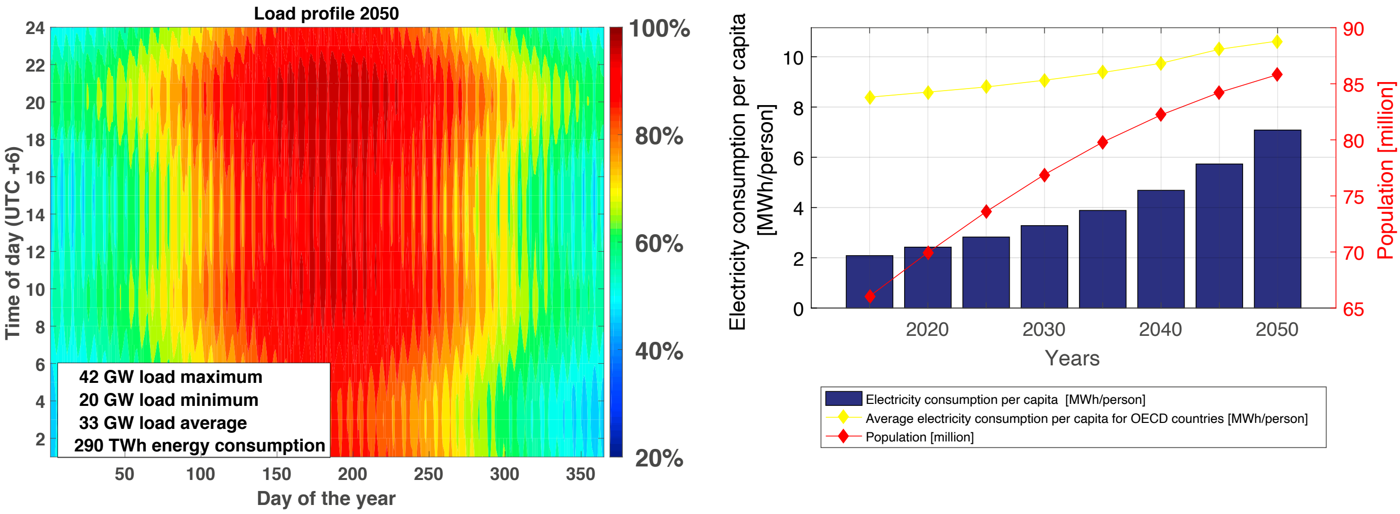

Figure A3.3: Annual distribution of the hourly load profile in 2050 (left) and development of the per capita electricity consumption (right) during the energy transition from 2015 to 2050 in Andhra Pradesh.

The electricity demand is assumed to increase from 81 TWh in 2020 to around 290 TWh by 2050. The load profile in 2050 will be different for the centralised system due to partial load covering by prosumers, as shown in Figure A3.3. However, the seasonal variations in demand in Andhra Pradesh are clearly evident, with peaks in the summer and the pre-monsoon seasons.

Resource

The resource of solar PV and wind, which are the most relevant sources in the energy transition across Andhra Pradesh, are highlighted in Figure A3.4. Solar PV is more evenly distributed throughout the state, with high potential in the western regions, while the wind potential is mainly concentrated in the southern and western parts of the state and indicates moderate offshore wind potential in the region, as highlighted in Figure A3.4.

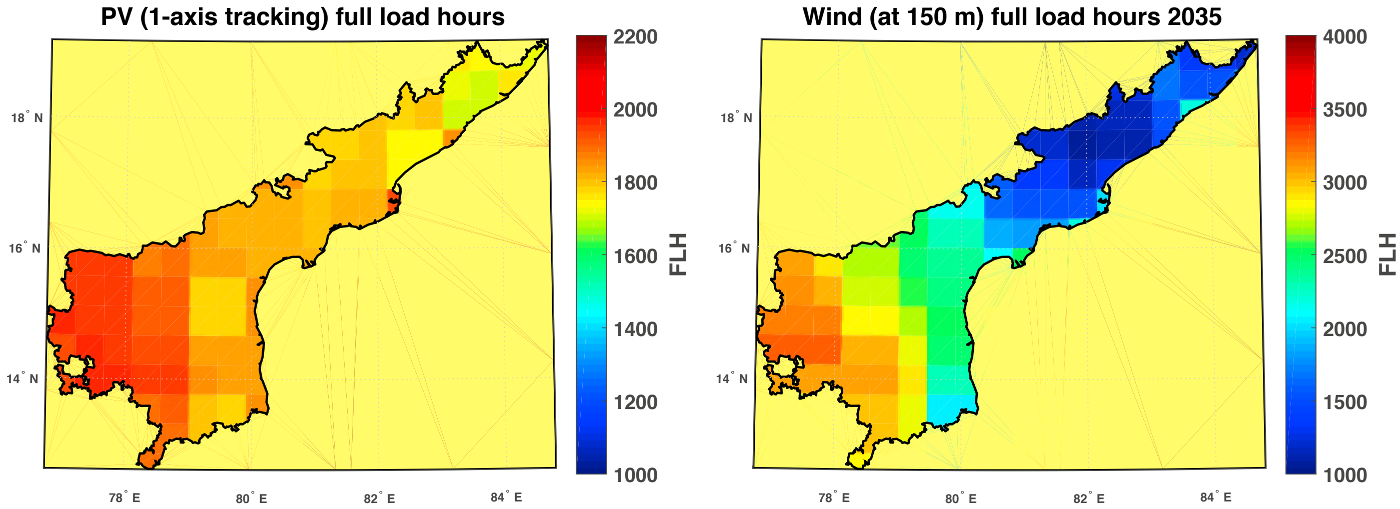

Figure A3.4: Regional distribution of capacity factors/full load hours for solar PV (left) and wind energy (right) across Andhra Pradesh. The wind capacity factor/full load hours shown are for 2035 and beyond.

The capacity factors for the wind energy generation potential are taken from Bloomberg projections for the whole of India, which increase from 29% in 2020 to 36% in 2035. The best sites have maximum capacity factors of 48% (about 4200 FLH) in 2035. Beyond 2035, the same capacity factor/FLH is assumed until 2050.

The annual variations in aggregated hourly generation profiles of solar PV and wind are shown in Figure A3.5. Wind energy generation is predominant in the monsoon months and overcomes the solar resource unavailability and complements perfectly in periods of low solar radiation; solar PV on the other hand is more evenly distributed through the year, as shown in Figure A3.5.

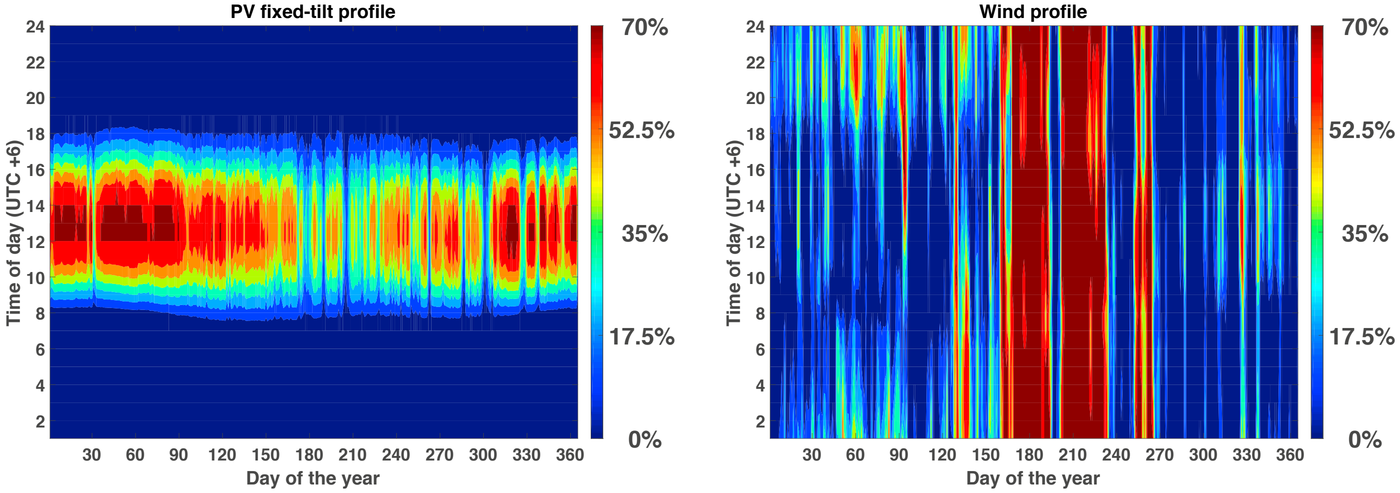

Figure A3.5: Annual distribution of the hourly generation profile for solar PV (left) and wind energy (right) in Andhra Pradesh.

The monthly averaged resource availability throughout the year for solar PV and wind is highlighted in Figure A3.6. The seasonal complementary nature of solar PV and wind energy is clearly evident and ensures the demand, which is rather stable through the year, is satisfied. In the winter months solar and wind are quite low, and this necessitates more seasonal storage demand. Monthly values are normalised to the highest monthly value throughout the year.

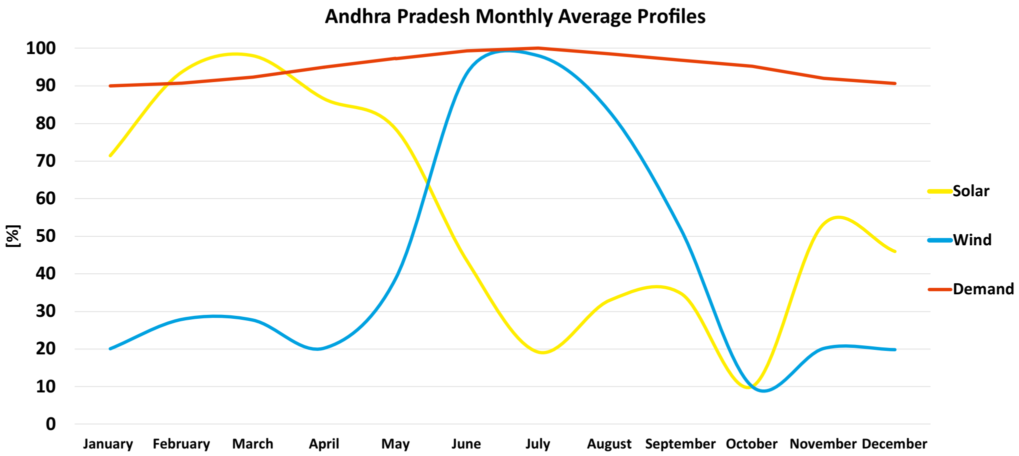

Figure A3.6: Annual distribution of the monthly average electricity generation profiles for solar PV and wind energy, and the demand profile in Andhra Pradesh in 2050.

Electricity

The electricity generation capacity in Andhra Pradesh satisfies demand from the power sector during the transition. The total installed capacity grows massively from about 20 GW in 2020 to around 240 GW by 2050, as shown in Figure A3.7. In the initial period of the transition, a larger share of wind capacities is installed up to 2025, but in the later part of the transition solar PV dominates the shares of installed capacities, reaching almost 175 GW by 2050. On the other hand, the share of fossil fuels declines through the transition, with installed capacities of coal at risk of becoming stranded assets and having very low full load hours during the transition years as the share of renewables increases. Reciprocating gas engines are increasingly installed from 2030 onwards to provide flexibility to the system, which is already 75% renewable based.

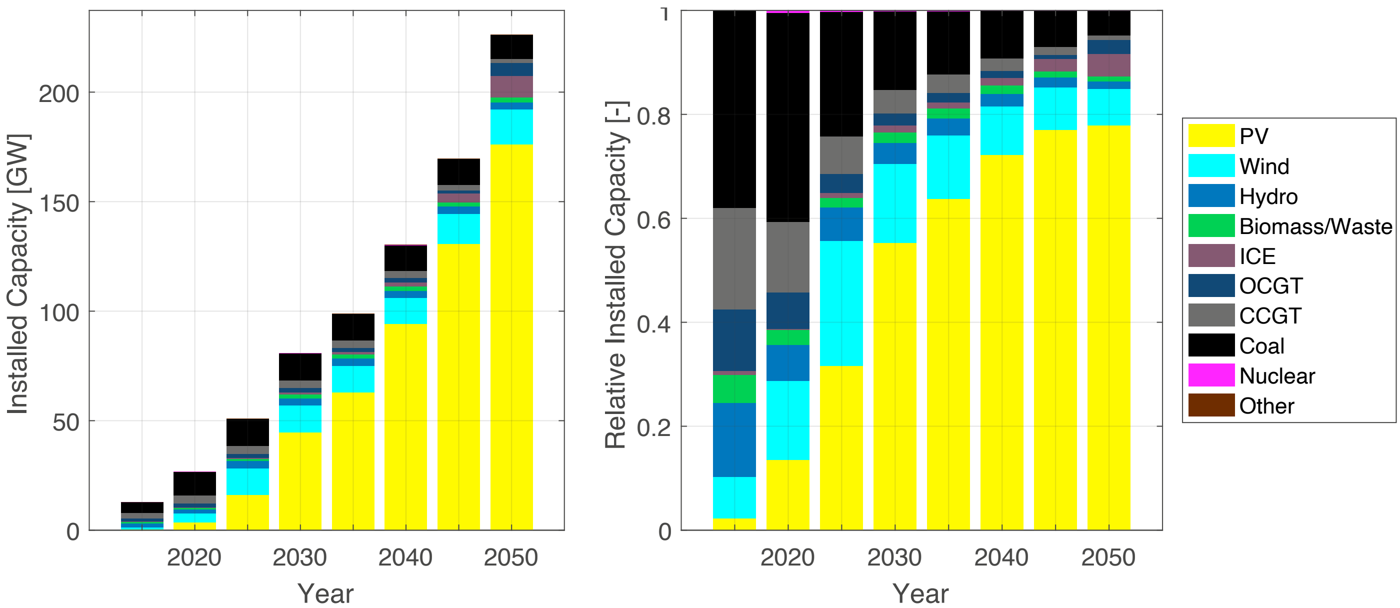

Figure A3.7: Installed capacities by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Andhra Pradesh.

As shown in Figure A3.8, the share of coal in electricity generation increases slightly in 2020 to provide the electricity needed to meet the increasing power demand, as coal is cheaper than gas and oil.

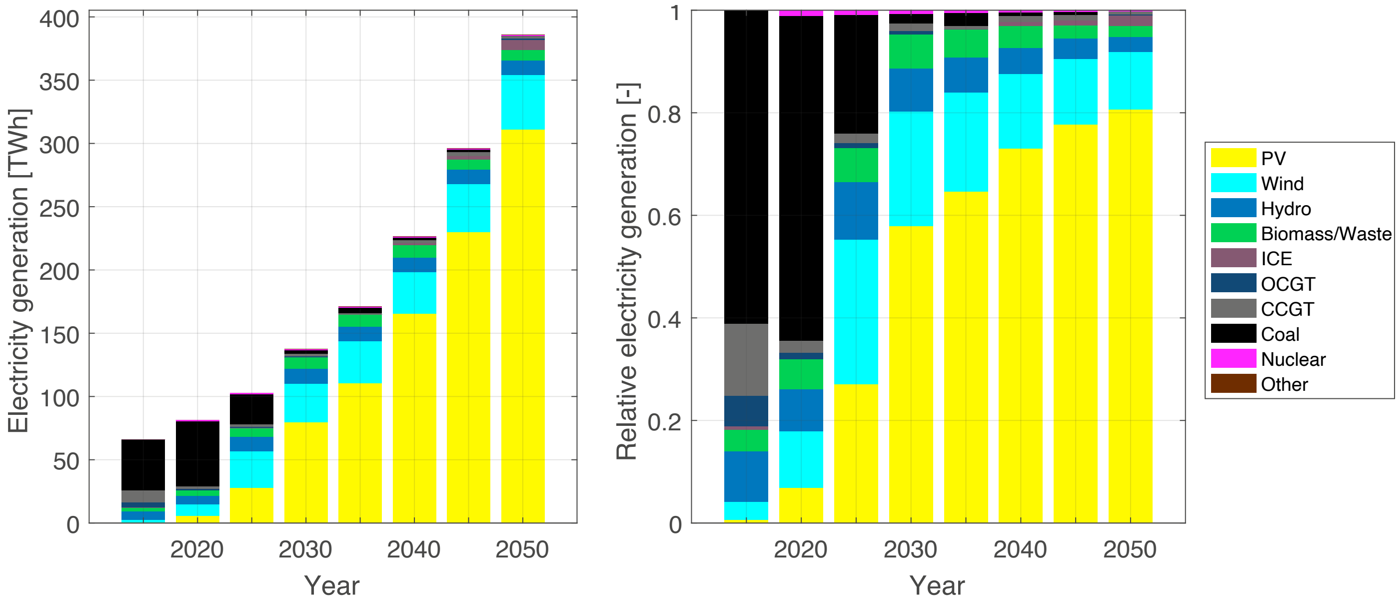

Figure A3.8: Electricity generation by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Andhra Pradesh.

Beyond 2020, the share of coal continues to drop as the share of wind energy (28%) in 2025 and then solar PV (58%) in 2030 increase in the total electricity generation as they become more cost competitive (see Figure A3.8). Reciprocating gas engines have a share of 2.1% in electricity generation in 2050, mainly driven by their higher efficiency and lower cost, while having FLH of nearly 1450, mainly utilised for peak supply and balancing. The fuel mix for reciprocating gas engines develops from 100% fossil gas in 2020 to 86% synthetic natural gas and 14% biomethane in 2050.

Storage

Energy storage technologies play a critical role in enabling a secure energy supply in the power sector of Andhra Pradesh, which by 2050 is fully based on renewable energy. The installed electricity storage capacity increases from just 0.5 TWh in 2030 to around 11 TWh by 2050, as shown in Figure A3.9. Utility-scale and prosumer batteries, with major shares of gas storage, are installed during the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with more than 98% by 2050, as highlighted by Figure A3.9. Storage output covers about 41% of electricity demand in 2050.

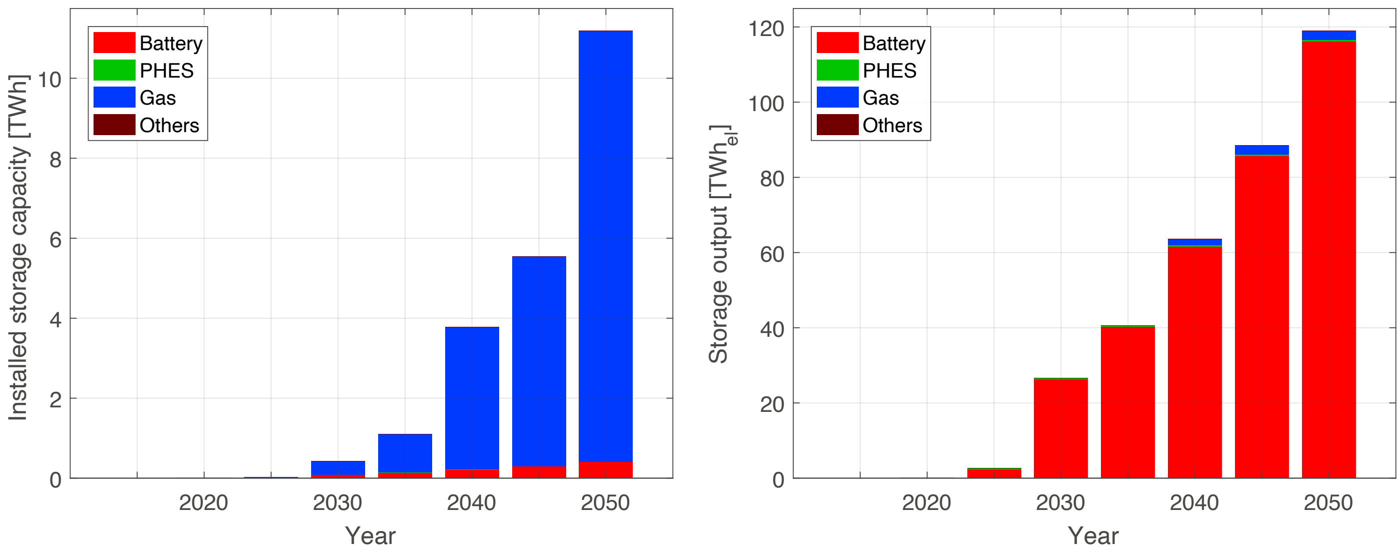

Figure A3.9: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Andhra Pradesh.

Gas storage, which is synthetic natural gas produced through the power-to-gas process, has large capacities and fewer operating hours as it contributes vital seasonal storage during the transition. Battery storage mainly plays a role in providing diurnal storage, as indicated in Figure A3.10.

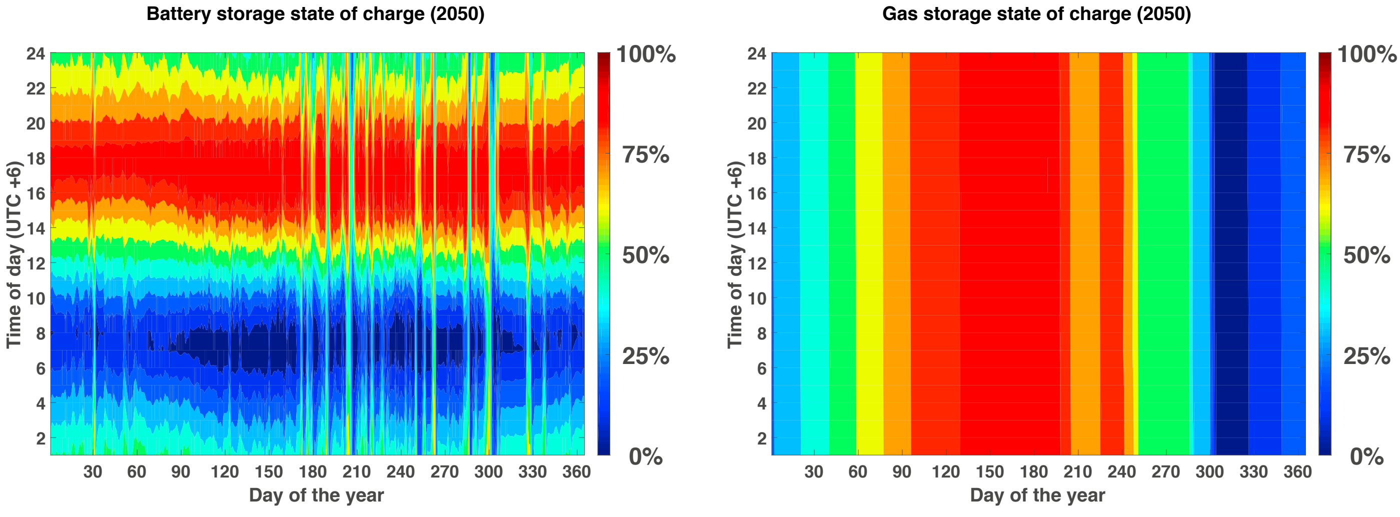

Figure A3.10: State of charge for battery storage (left) and gas storage (right) in 2050 for Andhra Pradesh.

Gas storage mainly plays a role in providing seasonal storage, which is especially needed in the monsoon and winter seasons when the solar resource is at its lowest. The gas storage discharges slowly over the monsoon and winter periods and is completely discharged by the end of winter, as can be observed in Figure A3.10. Some hydropower reservoirs provide complementarity with solar and wind but are used mainly for seasonal balancing.

System outlook

The power system in Andhra Pradesh has distinctive operational characteristics, which vary according to the seasonal pattern. This is highlighted by a summer week in 2050 (see Figure A3.11) and monsoon week in 2050 (see Figure A3.12).

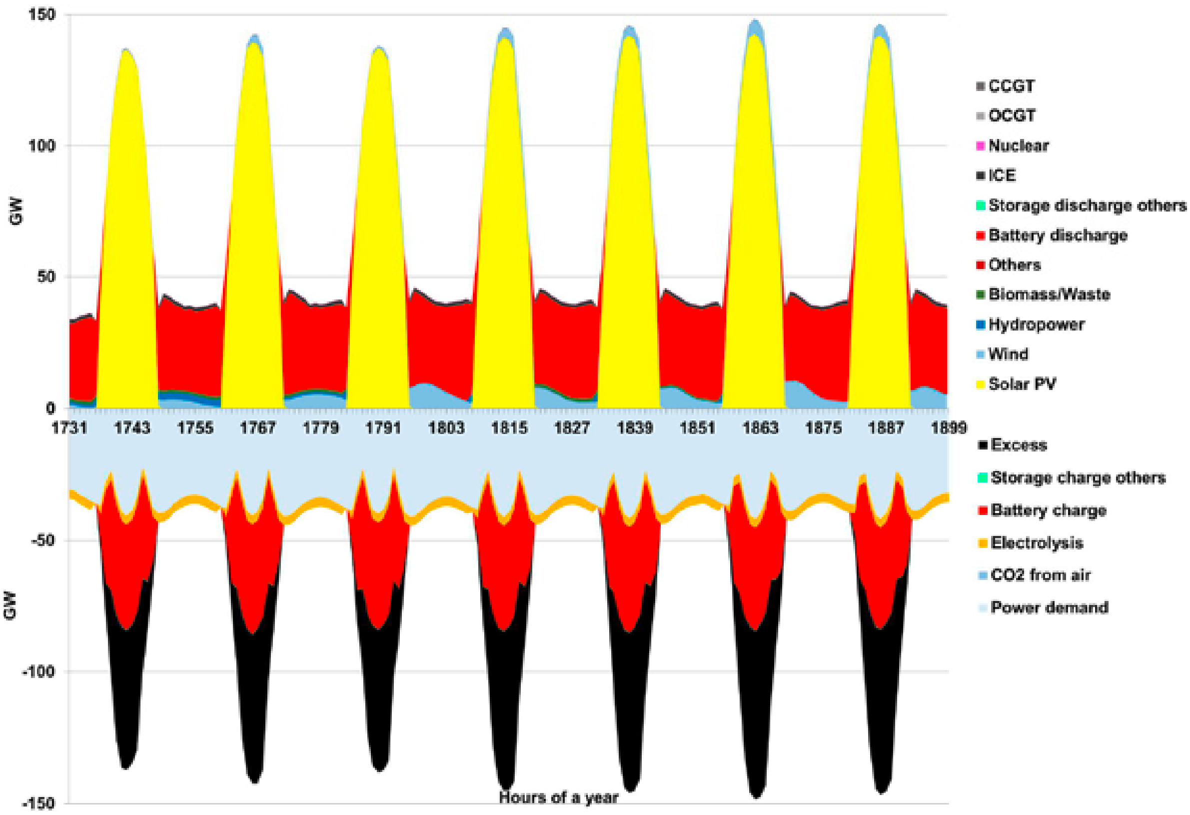

Figure A3.11: Time series of the power system in Andhra Pradesh during a best solar week in 2050.

During the summer period, solar PV and low shares of complementary wind energy are the main electricity generation sources. Batteries are used daily, charging during the day and discharging during the evening and night to meet peak consumption, as highlighted in Figure A3.11.

During the monsoon period, solar PV generation decreases along with wind generation and a combination of technologies becomes the main source of electricity generation. Some shares of dispatchable bioenergy and hydropower compensate for the lack of solar PV and wind generation. Reciprocating gas engines are utilised in periods of low generation, especially in the beginning of the week when wind generation is low and when solar generation is also low in the middle and end of the week, as shown in Figure A3.12.

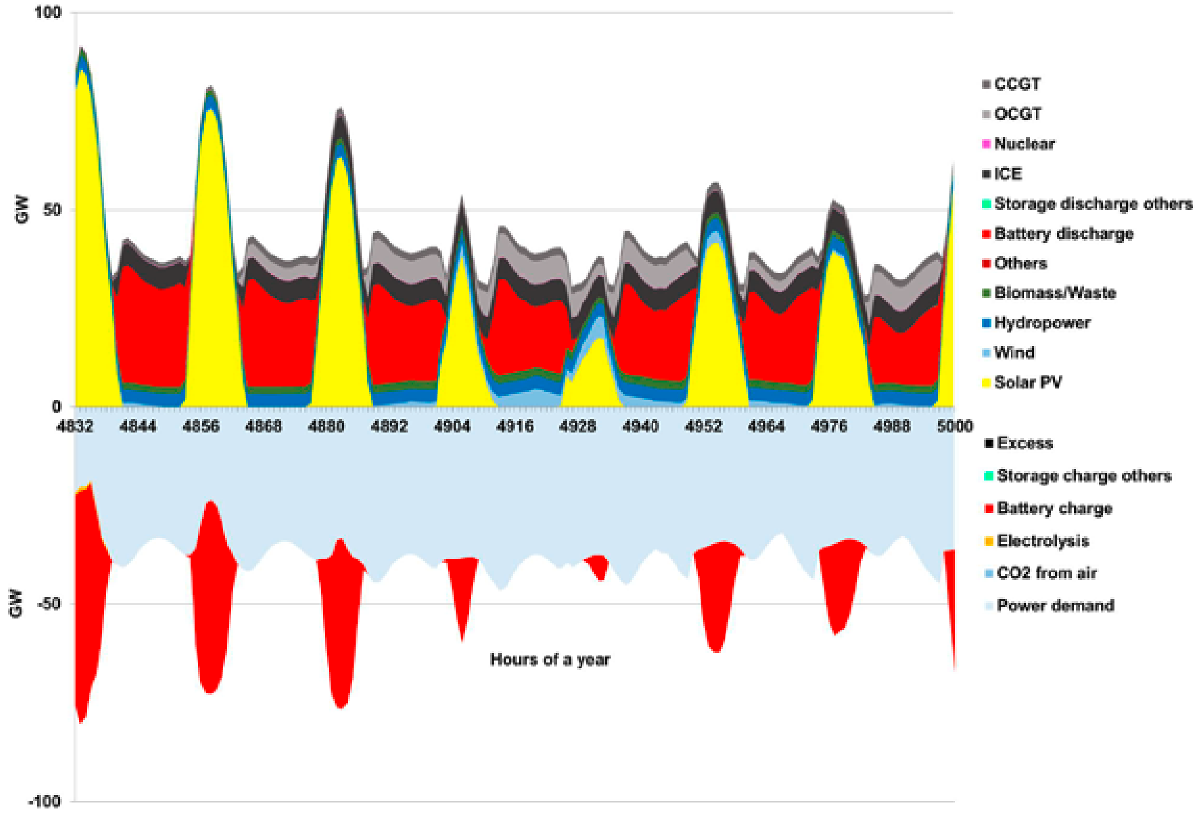

Figure A3.12: Time series of the power system in Andhra Pradesh during a worst solar week in 2050.

Costs and investments

As indicated in Figure A3.13, capex increases during the transition, with wind initially and later solar and batteries being dominant.

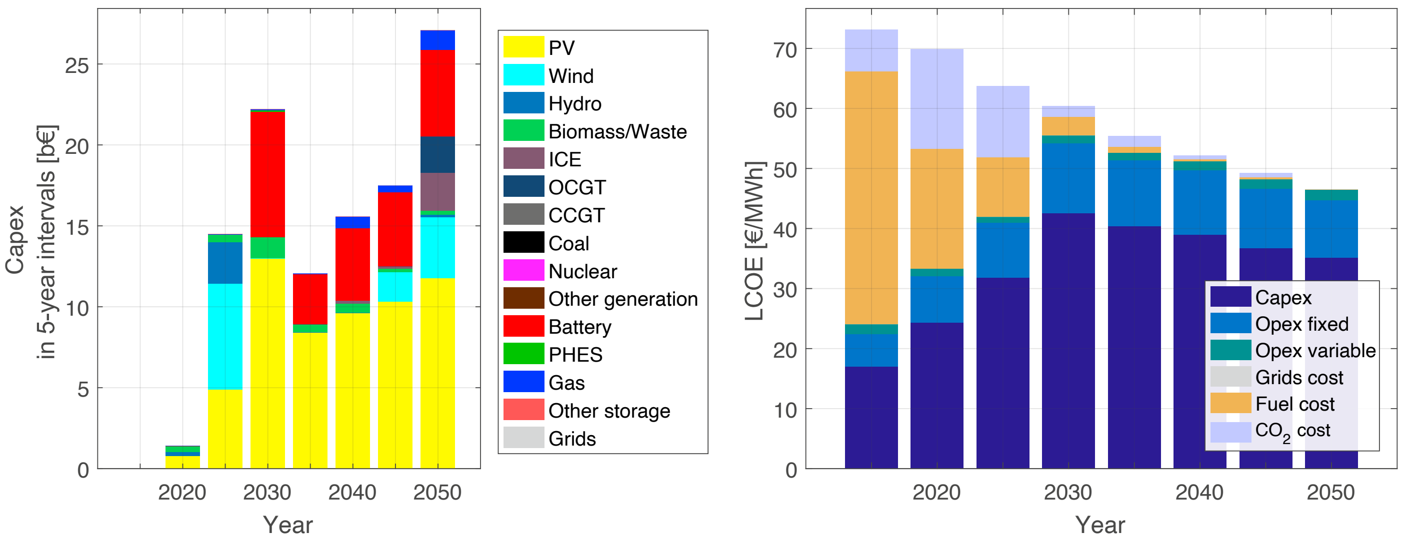

Figure A3.13: Capital expenditures for five-year intervals (left) and levelised cost of electricity (right) during the energy transition from 2015 to 2050 in Andhra Pradesh.

The levelised cost of electricity declines from around 70 €/MWh in 2020 to around 48 €/MWh by 2050 (see Figure A3.13) and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which could mean increased self-reliance in terms of energy for Andhra Pradesh by 2050. Capital costs are distributed across a range of technologies with major investments in solar PV, wind energy, batteries and gas storage up to 2050, as shown in Figure A3.13.

The steady increase in capex-related energy system costs indicates that fuel imports from other states across the country and the respective negative impacts on trade balances will fade during the transition.

GHG emissions

The results of the power system transition in Andhra Pradesh indicate that GHG emissions can be reduced from 48 $MtCO_{2eq}$ in 2020 to zero by 2050 across the power sector, as shown in Figure A3.14. The CO_{2eq} intensity of electricity generation rapidly declines during the transition, enabled by the phase-out of fossil-based power plants, which indicates a deep defossilisation by 2030 (see Figure A3.14).

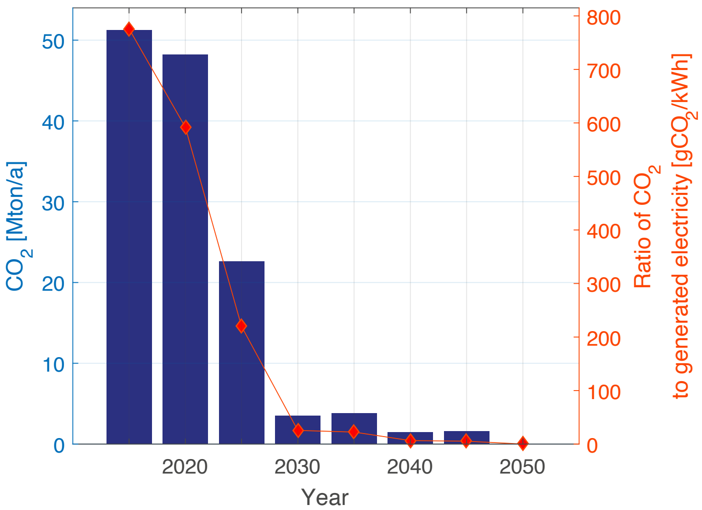

Figure A3.14: GHG emissions from the power sector during the energy transition from 2020 to 2050 in Andhra Pradesh.

The presented 100% RE scenario for the power sector of Andhra Pradesh is compatible with the goals of the Paris Agreement and will enable India to meet its commitments and take a leadership role. A deep defossilisation of the power sector is possible by 2030, and a steady decline in emissions is possible up to 2050.

A4. KARNATAKA

The state of Karnataka, which is part of the southern grid in the Indian power system (see Figure A4.1), has undergone rapid urbanisation led by one of the first IT hubs in the country and has a growing energy demand. It is modelled to be self-sufficient in terms of meeting its future power demand as part of this research. Furthermore, no imports or exports with other neighbouring states are considered. It is also assumed that the existing network of AC lines, mainly for distribution of electricity within Karnataka, will provide electricity to all consumers in the future.

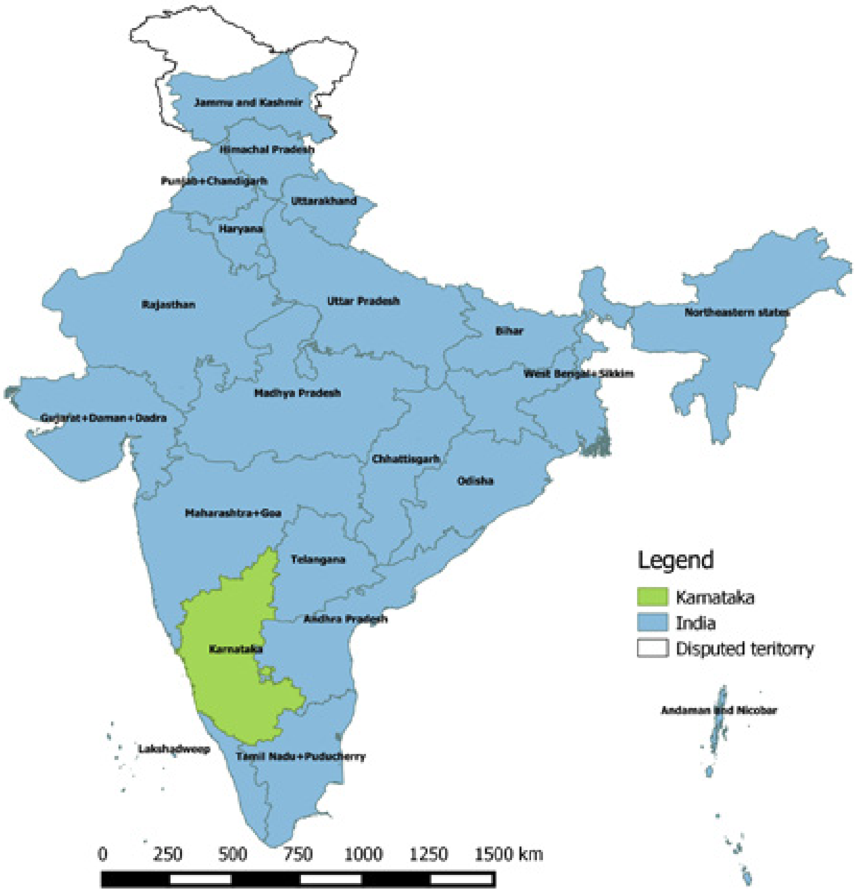

Figure A4.1: Karnataka within the regional setup of India.

Historically, the power sector in Karnataka has relied on coal-based generation and hydropower to satisfy the growing electricity demand across the state. In recent times, significant growth in the share of installed capacity of renewables has been observed, and Karnataka is now among the leading states in the country in terms of renewables (see Figure A4.2). As indicated in Figure A4.2, coal still accounts for around 42% of the electricity; however the capacity factors, or alternately the Full Load Hours (FLH), of coal power plants across the country have been decreasing on a year-on-year basis. In addition, several of these plants are in financial distress. Air pollution has increasingly become a national problem causing adverse health impacts and negative economic consequences. The huge water requirements of coal power plants are causing increased levels of water stress and competing with irrigation demand for agriculture. These challenges indicate that the trend of growing the capacity addition of renewables is expected to continue and is required to be accelerated to meet India's ambitious climate targets.

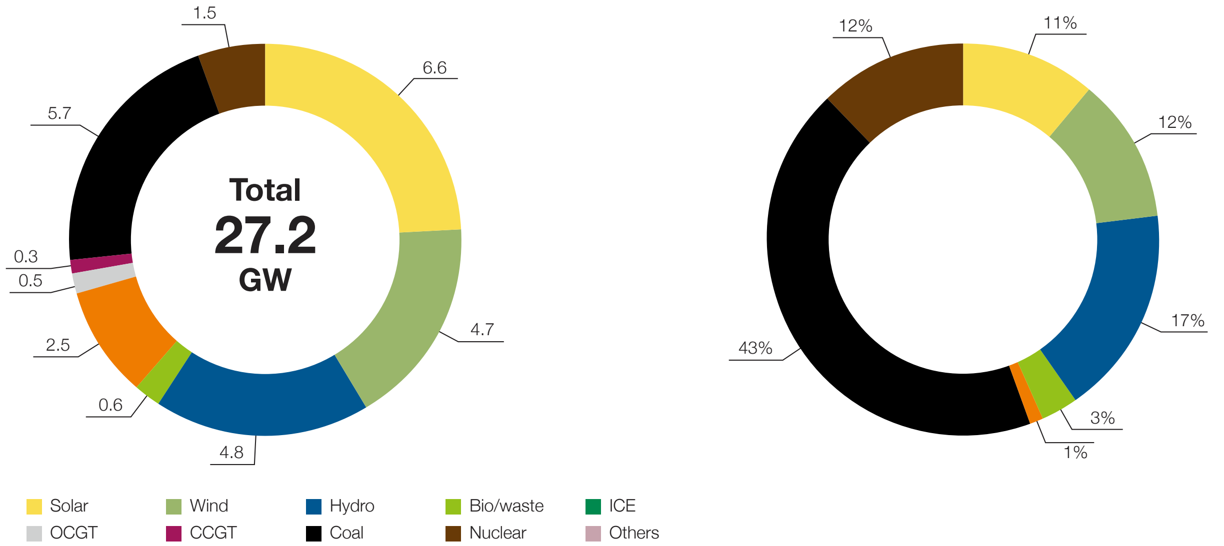

Figure A4.2: Resource-based electricity generation capacities (left) and generation share (right) of the Karnataka power sector in 2020.

Demand

The cumulative average annual growth rate of electricity consumption is about 4.9% during the energy transition period from 2015 to 2050 compared to the 7% average growth rate of electricity demand across the country in recent times. The population of Karnataka is expected to grow from 70 million in 2020 to 86 million by 2050, while the average per capita electricity demand rises from 1.3 MWh in 2020 to 3.9 MWh by 2050, as indicated in Figure A4.3.

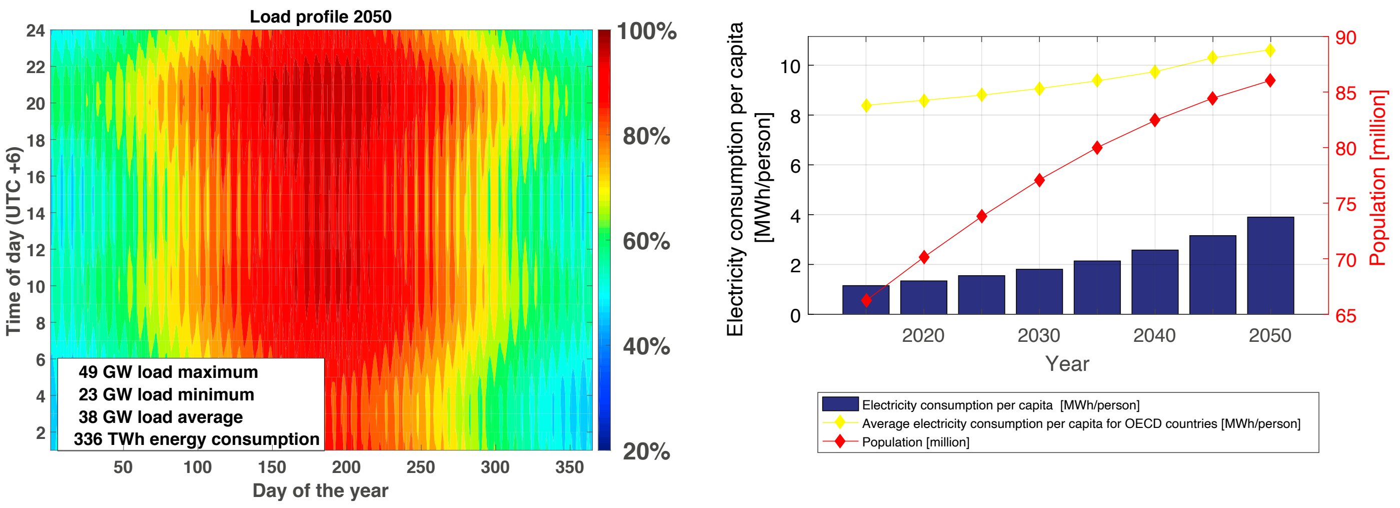

Figure A4.3: Annual distribution of the hourly load profile in 2050 (left) and development of the per capita electricity consumption (right) during the energy transition from 2015 to 2050 in Karnataka.

The electricity demand is assumed to increase from 94 TWh in 2015 to around 336 TWh by 2050. The load profile in 2050 will be different for the centralised system due to partial load covering by prosumers, as shown in Figure A4.3. However, the seasonal variations in demand in Karnataka are clearly evident, with peaks in the summer and pre-monsoon seasons.

Resource

The resource of solar PV and wind, which are the most relevant sources in the energy transition across Karnataka, are highlighted in Figure A4.4. Solar PV is more evenly distributed throughout the state, with high potential in the northern regions, while the wind potential is mainly concentrated in the central regions of the state along the wind corridors; some offshore wind potential in the western coast is evident, as highlighted in Figure A4.4.

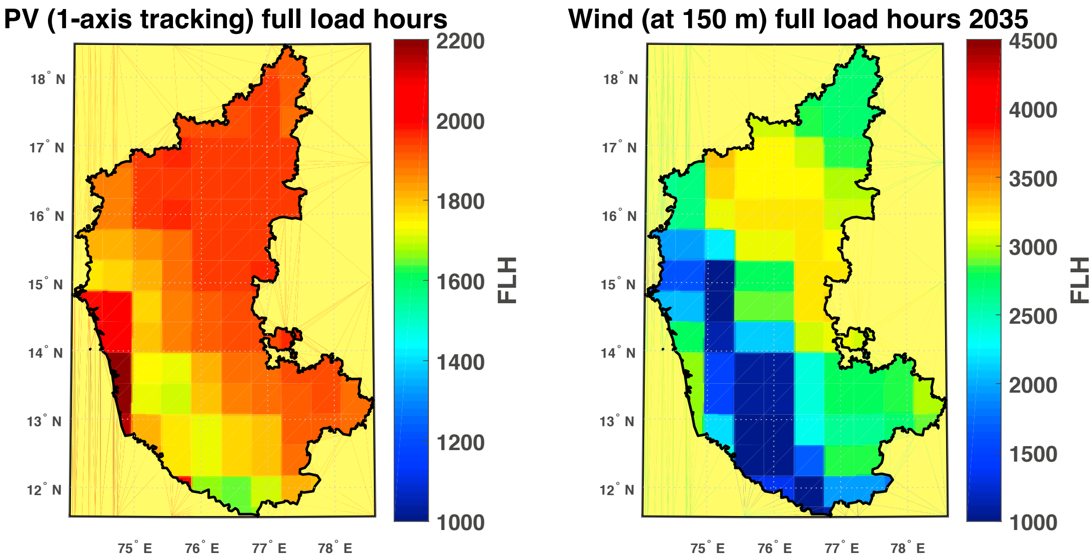

Figure A4.4: Regional distribution of capacity factors/full load hours for solar PV (left) and wind energy (right) across Karnataka. The wind capacity factor/full load hours shown are for 2035 and beyond.

The capacity factors for the wind energy generation potential are taken from Bloomberg projections for the whole of India, which increase from 29% in 2020 to 36% in 2035. The best sites have maximum capacity factors of 48% (about 4200 FLH) in 2035. Beyond 2035, the same capacity factor/FLH is assumed until 2050.

The annual variations in aggregated hourly generation profiles of solar PV and wind are shown in Figure A4.5. Wind energy generation is predominant in the monsoon months and overcomes the solar resource unavailability and complements perfectly in periods of low solar radiation; solar PV on the other hand is more evenly distributed through the year, as shown in Figure A4.5.

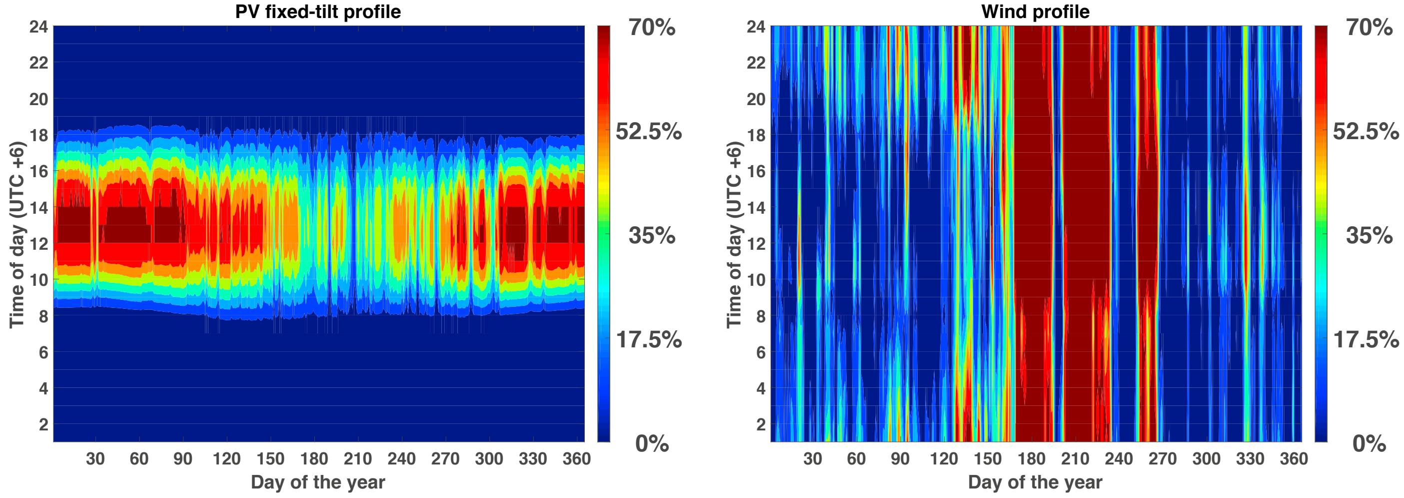

Figure A4.5: Annual distribution of the hourly generation profile for solar PV (left) and wind energy (right) in Karnataka.

The monthly averaged resource availability throughout the year for solar PV and wind is highlighted in Figure A4.6. The seasonal complementary nature of solar PV and wind energy is clearly evident and ensures that demand, which is rather stable through the year, is satisfied. Monthly values are normalised to the highest monthly value throughout the year.

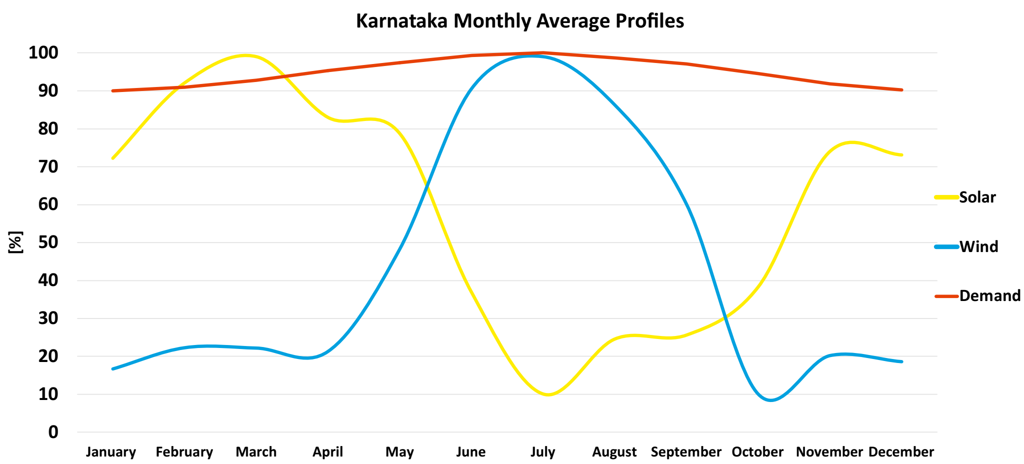

Figure A4.6: Annual distribution of the monthly average electricity generation profiles for solar PV and wind energy, and the demand profile in Karnataka in 2050.

Electricity

The electricity generation capacity in Karnataka satisfies demand from the power sector. The total installed capacity grows massively from about 22 GW in 2020 to around 240 GW by 2050 as shown in Figure A4.7. In the initial period of the transition, a larger share of wind and hydropower capacities are installed up to 2025, but in the later part of the transition solar PV dominates the shares of installed capacities, reaching almost 180 GW by 2050. On the other hand, the share of fossil fuels and nuclear energy declines during the transition, with installed capacities of coal at risk of becoming stranded assets and having very low full load hours during the transition years as the share of renewables increases. Reciprocating gas engines are increasingly installed from 2025 onwards to provide flexibility to the system, which is already 70% renewable based.

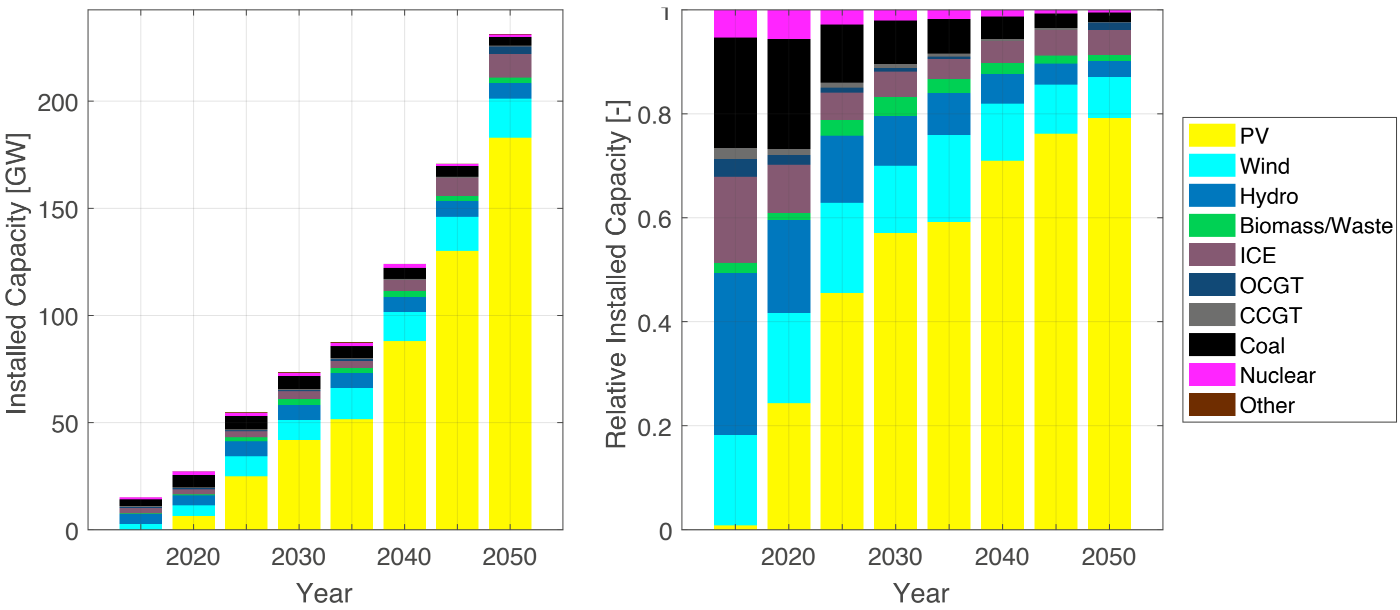

Figure A4.7: Installed capacities by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Karnataka.

As shown in Figure A4.8, the share of coal in electricity generation increases in 2020 in order to provide the electricity needed to meet the increasing power demand, as coal is cheaper than gas and oil. Beyond 2020, the share of coal continues to drop as the share of wind energy (19%) in 2025 and then solar PV (50%) in 2030 increase in the total electricity generation as they become more cost competitive (see Figure A4.8). Reciprocating gas engines have a share of 1.8% in electricity generation in 2050, mainly driven by their higher efficiency and lower cost, while having FLH of over 1250, mainly utilised for peak supply and balancing. The fuel mix for reciprocating gas engines develops from 100% fossil gas in 2020 to 90% synthetic natural gas and 10% biomethane in 2050.

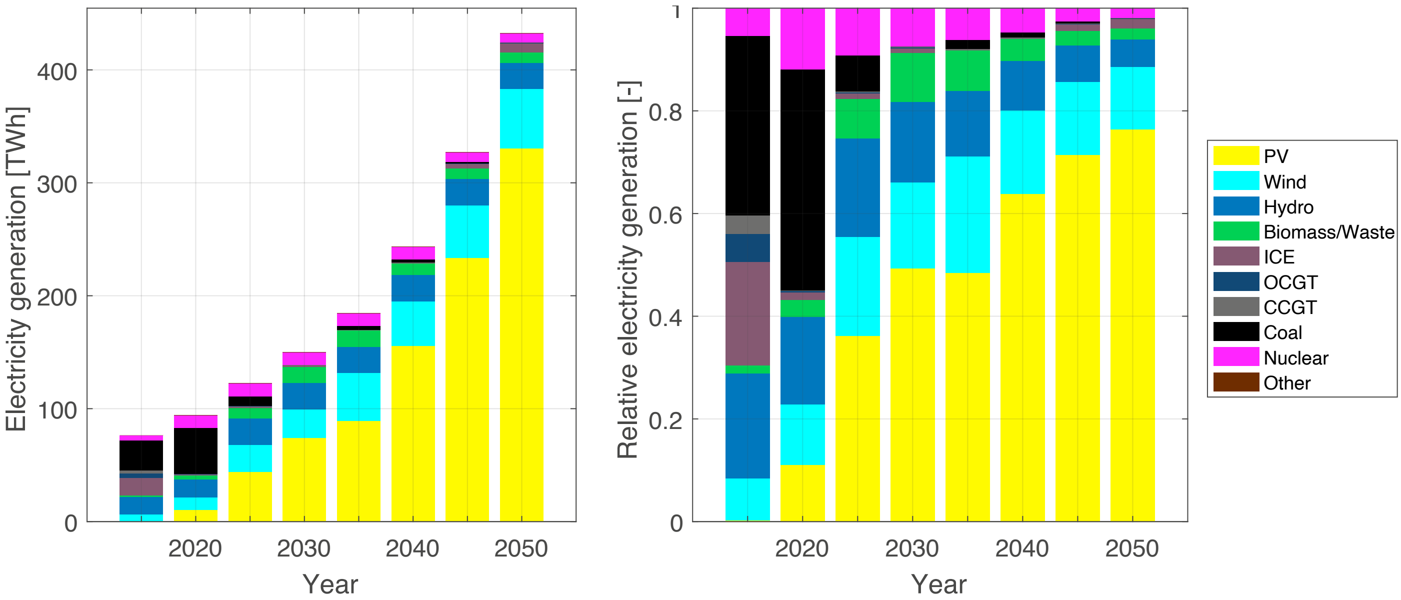

Figure A4.8: Electricity generation by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Karnataka.

Storage

Energy storage technologies play a critical role in enabling a secure energy supply in the power sector of Karnataka, which by 2050 is fully based on renewable energy. The installed electricity storage capacity increases from just 0.2 TWh in 2030 to around 8 TWh by 2050, as shown in Figure A4.9. Utility-scale and prosumer batteries, with major shares of gas storage, are installed during the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with more than 99% by 2050, as highlighted by Figure A4.9. Storage output covers about 37% of the electricity demand in 2050.

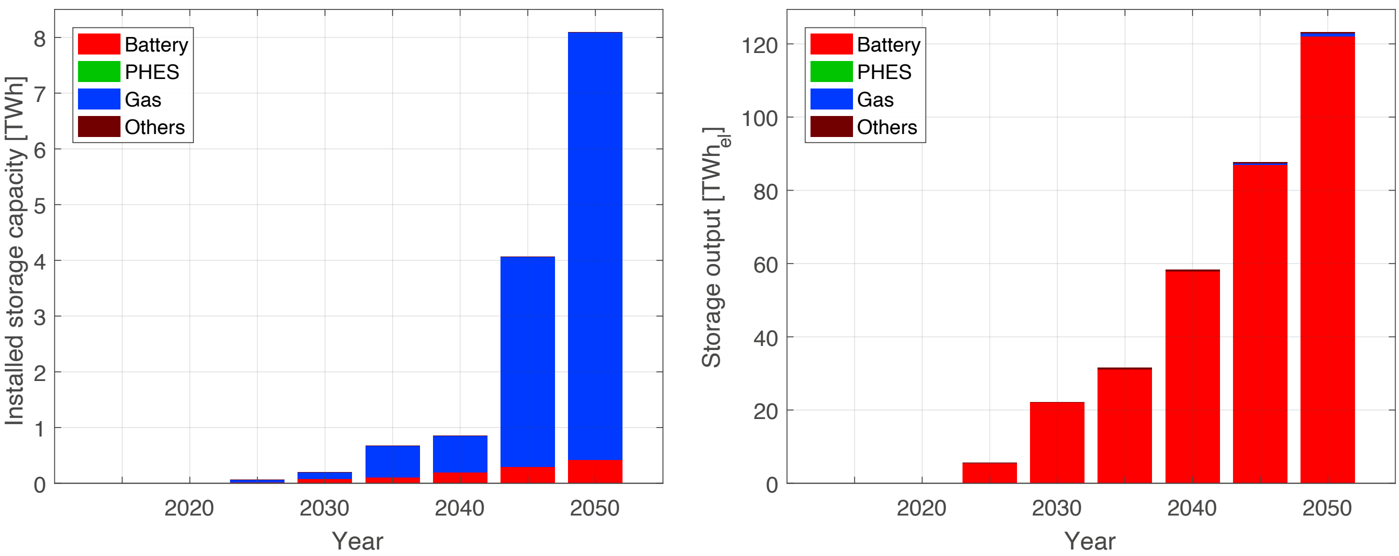

Figure A4.9: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Karnataka.

Gas storage, which is synthetic natural gas produced through the power-to-gas process, has large capacities and fewer operating hours as it contributes vital seasonal storage during the transition. Battery storage mainly plays a role in providing diurnal storage, as indicated in Figure A4.10.

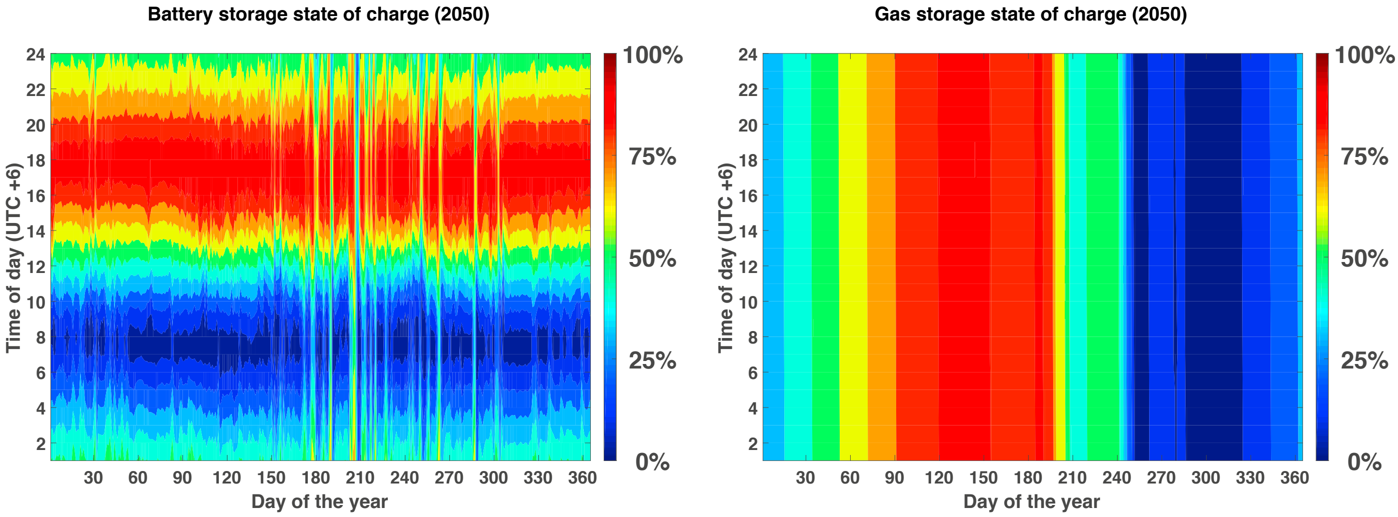

Figure A4.10: State of charge for battery storage (left) and gas storage (right) in 2050 for Karnataka.

Gas storage mainly plays a role in providing seasonal storage, which is especially needed in the monsoon season, when the solar resource is at its lowest. The gas storage discharges slowly over the monsoon period and is completely discharged by the end of winter, as can be observed in Figure A4.10. Some hydropower reservoirs provide complementarity with solar and wind but are used mainly for seasonal balancing.

System outlook

The power system in Karnataka has distinctive operational characteristics, which vary according to the seasonal pattern. This is highlighted by a summer week in 2050 (see Figure A4.11) and a monsoon week in 2050 (see Figure A4.12). During the summer period, solar PV and low shares of complementary wind energy are the main electricity generation sources. Batteries are used daily, charging during the day and discharging during the evening and night to meet peak consumption, as highlighted in Figure A4.11.

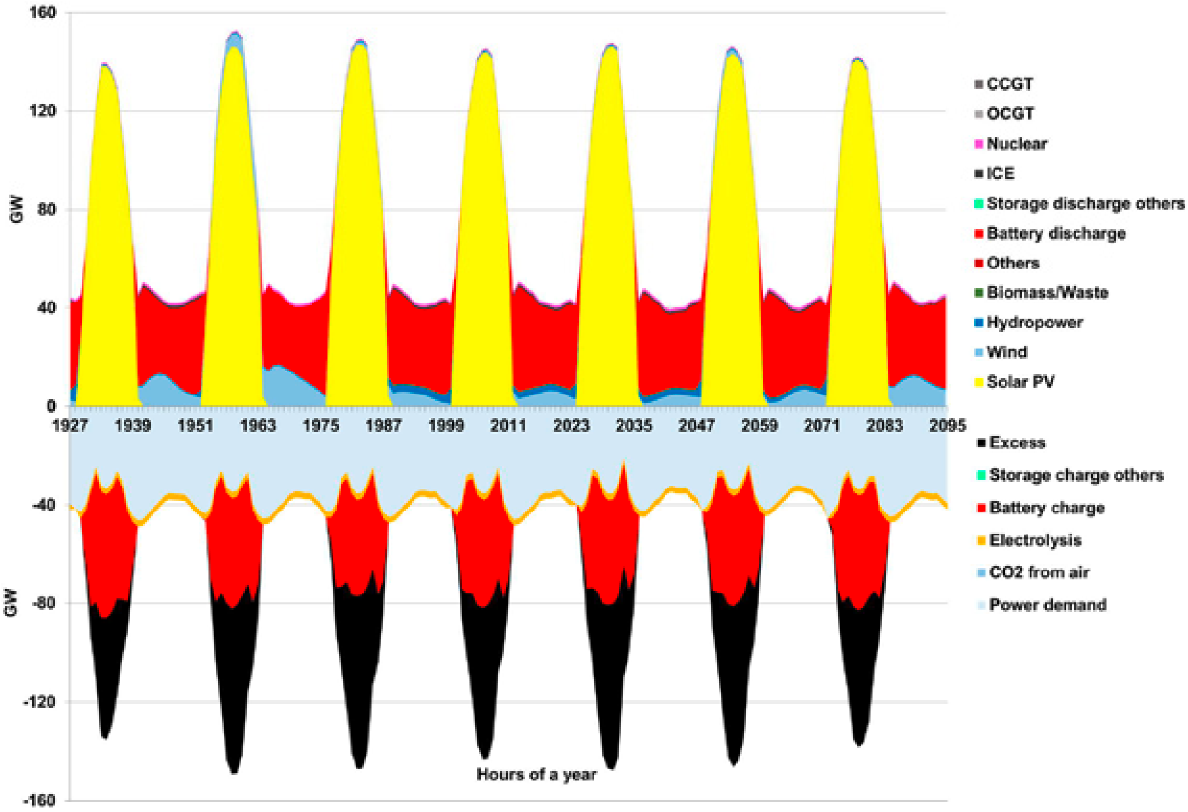

Figure A4.11: Time series of the power system in Karnataka during a best solar week in 2050.

During the monsoon period, solar PV generation decreases while wind and hydropower generation increase and become the main source of electricity generation. A share of dispatchable bioenergy compensates for the lack of solar PV and wind generation. Reciprocating gas engines are utilised in periods of low generation, especially in the beginning of the week when wind generation is low and when solar generation is also low in the middle and end of the week, as shown in Figure A4.12.

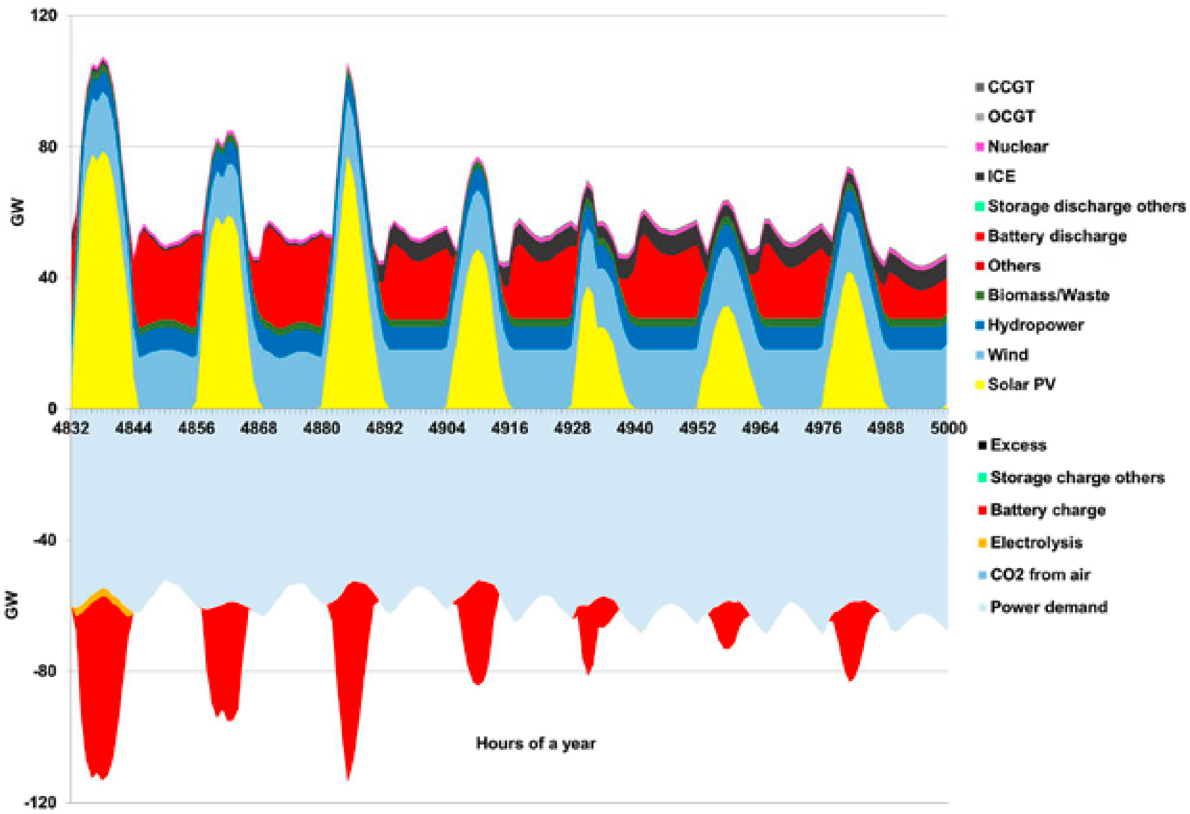

Figure A4.12: Time series of the power system in Karnataka during a worst solar week in 2050.

Costs and investments

As indicated in Figure A4.13, capex increases during the transition, with wind initially and later solar and batteries being dominant.

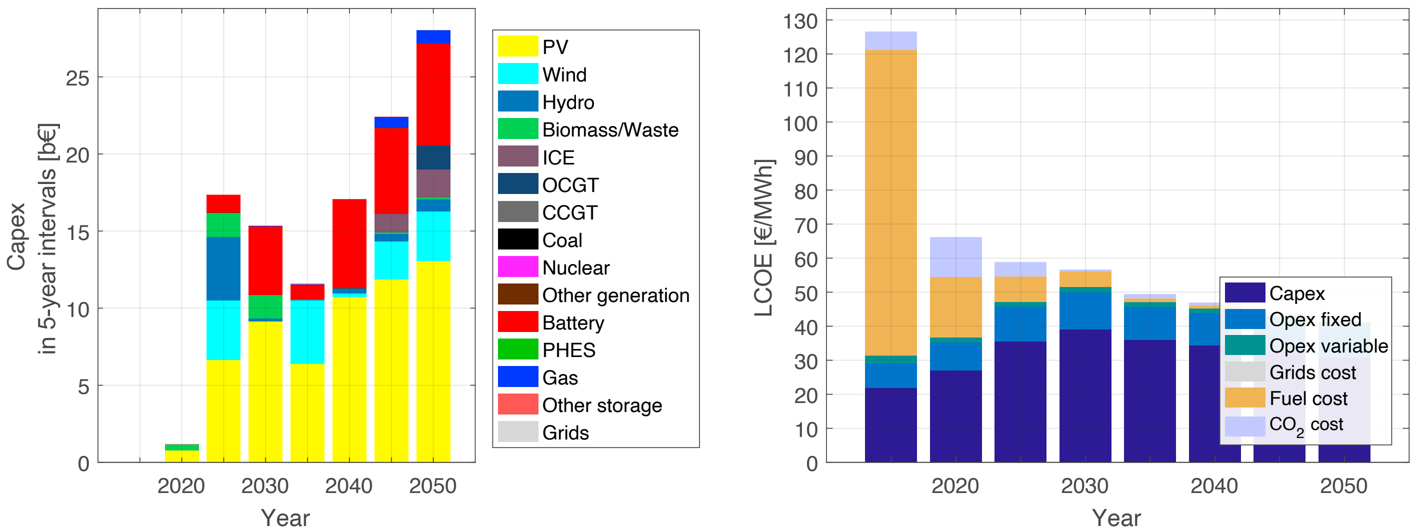

Figure A4.13: Capital expenditures for five-year intervals (left) and levelised cost of electricity (right) during the energy transition from 2015 to 2050 in Karnataka.

The levelised cost of electricity declines from around 65 €/MWh in 2020 to around 41 €/MWh by 2050 (see Figure A4.13) and is increasingly dominated by capital costs as fuel costs continue to decline during the transition period, which could mean increased self-reliance in terms of energy for Karnataka by 2050. Capital costs are divided across a range of technologies, with major investments in solar PV, wind energy, batteries and gas storage up to 2050, as shown in Figure A4.13.

The steady increase in capex-related energy system costs indicates that fuel imports from other states across the country and the respective negative impacts on trade balances will fade during the transition.

GHG emissions

The results of the power system transition in Karnataka indicate that GHG emissions can be reduced from 38 $MtCO_{2eq}$ in 2020 to zero by 2050 across the power sector, as shown in Figure A4.14. The CO_{2eq} intensity of electricity generation rapidly declines during the transition, enabled by the phase-out of fossil-based power plants, which indicates a deep defossilisation by 2030 (see Figure A4.14).

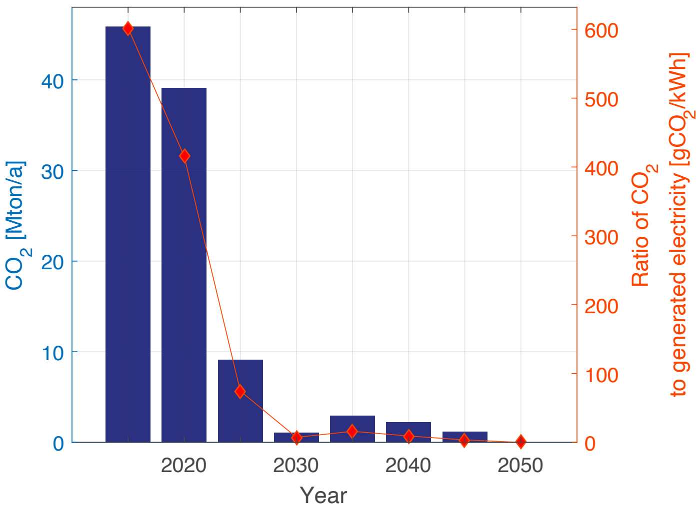

Figure A4.14: GHG emissions from the power sector during the energy transition from 2020 to 2050 in Karnataka.

The presented 100% RE scenario for the power sector of Karnataka is compatible with the goals of the Paris Agreement and will enable India to meet its commitments and take a leadership role. A deep defossilisation of the power sector is possible by 2030, and a steady decline in emissions is possible beyond 2030 up to 2050.

A5. TAMIL NADU

The state of Tamil Nadu, which is part of the southern grid in the Indian power system (see Figure A5.1), is one of the most industrialised states in the country and has a growing energy demand. It is modelled to be self-sufficient in terms of meeting its future power demand as part of this research. Furthermore, no imports or exports with other neighbouring states are considered. It is also assumed that the existing network of AC lines, mainly for distribution of electricity within Tamil Nadu, will provide electricity to all consumers in the future.

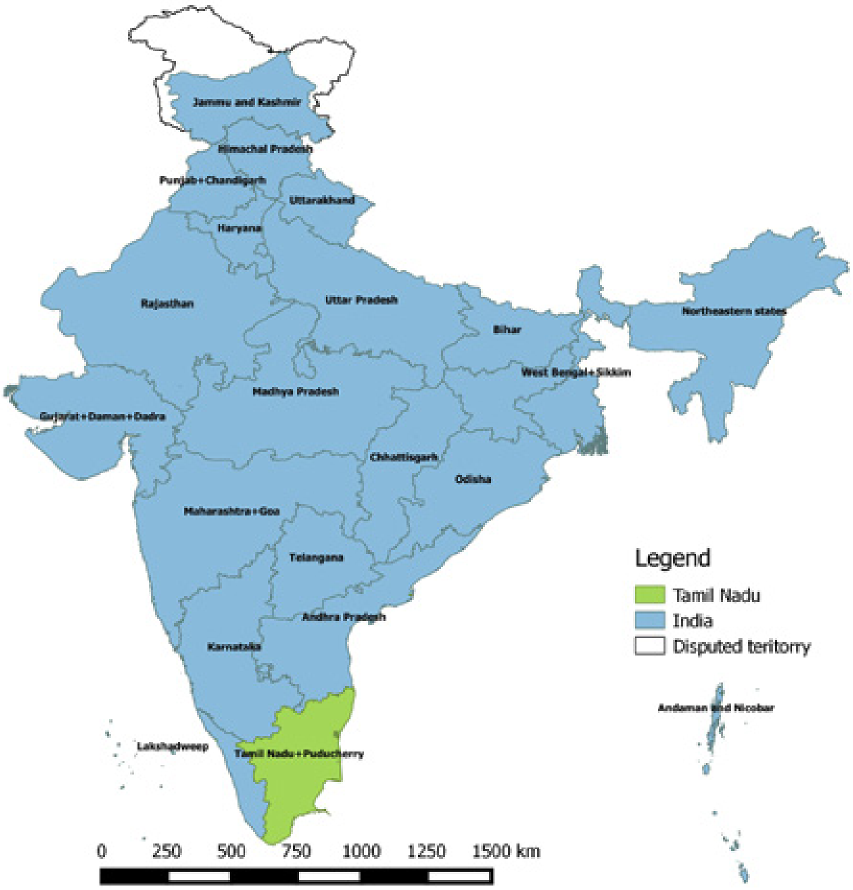

Figure A5.1: Tamil Nadu within the regional setup of India.

Historically, the power sector in Tamil Nadu has relied on coal-based generation and nuclear power to satisfy the growing electricity demand across the state. In recent times, significant growth in the share of installed capacity of renewables has been observed, and Tamil Nadu is now among the leading states in the country in terms of wind power installations (see Figure A5.2). As indicated in Figure A5.2, coal still accounts for around 51% of the electricity; however the capacity factors, or alternately the Full Load Hours (FLH), of coal power plants across the country have been decreasing on a year-on-year basis. In addition, several of these plants are in financial distress. Air pollution has increasingly become a national problem causing adverse health impacts as well as negative economic consequences. The huge water requirements of coal power plants are causing increased levels of water stress and competing with irrigation demand for agriculture. These challenges indicate that the trend of growing the capacity addition of renewables is expected to continue and is required to be accelerated to meet India's ambitious climate targets.

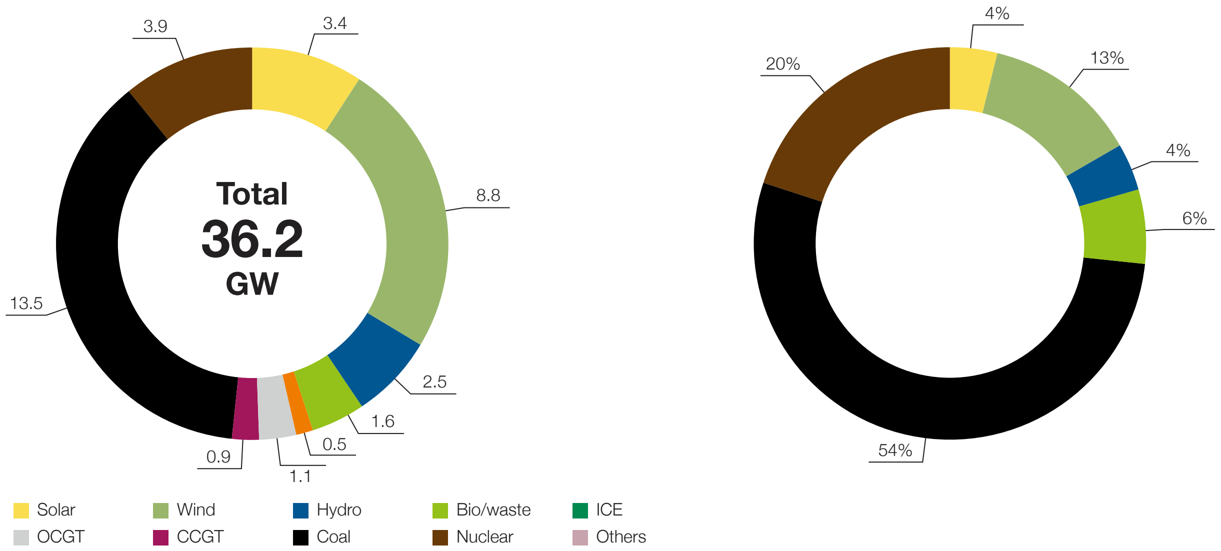

Figure A5.2: Resource-based electricity generation capacities (left) and generation share (right) of the Tamil Nadu power sector in 2020.

Demand

The cumulative average annual growth rate of the electricity consumption is about 4.9% during the energy transition period from 2015 to 2050 compared to a 7% average growth rate of electricity demand across the country in recent times. The population of Tamil Nadu is expected to grow from 84 million in 2020 to 103 million by 2050, while the average per capita electricity demand rises from 1.8 MWh in 2020 to 5.2 MWh by 2050, as indicated in Figure A5.3.

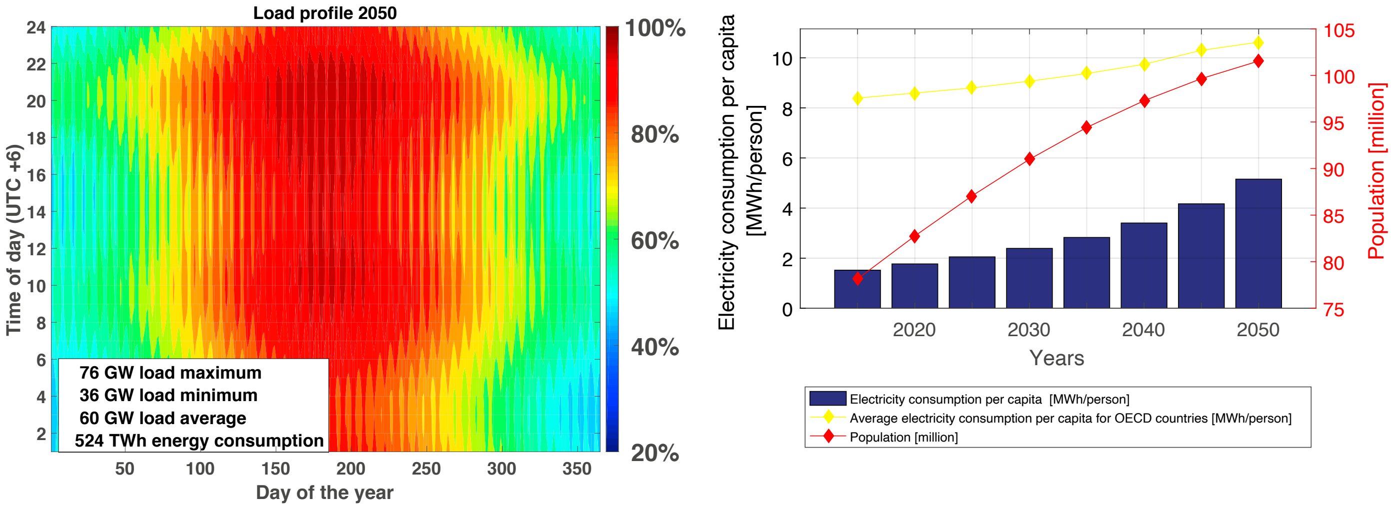

Figure A5.3: Annual distribution of the hourly load profile in 2050 (left) and development of the per capita electricity consumption (right) during the energy transition from 2015 to 2050 in Tamil Nadu.

The electricity demand is assumed to increase from 147 TWh in 2020 to around 524 TWh by 2050. The load profile in 2050 will be different for the centralised system due to partial load covering by prosumers, as shown in Figure A5.3. However, the seasonal variations in demand in Tamil Nadu are quite evident, with peaks in the summer and the pre monsoon seasons.

Resource

The resource of solar PV and wind, which are the most relevant sources in the energy transition across Tamil Nadu, are highlighted in Figure A5.4. Solar PV is more evenly distributed throughout the state, with high potential in the southern regions, while the wind potential is mainly concentrated in the southern and some northern regions of the state and indicates high offshore wind potential in the south east region, as highlighted in Figure A5.4.

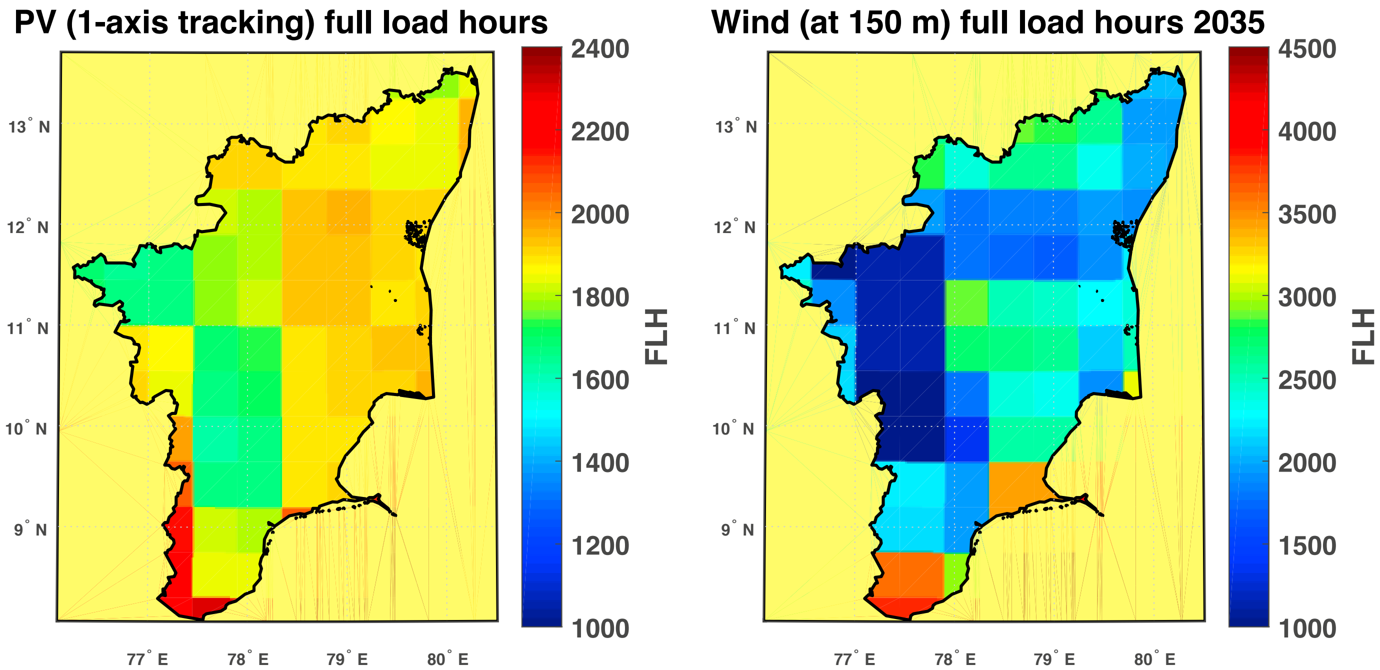

Figure A5.4: Regional distribution of capacity factors/full load hours for solar PV (left) and wind energy (right) across Tamil Nadu. The wind capacity factor/full load hours shown are for 2035 and beyond.

The capacity factors for the wind energy generation potential are taken from Bloomberg projections for the whole of India, which increase from 29% in 2020 to 36% in 2035. The best sites have maximum capacity factors of 48% (about 4200 FLH) in 2035. Beyond 2035, the same capacity factor/FLH is assumed until 2050.

The annual variations in aggregated hourly generation profiles of solar PV and wind are shown in Figure A5.5. Wind energy generation is predominant in the monsoon months and overcomes the solar resource unavailability and complements perfectly in periods of low solar radiation; solar PV on the other hand is more evenly distributed through the year, as shown in Figure A5.5.

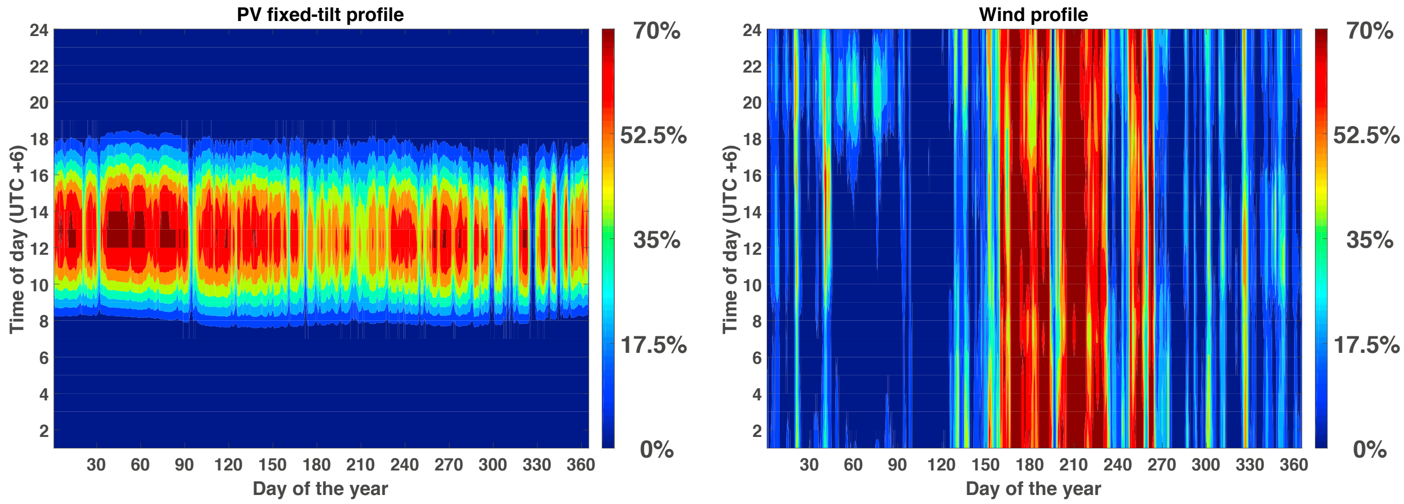

Figure A5.5: Annual distribution of the hourly generation profile for solar PV (left) and wind energy (right) in Tamil Nadu.

The monthly averaged resource availability throughout the year for solar PV and wind is highlighted in Figure A5.6. The seasonal complementary nature of solar PV and wind energy is clearly evident and ensures the demand, which is rather stable through the year, is satisfied. In the winter months, both solar and wind have low generation profiles and necessitate seasonal storage. Monthly values are normalised to the highest monthly value throughout the year.

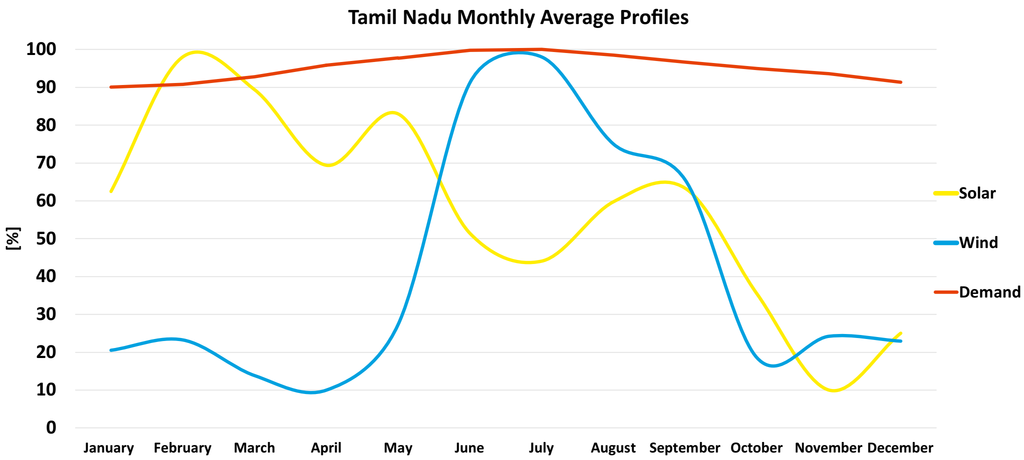

Figure A5.6: Annual distribution of the monthly average electricity generation profiles for solar PV and wind energy, and the demand profile in Tamil Nadu in 2050.

Electricity

The electricity generation capacity in Tamil Nadu satisfies demand from the power sector through the transition. The total installed capacity grows massively from about 30 GW in 2020 to around 370 GW by 2050 as shown in Figure A5.7. In the initial period of the transition, a larger share of wind capacities is installed up to 2025, but in the later part of the transition solar PV dominates the shares of installed capacities, reaching almost 300 GW by 2050. On the other hand, the share of fossil fuels and nuclear declines during the transition, with installed capacities of coal at risk of becoming stranded assets and having very low full load hours during the transition years as the share of renewables increases. Reciprocating gas engines are increasingly installed from 2030 onwards to provide flexibility to the system, which is already 75% renewable based.

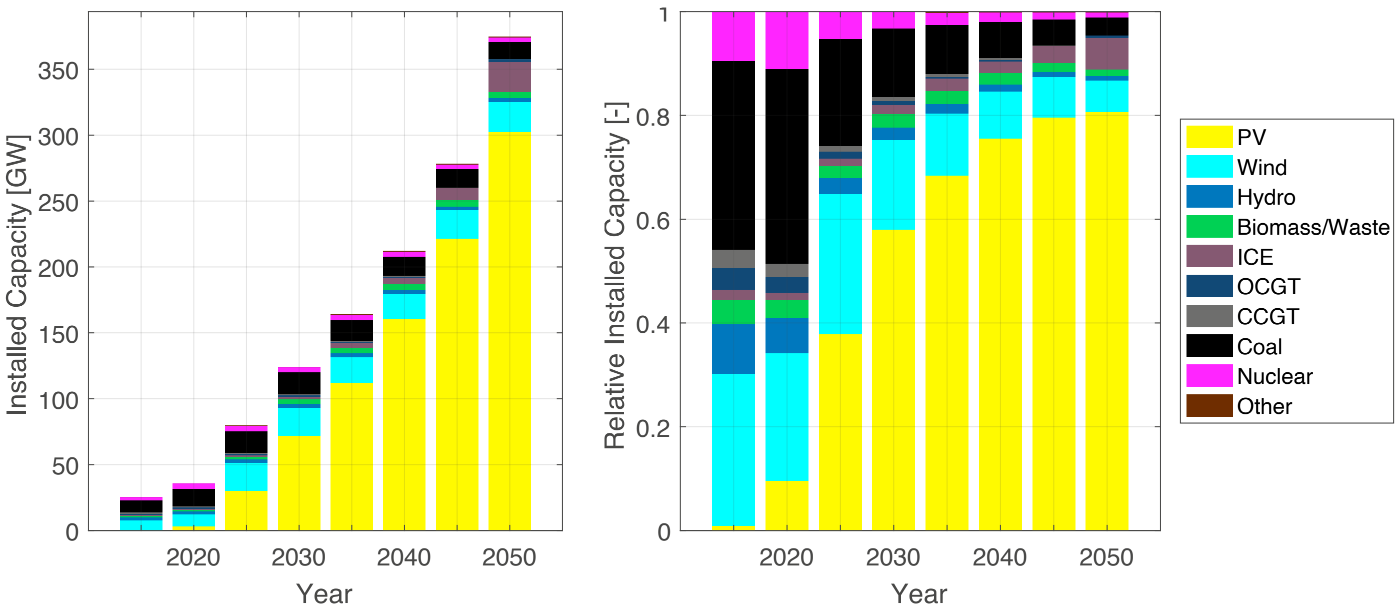

Figure A5.7: Installed capacities by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Tamil Nadu.

As shown in Figure A5.8, the share of coal in electricity generation increases in 2020 to provide electricity needed to meet the increasing power demand, as coal is cheaper than gas and oil. Beyond 2020, the share of coal continues to drop as the share of wind energy (26%) in 2025 and then solar PV (53%) in 2030 increase in the total electricity generation as they become more cost competitive (see Figure A5.8). Reciprocating gas engines have a share of 2.3% in electricity generation in 2050, mainly driven by their higher efficiency and lower cost, while having FLH of about 1030, mainly utilised for peak supply and balancing. The fuel mix for reciprocating gas engines develops from 100% fossil gas in 2020 to 92% synthetic natural gas and 8% biomethane in 2050.

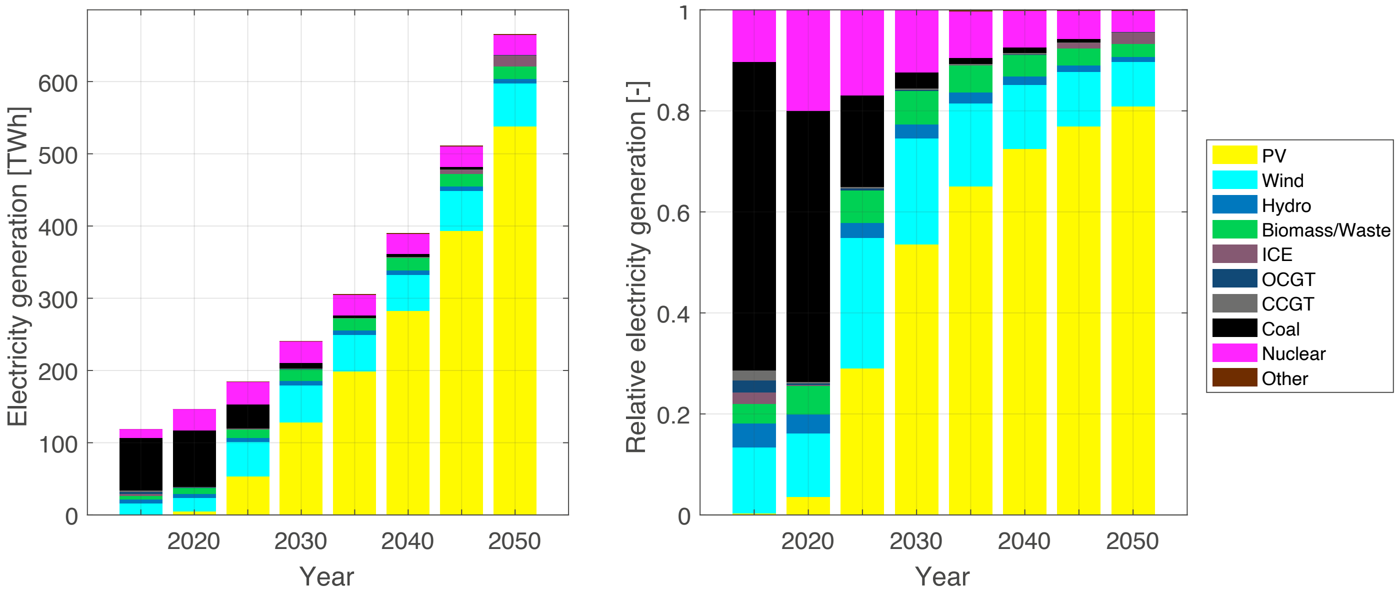

Figure A5.8: Electricity generation by technology (left) and corresponding shares (right) during the energy transition from 2015 to 2050 in Tamil Nadu.

Storage

Energy storage technologies play a critical role in enabling a secure energy supply in the power sector of Tamil Nadu, which by 2050 is fully based on renewable energy. The installed electricity storage capacity increases from just 0.3 TWh in 2030 to around 12 TWh by 2050, as shown in Figure A5.9. Utility-scale and prosumer batteries, with major shares of gas storage, are installed during the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with more than 99% by 2050, as highlighted by Figure A5.9. Storage output covers 41% of total electricity demand in 2050.

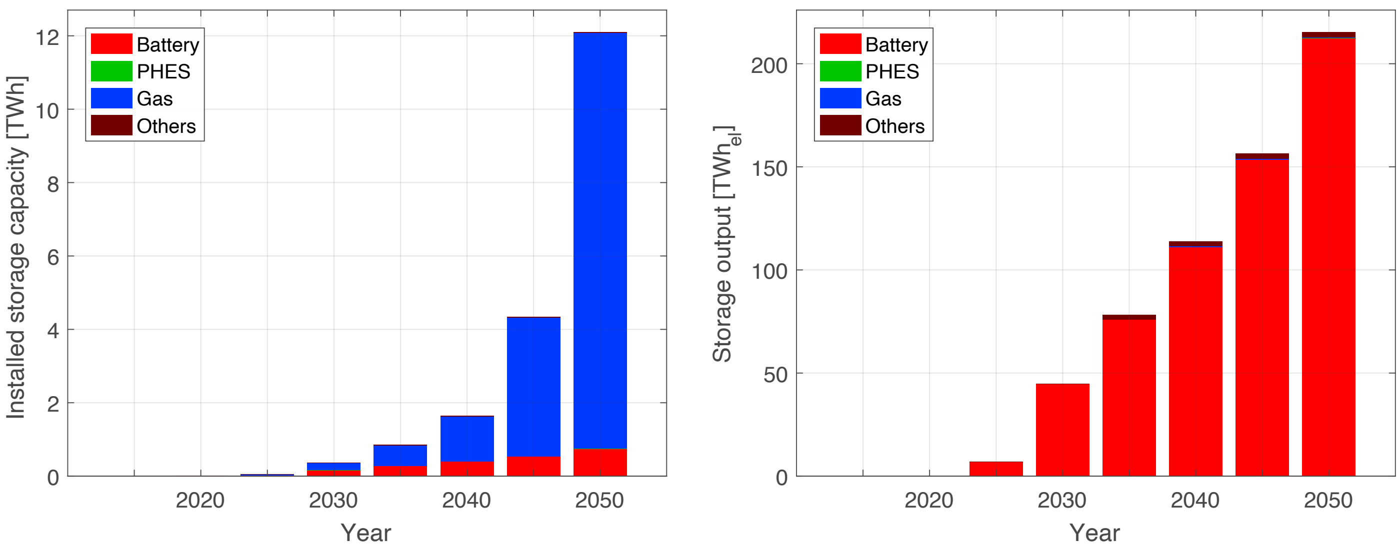

Figure A5.9: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Tamil Nadu.

Gas storage, which is synthetic natural gas produced through the power-to-gas process, has large capacities and fewer operating hours as it contributes vital seasonal storage during the transition. Battery storage mainly plays a role in providing diurnal storage, as indicated in Figure A5.10.

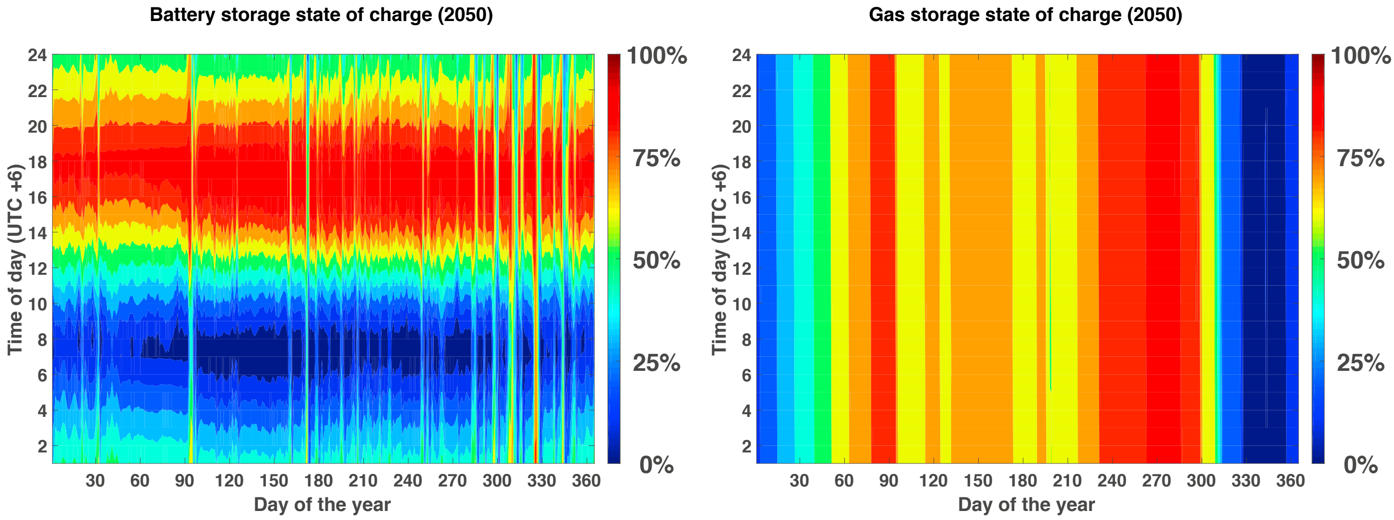

Figure A5.10: State of charge for battery storage (left) and gas storage (right) in 2050 for Tamil Nadu.

Gas storage mainly plays a role in providing seasonal storage, which is especially needed in the monsoon season when the solar resource is at its lowest. The gas storage discharges slowly over the monsoon period and is completely discharged by the end of winter, as can be observed in Figure A5.10. Some hydropower reservoirs provide complementarity with solar and wind but are used mainly for seasonal balancing.

System Outlook

The power system in Tamil Nadu has distinctive operational characteristics, which vary according to the seasonal pattern. This is highlighted by a summer week in 2050 (see Figure A5.11) and a monsoon week in 2050 (see Figure A5.12). During the summer period, solar PV and low shares of complementary wind energy are the main electricity generation sources. Batteries are used daily, charging during the day and discharging during the evening and night to meet peak consumption, as highlighted in Figure A5.11.

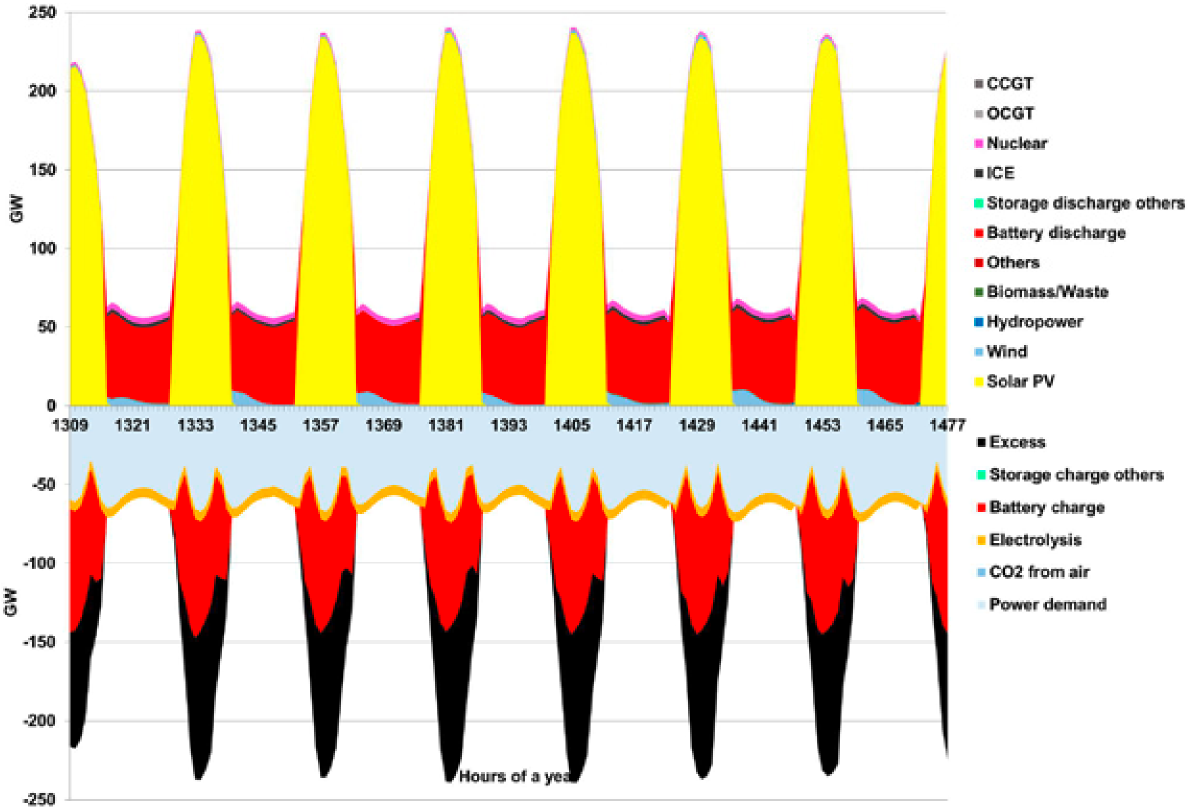

Figure A5.11: Time series of the power system in Tamil Nadu during a best solar week in 2050.

During the monsoon period, solar PV generation decreases while wind generation increases and becomes the main source of electricity generation. Some shares of dispatchable bioenergy and hydropower compensate for the lack of solar PV and wind generation. Reciprocating gas engines are utilised in periods of low generation, especially in the beginning of the week when wind generation is low and when solar generation is also low in the middle and end of the week, as shown in Figure A5.12.

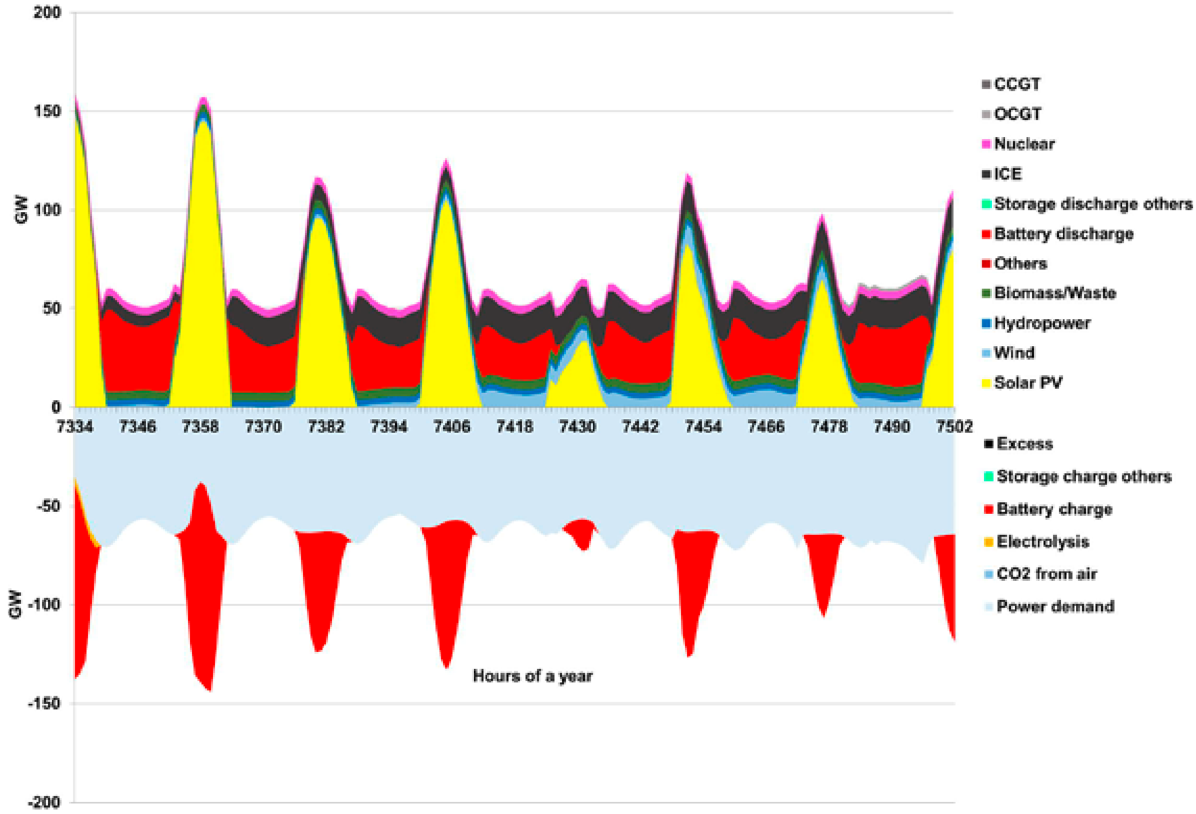

Figure A5.12: Time series of the power system in Tamil Nadu during a worst solar week in 2050.

Costs and investments

As indicated in Figure A5.13, capex increases during the transition, with wind initially and later solar and batteries being dominant. The levelised cost of electricity declines from around 72 €/MWh in 2020 to around 47 €/MWh by 2050 (see Figure A5.13) and is increasingly dominated by capital costs as fuel costs continue to decline during the transition period, which could mean increased self-reliance in terms of energy for Tamil Nadu by 2050.

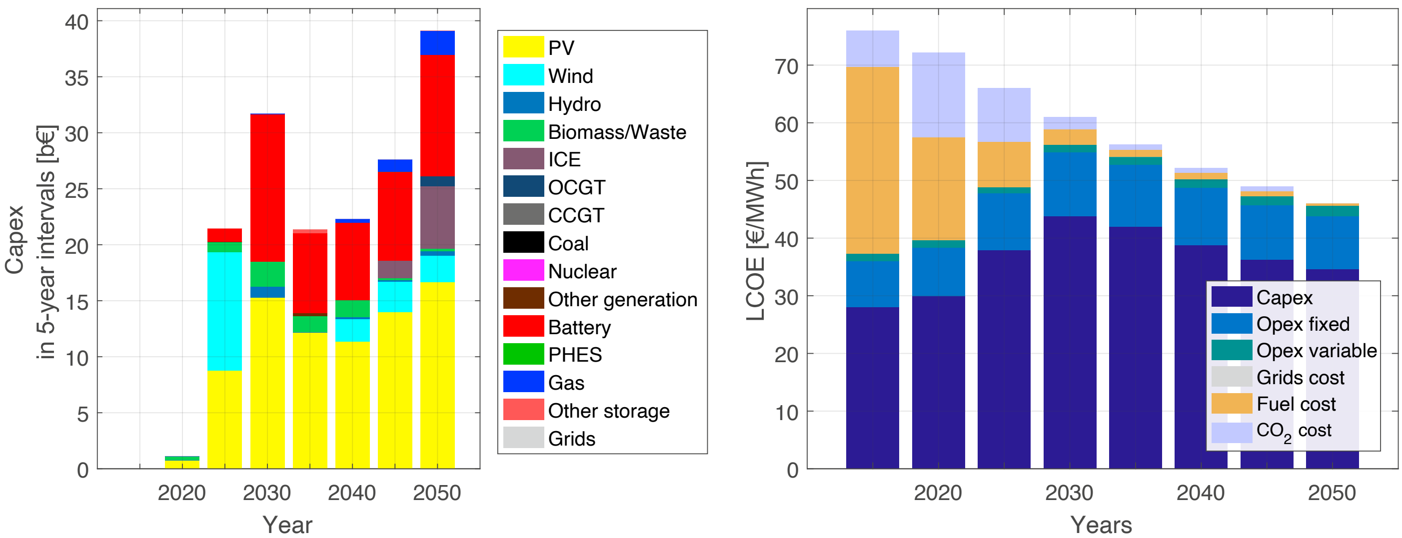

Figure A5.13: Capital expenditures for five-year intervals (left) and levelised cost of electricity (right) during the energy transition from 2015 to 2050 in Tamil Nadu.

Capital costs are divided across a range of technologies, with major investments in solar PV, wind energy, batteries and gas storage up to 2050, as shown in Figure A5.13. The steady increase in capex-related energy system costs indicates that fuel imports from other states across the country and the respective negative impacts on trade balances will fade out through the transition.

GHG emissions

The results of the power system transition in Tamil Nadu indicate that GHG emissions can be reduced from 77 $MtCO_{2eq}$ in 2020 to zero by 2050 across the power sector, as shown in Figure A5.14. The CO_{2eq} intensity of electricity generation rapidly declines during the transition, enabled by the phase-out of fossil-based power plants, which indicates a deep defossilisation by 2035 (see Figure A5.14).

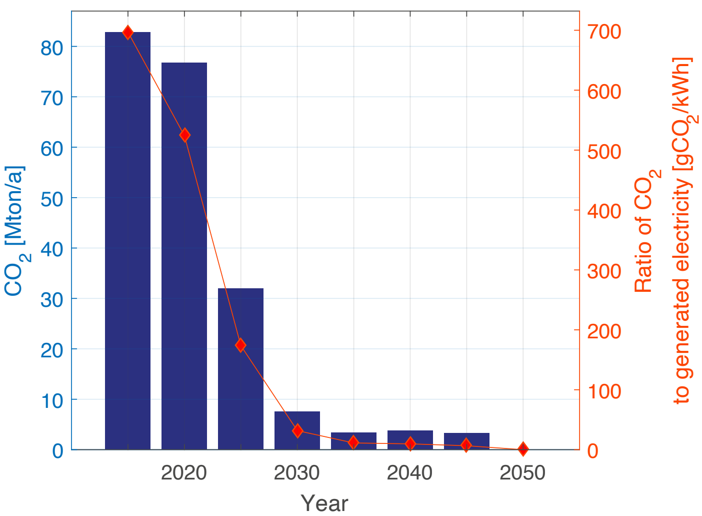

Figure A5.14: GHG emissions from the power sector during the energy transition from 2020 to 2050 in Tamil Nadu.

The presented 100% RE scenario for the power sector of Tamil Nadu is compatible with the goals of the Paris Agreement and will enable India to meet its commitments and take a leadership role. A deep defossilisation of the power sector is possible by 2030, and a steady decline in emissions is possible beyond 2030 up to 2050.

B. METHODS

The optimisation model of the energy system is based on a linear optimisation of the system parameters under a set of applied constraints with the assumption of perfect foresight into RE power generation and power demand. A multi-node approach enables the description of any desired configuration of sub-regions and power transmission interconnections. The main constraint on the optimisation is the matching of all types of generation and demand values for every hour of the applied year, and the optimisation criteria is the minimum of the total annual cost of the integrated system. While the hourly resolution of the model significantly increases the computation time, it guarantees that for every hour of the year the total supply within a sub-region covers the local demand and enables a more precise system description including the synergy effects of the different system components.

The optimisation was performed using a third-party solver. Currently, the main option is MOSEK version 8, but other solvers (Gurobi, CPLEX, etc.) also can be used. The model is compiled in the matlab environment in LP file format, meaning it can be read by most available solvers. After the simulation, results are parsed back into matlab data structure and post processed.

Target function

The target of the system optimisation is the minimisation of the total annual cost of the integrated system, calculated as the sum of the annual costs of installed capacities of the different technologies, costs of energy and product generation and production ramping. This target function includes annual costs of the power, heating, mobility, desalination and industrial fuel generation sectors. The target function of the applied energy model for minimising annual costs is presented in Eq.(1) using the abbreviations: sub-regions (r, reg), generation, storage and transmission technologies (t, $tech$), capital expenditures for technology t ($CAPEX_t$), capital recovery factor for technology t (crf_t), fixed operational expenditures for technology t ($OPEXfix_t$), variable operational expenditures technology t ($OPEXvar_t$), installed capacity in the region r of technology t ($instCap_{t,r}$), annual generation by technology t in region r ($E_{gen,t,r}$), cost of ramping of technology t ($rampCost_t$) and sum of power ramping values during the year for the technology t in the region r ($totRamp_{t,r}$).

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t)\cdot instCap_{t,r} + OPEXvar_t \cdot E_{gen,t,r} + rampCost_t \cdot totRamp_{t,r}\right) \quad (1)$$

The prosumers system is realised in an independent sub-model with a slightly different target function. The system is optimised for each sub-region independently even if the sub-region is connected to its neighbours within the region. The target function includes annual costs of prosumer power generation and storage, heating equipment, and the cost of electricity bought from the distribution grid; the cost of electricity sold to the distribution grid is deducted from the total annual cost. The target function of the applied energy model for minimising annual costs is presented in Eq. (2) using the abbreviations: generation and storage technologies (t, $tech$), capital expenditures for technology t ($CAPEX_t$), capital recovery factor for technology t (crf_t), fixed operational expenditures for technology t ($OPEXfix_t$), variable operational expenditures technology t ($OPEXvar_t$), installed capacity of technology t ($instCap_t$), annual generation by technology t ($E_{gen,t}$), retail price of electricity ($elCost$), feed-in price of electricity ($elFeedIn$), annual amount of electricity bought from the grid (E_{grid}), annual amount of electricity sold to the grid (E_{curt}).

$$\min\left(\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t) \cdot instCap_t + OPEXvar_t \cdot E_{gen,t} + elCost \cdot E_{grid} + elFeedIn \cdot E_{curt}\right) \quad (2)$$

Energy balance constraints

The main constraint for the power sector optimisation is the matching of the power generation and demand for every hour of the applied year; for every hour of the year the total generation within a sub-region and electricity import cover the local electricity demand.

$$\forall h \in [1.8760] \sum_{t}^{tech} E_{gen,t} + \sum_{r}^{reg} E_{imp,r} + \sum_{t}^{stor} E_{stor,disch} = E_{demand} + \sum_{r}^{reg} E_{exp,r} + \sum_{t}^{stor} E_{stor,ch} + E_{curt} \quad (3)$$

Eq. (3) describes the constraints on the energy flows of a sub-region. Abbreviations: hours (h), technology (t), all modelled power generation technologies ($tech$), sub-region (r), all sub-regions (reg), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies ($stor$), electricity from discharging storage ($E_{stor,disch}$), electricity demand (E_{demand}), electricity exported (E_{exp}), electricity for charging storage ($E_{stor,ch}$), electricity consumed by other sectors (heating, mobility desalination, industrial fuel production) (E_{other}), curtailed excess energy (E_{curt}). The energy loss in the high voltage direct current (HVDC) and alternating current (HVAC) transmission grids and energy storage technologies are considered in storage discharge and grid import value calculations.

Apart from this, various financial and technical assumptions that are utilised for the cost optimisation of the model are presented in the next section.

C. TECHNICAL AND FINANCIAL ASSUMPTIONS

The following tables show the various technical and financial assumptions that were factored into the modelling of the energy transition scenarios.

Table C1: Technical and financial assumptions of energy system technologies used in the energy transition from 2015 to 2050.

Technology		Unit	2015/ 2017	2020	2025	2030	2035	2040	2045	2050	Ref
PV rooftop - residential	Capex	€/kW_{el}	1360	1045	842	715	622	551	496	453	16
	Opex fix	€/(kW_{el} a)	20.4	9.1	7.7	6.7	5.9	5.3	4.8	4.4	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kW_{el}	1360	689	544	456	393	345	308	280	16
	Opex fix	€/(kW_{el} a)	20.4	9.1	7.7	6.7	5.9	5.3	4.8	4.4	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kW_{el}	1360	512	397	329	281	245	217	197	16
	Opex fix	€/(kW_{el} a)	20.4	9.1	7.7	6.7	5.9	5.3	4.8	4.4	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally tilted	Capex	€/kW_{el}	733	432	336	278	237	207	184	166	16.18
	Opex fix	€/(kW_{el} a)	9.3	7.8	6.5	5.7	5	4.5	4	3.7	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kW_{el}	1150	475	370	306	261	228	202	183	16.43
	Opex fix	€/(kW_{el} a)	17.3	9	7	6	6	5	4	4	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW_{el}	800	800	783.3	767	749	749	749	749	16.18
	Opex fix	€/(kW_{el} a)	15	15	13	11	8	8	8	8	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
Wind offshore	Capex	€/kW_{el}	2061	2003	1995	1979	1909	1896	1899	1897	
	Opex fix	€/(kW_{el} a)	67.7	59.9	50.2	41.2	29.4	28.5	25.4	23.1	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Lifetime	years	20	25	25	25	25	25	25	25	
Hydro reservoir/ Dam	Capex	€/kW_{el}	1650	1650	1650	1650	1650	1650	1650	1650	21
	Opex fix	€/(kW_{el} a)	49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5	
	Opex var	€/(kWh_{el})	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
	Lifetime	years	50	50	50	50	50	50	50	50	
Hydro run-of-river	Capex	€/kW_{el}	2560	2560	2560	2560	2560	2560	2560	2560	21
	Opex fix	€/(kW_{el} a)	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8	
	Opex var	€/(kWh_{el})	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	
	Lifetime	years	50	50	50	50	50	50	50	50	
Geothermal power	Capex	€/kW_{el}	5250	4970	4720	4470	4245	4020	3815	3610	21.28
	Opex fix	€/(kW_{el} a)	80	80	80	80	80	80	80	80	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	
	Lifetime	years	40	40	40	40	40	40	40	40	

Technology		Unit	2015/ 2017	2020	2025	2030	2035	2040	2045	2050	Ref
Coal PP	Capex	€/(kW_{el})	867	934	1045	1156	1267	1378	1489	1600	
	Opex fix	€/(kW_{el} a)	24	23.6	23	22.4	21.8	21.2	20.6	20	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	17
	Efficiency	%	32	42	42	42	43	43	43	43	
	Lifetime	years	40	40	40	40	40	40	40	40	
Nuclear PP	Capex	€/(kW_{el})	4511	4571	4672	4773	4874	4974	5075	5175	
	Opex fix	€/(kW_{el} a)	85	86.1	88	83	84.8	79.3	80.9	78.8	
	Opex var	€/(kWh_{el})	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	44–46
	Efficiency	%	34	34	34	35	35	35	35	35	
	Lifetime	years	40	40	40	40	40	40	40	40	
CCGT	Capex	€/(kW_{el})	623	637	660	683	706	729	752	775	
	Opex fix	€/(kW_{el} a)	23.44	23.1	22.5	21.9	21.3	20.7	20	19.375	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	17.19
	Efficiency	%	52.2	52.2	52.2	52.2	53.1	54	54	54	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT HD	Capex	€/(kW_{el})	450	445	440	435	430	425	420	415	
	Opex fix	€/(kW_{el} a)	23.4	11.3	10.6	9.9	9.2	8.5	7.8	7.1	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	17.19
	Efficiency	%	28	30	33	35	38	40	43	45	
	Lifetime	years	35	35	35	35	35	35	35	35	
Open cycle Aero-derivative	Capex	€/(kW_{el})	550	540	530	520	510	500	490	480	
	Opex fix	€/(kW_{el} a)	11.3	11.3	10.6	9.9	9.2	8.5	7.8	7.1	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	0.39	0.4	0.42	0.42	0.43	0.44	0.45	0.45	
	Lifetime	years	35	35	35	35	35	35	35	35	
RECIP oil based	Capex	€/(kW_{el})	385	385	385	385	385	385	385	385	
	Opex fix	€/(kW_{el} a)	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	47
	Efficiency	%	28	28	28	28	29	29	30	30	
	Lifetime	years	20	20	20	20	20	20	20	20	
RECIP gas	Capex	€/(kW_{el})	578.5	569	553	537	522	506	491	475	
	Opex fix	€/(kW_{el} a)	15.3	15.3	14.6	13.9	13.2	12.5	11.8	11.1	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	0.47	0.48	0.48	0.49	0.49	0.5	0.5	0.51	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biomass PP	Capex	€/(kW_{el})	760	857	1019	1181	1343	1505	1668	1830	
	Opex fix	€/(kW_{el} a)	53.3	51.5	48.4	45.3	42.2	39.1	36	32.9	
	Opex var	€/(kWh_{el})	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	16.18
	Efficiency	%	35	36	37	37	38	38	39	39	
	Lifetime	years	25	25	25	25	25	25	25	25	
Steam turbine (CSP)	Capex	€/(kW_{el})	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW_{el} a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	37.2	38.3	40.3	43	43	43	43	43	
	Lifetime	years	25	25	25	25	30	30	30	30	

Technology		Unit	2015/ 2017	2020	2025	2030	2035	2040	2045	2050	Ref
CHP biogas	Capex	€/kW$_{el}$	1580	1463	1269	1074	880	685	491	296	16.18
	Opex fix	€/(kW$_{el}$ a)	70.4	65.1	56.2	47.3	38.4	29.5	20.7	11.84	
	Opex var	€/(kWh$_{el}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency elec.	%	33	34	37	40	42	44	44	45	
	Efficiency heat	%	41.9	43	46.5	50	52.3	54.7	54.7	54.7	
	Lifetime	years	30	30	30	30	30	30	30	30	
Waste incinerator	Capex	€/kW$_{el}$	5940	5630	5440	5240	5030	4870	4690	4540	21
	Opex fix	€/(kW$_{el}$ a)	267.3	253.4	244.8	235.8	226.4	219.2	211.1	204.3	
	Opex var	€/(kWh$_{el}$)	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	
	Efficiency elec.	%	24	26	26	26	26	26	26	26	
	Efficiency heat	%	65.5	71	71	71	71	71	71	71	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW$_{th}$	771	731	706	680	653	632	609	589	48
	Opex fix	€/(kW$_{th}$ a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh$_{th}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW$_{th}$	340	290	270	250	230	220	210	200	48
	Opex fix	€/(kW$_{th}$ a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh$_{th}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	98 %	98 %	98 %	98 %	98 %	98 %	98 %	98 %	
	Lifetime	years	20	20	20	20	25	25	25	25	
CSP (solar field. parabolic trough)	Capex	€/kW$_{th}$	438.3	344.5	303.6	274.7	251.1	230.2	211.9	196	26.27
	Opex fix	€/(kW$_{th}$ a)	10.1	7.9	7	6.3	5.8	5.3	4.9	4.5	
	Opex var	€/(kWh$_{th}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
	Opex var	€/(kWh$_{th}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	95	95	95	95	95	95	95	95	
	Lifetime	years	22	22	22	22	22	22	22	22	
Water electrolysis	Capex	€/kW$_{H2}$	800	685	500	363	325	296	267	248	29.30
	Opex fix	€/(kW$_{H2}$ a)	32	27	20	12.7	11.4	10.4	9.4	8.7	
	Opex var	€/(kWh$_{H2}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	84	84	84	84	84	84	84	84	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW$_{CH4}$	547	502	368	278	247	226	204	190	
	Opex fix	€/(kW$_{CH4}$ a)	25.16	23.09	16.93	12.79	11.36	10.4	9.38	8.74	29.30
	Opex var	€/(kWh$_{CH4}$)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
	Efficiency	%	77	77	77	77	77	77	77	77	
	CO2 input	kg$_{CO2}$/kWh$_{th}$	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	
	Lifetime	years	30	30	30	30	30	30	30	30	
CO_2 direct air capture	Capex	€/tCO_2 a	1000	730	493	335	274.4	234	210.6	195	49
	Opex fix	€/tCO_2 a	40	29.2	19.7	13.4	11	9.4	8.4	7.8	
	Opex var	€/tCO_2	0	0	0	0	0	0	0	0	
	Elec. cons	kWh$_{el}$/tCO_2	250	242	236	225	214	203	192	182	
	Heat cons	kWh$_{th}$/tCO_2	1750	1670	1590	1500	1393	1286	1194	1102	
	Lifetime	years	20	20	30	30	30	30	30	30	

Technology		Unit	2015/ 2017	2020	2025	2030	2035	2040	2045	2050	Ref
Fischer-Tropsch unit	Capex	€/$kW_{FTLiq, output}$	947	947	947	947	947	852.3	852.3	852.3	50
	Opex fix	€/$kW_{FTLiq, output}$	28.41	28.41	28.41	28.41	28.41	25.57	25.57	25.57	
	Opex var	€/$kW_{FTLiq, output}$	0	0	0	0	0	0	0	0	
	Efficiency	%	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	
	CO2 input	$kgCO_2/kWh_{th}$	0.284	0.284	0.284	0.284	0.284	0.284	0.284	0.284	
	Lifetime	years	30	30	30	30	30	30	30	30	
Battery storage	Capex	€/kWhel	400	270	182	134	108	92	78	70	51
	Opex fix	€/(kWhel a)	24	9	5	3.8	3	2.5	2.1	1.9	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
PHES	Capex	€/kWh_{el}	89	89	89	89	89	89	89	89	
	Opex fix	€/(kWh_{el} a)	1	1	1	1	1	1	1	1	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	85	85	85	85	85	85	85	85	
	Self-discharge	%/h	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	
A-CAES	Capex	€/kWh_{el}	80.4	80.4	70.7	63.3	59	56.2	52.4	49.2	
	Opex fix	€/(kWh_{el} a)	1	1	1	1	1	1	1	1	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Self-discharge	%/h	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh_{el}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh_{el} a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Self-discharge	%/h	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	
Hydrogen storage	Capex	€/kWh_{th}	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	52
	Opex fix	€/(kWh_{th} a)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
	Opex var	€/(kWh_{th})	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Self-discharge	%/h	0	0	0	0	0	0	0	0	
	Lifetime	years	15	15	15	15	15	15	15	15	
CO_2 storage	Capex	€/ton	142	142	142	142	142	142	142	142	53
	Opex fix	€/(ton a)	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	
	Opex var	€/ton	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Self-discharge	%/h	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	30	30	30	30	30	30	

Table C2: Ramping costs for power generation technologies. Data adopted from Deutsches Institut für Wirtschaftsforschung 54 .

Technology	Unit	
Geothermal power	€/MW	0
Coal PP	€/MW	54.3
Nuclear PP	€/MW	54.3
CCGT	€/MW	25
OCGT	€/MW	22.9
Internal combustion generator	€/MW	0
Biomass PP	€/MW	54.3
Steam turbine (CSP)	€/MW	0
CHP biogas	€/MW	22.9
Waste incinerator	€/MW	54.3

Table C3: Financial assumptions for the fossil-nuclear fuel prices and GHG emission cost. The referenced values are valid until 2040 and are assumed to be stable for later periods (fuels) or are assumed to further increase in order to match the goals of the Paris Agreement (GHG emissions).

Name of component	Unit	2015/ 2017	2020	2025	2030	2035	2040	2045	2050	Ref.
Coal	€/MWh_{th}	9.9	9.9	10.8	11.8	13.1	14.3	14.3	14.3	55
Fuel oil	€/MWh_{th}	101.1	101.1	114.3	127.5	126	124.9	124.9	124.9	56.57
Fossil gas	€/MWh_{th}	36.1	36.1	48.8	53.2	58.8	65.4	65.4	65.4	57.58
Uranium	€/MWh_{th}	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	46
GHG emissions	€/tCO_{2eq}	9	28	52	61	68	75	100	150	59
WACC		11.00 %	11.00 %	9.70 %	8.50 %	7.00 %	7.00 %	7.00 %	7.00 %	60

GHG emissions by fuel type tCO_{2eq}/MWh_{th}		
Coal [61]	**Oil** [61]	**Fossil gas** [62]
0.34	0.25	0.21

Table C4: Efficiency assumptions for HVAC and HVDC transmission lines 63.

Component	Power losses
HVAC line	9.4 % / 1000 km
HVDC line	1.6 % / 1000 km
HVDC converter pair	1.40 %

Table C5: Financial and technical assumptions for HVAC and HVDC transmission lines.

		Unit	2015/ 2017	2020	2025	2030	2035	2040	2045	2050
HVDC transmission line Blend: 30% overhead. 70% cable	Capex	€/(kW*km)	0.92	0.92	0.92	0.92	0.92	1.05	1.05	1.05
	Opex fix	€/(kW*km)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh*km)	0	0	0	0	0	0	0	0
	Lifetime	year	50	50	50	50	50	50	50	50
	Efficiency	Per 1000 km	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
HVDC transmission line (cable)	Capex	€/(kW*km)	1.23	1.23	1.23	1.23	1.23	1.37	1.37	1.37
	Opex fix	€/(kW*km)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh*km)	0	0	0	0	0	0	0	0
	Lifetime	year	50	50	50	50	50	50	50	50
	Efficiency	Per 1000 km	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
HVDC transmission line (overhead)	Capex	€/(kW*km)	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
	Opex fix	€/(kW*km)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh*km)	0	0	0	0	0	0	0	0
	Lifetime	year	50	50	50	50	50	50	50	50
	Efficiency	Per 1000 km	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
HVAC transmission line (overhead)	Capex	€/(kW*km)	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
	Opex fix	€/(kW*km)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh*km)	0	0	0	0	0	0	0	0
	Lifetime	year	50	50	50	50	50	50	50	50
	Efficiency	Per 1000 km	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Converter stations pair - HVDC	Capex	€/(kW)	150	150	150	150	150	180	180	180
	Opex fix	€/(kW)	1.5	1.5	1.5	1.5	1.5	1.8	1.8	1.8
	Opex var	€/(kWh*a)	0	0	0	0	0	0	0	0
	Lifetime	year	50	50	50	50	50	50	50	50
	Efficiency		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Long-term exchange rate used: 1 € = 75 INR.

The way forward

The findings of this research show that India can be completely powered by renewable energy, storage and other flexible sustainable technologies by 2050. Solar PV based electricity emerges as the primary resource for the Indian power sector in 2050 as costs continue to decline, eventually delivering the lowest-cost electricity. Therefore, policies at national and individual state level for solar PV adoption have to be enhanced along with an exclusive push for the prosumer segment. The cost benefits are clearly evident from this research, with national average LCOE at around 39 €/MWh for 100% RE in 2050 compared to the total LCOE of 75 €/MWh (including GHG emissions costs) in 2020. To achieve long-term benefits, investments in storage and better transmission and distribution grids along with flexible power plants are crucial.

As the results of the interconnected pan-India energy transition and energy transition in individual states as isolated power systems highlights that transmission over a larger geographical area plays an important role in a fully renewable energy system. It enables access to resources distributed across the country and allows for optimal operation and stability of the system. This entails the need for investments in strong regional and interstate grids that will reduce curtailment and enable a smooth transition across the Indian power system.

The results indicate that full load hours (capacity factors/utilisation) of coal power plants across the country are in continual decline due to their increasing economic infeasibility, which suggests that coal phase-out and divestment strategies at both state and federal level have to be undertaken to enable the transition of the power sector.

Batteries and reciprocating gas engines must be supported to provide crucial flexibility for the future power system dominated by solar PV and wind energy. As the results indicate, the fuel mix for reciprocating gas engines transitions from 100% fossil gas in 2020 to 85% synthetic natural gas (from renewable electricity) and 15% biomethane in 2050. Therefore, efforts to support the production of synthetic fuels from renewable electricity must be initiated. Advanced energy system models must be adopted for enhanced energy planning and policy making, capturing the new solar age trends of flexibility, storage and sector coupling for the future power system of the country.

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