

Case studies for integration of renewable energy sources in power grid – lessons for India

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This article discusses three case studies of renewable energy integration in power grid from the international literature. Case studies in India and Gujarat in particular are discussed. Capacity and energy generation for 2019–20 actual and 2029–30 estimated are provided. Methods of renewable energy integration are discussed in detail. A brief review of energy storage technology is given. It is shown that with the setting up of Green Energy Corridors and Renewable Energy Management Centres, India would be able to integrate planned renewable energy generation without much difficulty. It must be noted that in the next 25 years renewable energy source, including hydro, will only provide 35–40% of electricity generation. Coal will remain the main energy source for power, and oil and gas for transport.

Keywords: Case studies, capacity and energy generation, green energy corridors, power grid, renewable energy integration.

RENEWABLE sources like solar and wind energy are now becoming important for power generation. They play a significant part in meeting climate change goals to reduce global warming. They provide virtually carbon-free energy. They are highly intermittent in nature and provide tough challenge to integrate into modern grid requiring 24 × 7 availability. Renewable energy prices have also dropped sharply to Rs 2.50–3.00/kWh compared to coal-based thermal energy price of around Rs 4.0–4.5/kWh.

India has set a target of 175 GW renewable energy by 2022, 100 GW solar, 60 GW wind and 15 GW from other sources. It is likely that this will be achieved. Only solar rooftop which is planned at 40 GW of 100 GW solar will fail to meet target. It will be of interest to note that hydroelectricity is a renewable source. In the early seventies, hydro share was 40% of electricity generation. Today renewables, including hydro, wind and solar contribute around 20%. This is also reflected in the carbon intensity of energy supply which was 1.20 (tonnes of CO₂/tonnes of oil equivalent) in the early seventies and has now doubled at 2.4. This shows the increasing share of fossil fuels like coal, oil and gas in energy supply. Carbon intensity of hydro-rich countries is considerably less – Brazil – 1.4, Finland and Norway – 1.30 and Iceland – 0.40. France with its predominant nuclear elec-

tricity has a carbon intensity of 1.20. In these countries fossil fuel use is mainly for transport and the residential sector^{1,2}.

The Government of India (GoI) has now planned for 450 GW of solar and wind by 2029–30.

Methods for renewable energy integration

Once renewable energy generation becomes more than 15%, significant steps are required for integration. This is because solar and wind generation can change significantly due to cloud cover as well as other weather-related events. Daily variations in solar energy can now be predicted with great accuracy due to extensive weather monitoring in the ground as well as satellites. Wind forecasting has also improved significantly. GoI has set up Renewable Energy Management Centres in all renewable energy-rich states. These centres use latest technology, including artificial intelligence to provide accurate forecasting for solar and wind.

Flexible sources of power generation

Hydro and natural gas power generation systems provide a fast and reliable flexible source. However, their share in energy supply in India is declining. Coal-based power stations have been designed as base-load stations, but are now being upgraded for flexible load. They operate at 60% load and are now being designed to operate at even

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40% load. However, reliability and long-term life expectancy under flexible operation is yet to be confirmed.

During lockdown due to the COVID pandemic, on 5 April 2020, lights across India were switched-off at 9 pm and switched on at 9.10 p.m. A swing of about 32 GW was successfully handled by the Indian grid mainly due to hydro flexibility (2.74 GW/min).

Energy storage system

Large-scale renewable energy systems integration requires development of an efficient energy storage system. Pump hydro storage still provides more than 95% of energy storage capacity. However, battery and other storage systems are fast developing. A brief review is provided here.

Integration with larger systems

Renewable generation is variable, but when spread over a large physical area provides better average availability. Also, larger grids provide opportunities of import and export.

GoI has taken up an ambitious project called green energy corridor. Under this project, the plan is to construct 9400 km of transmission lines and 19,000 MVA of transformer capacity at a cost of Rs 10,000 crores. This project is mostly completed. Inter-state and Intra-state transmission lines have been constructed. About 20,000 MW of solar and wind power will be evacuated.

Renewable energy technology for grid support

Now inverter-based solar and wind systems are being designed to provide flexibility in the form of power generation as well as reactive power support. Many new inverters can provide reactive support and can also operate at lower output level³. Several recent publications report the progress in making renewable energy sources themselves take up measures to support grid.

Demand management

Some loads can be curtailed to balance generation and demand. In some cases, reduction of voltage also helps in system balance. Sometimes renewable energy generation has to be curtailed due to technical and commercial reasons.

Review of energy storage technology

Pump hydro remains the predominant storage technology⁴. During the off-peak period, water is lifted to a higher-

level reservoir. During peak requirement energy is generated like conventional hydro generation. These systems require specific physical sites and are expensive to build. Pump hydro storage system in India provides 5000 MW capacity now and is likely to provide 10,000 MW by 2030. Pump storage plants are also designed using variable-speed drives to improve operational efficiency.

Battery storage

This technology has seen fast development in recent years, especially lithium ion. However, cost remains a major barrier. Sodium, sulphur, metal, hydro and redox flow batteries are other solutions. Fly wheel and super capacitors are other sources. Thermal storage is an important storage technology already being used in India.

Table 1 shows the characteristics of energy storage technologies.

Current and future status of renewable energy generation in India

Table 2 shows the variable renewable energy (VRE) capacity, generation and percentage share for VRE-rich states⁵. Table 3 shows the power generation capacity in 2019–20 and 2029–30, while Table 4 shows electricity generation in 2019–20 and 2029–30.

These data include conventional and renewable sources, and have been obtained from the Central Electricity Authority (CEA)⁶.

Data for 2029–30 are from a CEA report⁷ as well as a recent IEA study⁸. Both these reports use different models, but come to similar conclusion for 2029–30.

The following may be noted from Tables 3 and 4:

In 2019–20, generation is predominantly thermal accounting for 75% of the total generation. Hydro contributes about 11% and renewable, solar, wind and others about 10% and nuclear contributes about 3%.

Capacity-wise coal and accounts lignite for 56%, hydro 12%, gas 6.8%, while solar, wind and biomass accounts for 23%. Nuclear is 2%.

In 2029–30, the situation changes drastically. Coal and lignite account for 54% of generation, but only 33% for capacity. Hydro accounts for 8% of generation and 8% for capacity. Gas accounts for 3% of generation and 3% for capacity. Solar accounts for 19% generation and 34% for capacity. Wind accounts for 12% of generation and 17% for capacity.

Battery storage of about 27,000 MW/108,000 MWH and pumped hydro of about 10,000 MW provide energy storage capacity. Hydro and gas also provide flexible solution.

Table 1. Characteristics of energy storage technologies

Item	Lithium ion battery			Lead acid battery			Redox flow battery		
	Pump hydro	Compressed air	Flywheel	2018	2025	2018	2025	2018	2025
Capital cost	1500–3000 US\$/KW	1000–2000 US\$/KW	1000–3000 US\$/KW	1500–2000 US\$/KW	1200–1500 US\$/KW	1400–2500 US\$/KW	1200–1300 US\$/KW	2200–5000 \$/KW	2200–2800 US\$/KW
System efficiency	0.80	0.5–0.6	0.8	0.80	0.72	0.7	0.72	0.7	0.7
Response time (sec)	60–120	–	–	1	1	1	1	1	1
Life (years)	25	25	20	10	3	15	3	15	15

Note: The recent tender for the 415 kWh battery system was won by BHEL for Rs 2.51 crores. Thus it translates into: Rs 2.5 crores/415 kWh = Rs 60,000/kWh = US\$ 850/kWh.

Table 2. State-wise installed capacity of grid interactive renewable power (MW) as on 28 February 2021 (ref. 6)

States/Union Territories	Small hydro power	Wind power	Bio-power			Solar power				
			BM power/Bagasse cogeneration	BM cogeneration (non-Bagasse)	Waste to energy	Bio-power total	Ground-mounted	Rooftop	Total	Total capacity
Andhra Pradesh	162.11	4096.65	378.10	105.57	23.16	506.83	3858.24	138.26	3996.50	8762.09
Gujarat	78.94	8306.42	65.30	12.00	77.30	77.30	3125.17	943.13	4068.30	12,530.96
Karnataka	1280.73	4912.60	1867.10	20.20	1.00	1888.30	7091.75	255.10	7346.85	15,428.48
Kerala	230.02	62.50	–	2.27	–	2.27	150.00	107.00	257.00	551.79
Madhya Pradesh	99.71	2519.89	92.50	14.85	15.40	122.75	2386.31	76.91	2463.22	5205.57
Maharashtra	379.58	5000.33	2568.00	16.40	12.59	2596.99	1642.24	647.73	2289.97	10,266.87
Punjab	173.55	–	299.50	173.95	10.75	484.20	828.58	118.52	947.10	1604.85
Rajasthan	23.85	4326.82	119.25	2.00	6.40	121.25	5053.58	419.00	5472.58	9944.50
Tamil Nadu	123.05	9431.54	969.10	43.55	6.40	1019.05	4090.15	313.33	4403.48	14977.12
Telangana	90.87	128.10	158.10	2.00	45.80	205.90	3784.27	152.09	3936.36	4361.23
Total India	4783.06	38,789.15	9373.87	772.05	168.64	10,314.56	34,759.13	4324.58	39,083.71	92,970.48

Table 3. Power generation capacity in 2019–20 and 2029–30

	2019–20		2029–30	
	MW	Percentage	MW	Percentage
Hydro (MW)	45,699	12.4	60,977	7.46
Pump storage	5,000	1.1	10,151	1.24
Small hydro	4,683	1.2	5,000	1
Coal + lignite	198,734 + 6,610	56.17	266,911	32.66
Gas	24,955	6.8	25,080	3.07
Nuclear	6,780	1.8	18,980	2.32
Solar	34,406	9.41	280,155	34.28
Wind	37,669	81.7	140,000	17.13
Biomass	9,861	2.54	10,000	1
Total	36,5537		817,254	
Battery			27,000 MW/108,000 MWh	

Table 4. Electricity generation 2019–20 and 2029–30

	2019–20		2029–30	
	Billion units	Percentage	Billion units	Percentage
Coal + lignite + gas	1044.445	75.13	1357.78	54
Nuclear	46.381	3.33	113.0	5
Hydro	155.97	11.22	206.6	8
Biomass + small hydro	10.908	3.82	7.2	3
Gas			35.48	2
Solar	50.103	3.63	484.28	19
Wind	64.63	4.65	309.1	12
Total	1390		2518	

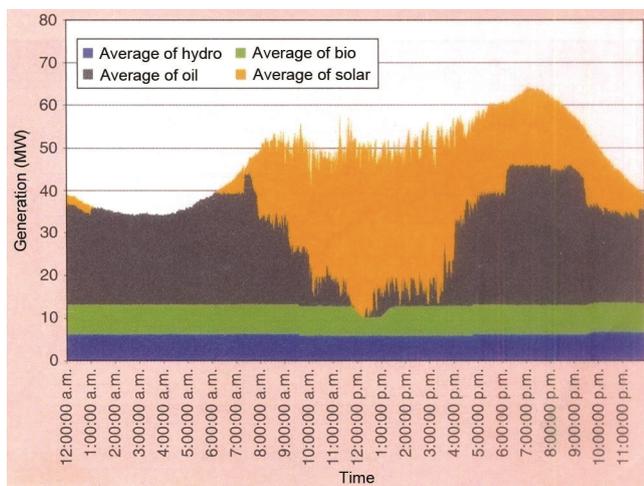


Figure 1. Dispatch of the Kauai Island Utility Cooperative system on 24 February 2019 with 100% renewable operation. Yellow: photovoltaic (solar); gray, oil, green, biomass (bio) and blue, hydroelectric.

Case studies^{9–11}

Denmark

Denmark depended on large coal plants for its electricity needs. The Government policy led to development of on-shore wind power, offshore wind power, combined heat and power and solar photovoltaic (PV) power. In Denmark solar resource is limited. In 2018, wind energy

supplied 40.7%, solar PV 2.8%, fossil fuel 23.5%, biomass and waste cogeneration 17.8% and 15.3% from imports. The Denmark approach is basically market-based. Vast majority of trade based on day ahead market lead to flexible generation and import from international connections.

Denmark has taken the following steps for integration: (1) Strong transmission grids and interconnections. (2) International electricity markets – wholesale. (3) Flexible and controllable generation system. (4) Specialized forecasting and operational planning tools. (5) Well-known rules and business models.

Denmark has planned 100% renewable electricity by 2030 and 100% renewable energy by 2050.

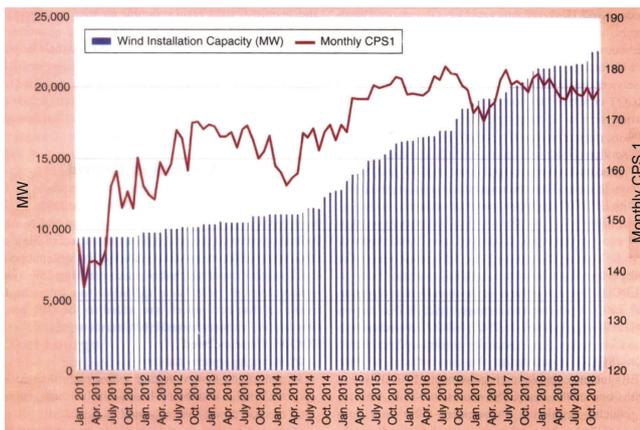
Kauai, Hawaii

Kauai Island Utility Cooperative (KIUC) is the sole electricity provider for Kauai Island in Hawaii. In 2010, 92% of electricity was provided by oil. At the end of 2018, it was 96 MW solar, for meeting the demand of 55–65 MW.

With increasing PV levels, flexibility was introduced for thermal oil-based production. Minimum load of operation was kept at 50% and further reduced to 25%; and now it is 10%. This has not proved enough supply and energy storage was increased. Tesla now provides 13 MW PV with 13 MW/52 MWh battery storage. Another 30 MW/100 MWh storage was commissioned in 2018.

Table 5. Renewable energy absorption on critical days

Scenario	Date	Renewable energy absorption (%)
Peak day/maximum energy demand day	7 October 2029	99.74
Maximum variable renewable energy (VRE) (wind + solar) generation day	3 July 2029	85.32
Maximum solar generation day	25 March 2030	89.56
Minimum solar generation day	8 August 2029	100
Minimum energy demand day	14 December 2029	97.19
Minimum VRE (wind + solar) generation day	1 February 2030	100
Maximum variation in demand day	27 January 2030	100
Maximum variation in net demand day	26 October 2029	86.76

**Figure 2.** Wind installation capacities (MW) versus monthly CPS 1.

KIUC daily peak demand occurs 1 h after sunset. This is achieved by thermal generation, battery storage PV with battery storage control system management. On-line fossil generation is now replaced with battery storage for spinning reserves. Figure 1 shows how system demand is maintained.

South Australia

The state of South Australia is on one end of the national electricity market. It is not an islanded system, but has only one double circuit AC interconnection with other regions. In 2018, wind generation exceeded demand for 5% of the time and instantaneous wind output 144% of demand. Thirty per cent of South Australian households have PV systems. This grid system can change from synchronous generators to wind system. Inverter-based wind systems require grid strength of synchronous machines. These synchronous machines are not flexible, nor can they operate as synchronous condensers. Detailed system studies came to the following conclusion: (1) 4–5 synchronous machines of 150–200 MVA must remain on-line all the time. (2) Wind output must be curtailed during peak generation. (3) Interconnection will provide balance as and when needed. Inverter-based systems are now required to provide many system functions.

For South Australia, 50% demand is met by distributed energy resources (DERs) and can go up 100% by 2027. DERs will require control and communication capacities as well as ride-through capability.

South Australia also has several DERs especially roof-top solar installations. This distributed energy capacity is likely to reach 100% of demand by 2027. Figure 2 shows wind capacity and total demand in the system.

Case studies in India, 2029–30

We have shown capacity and generation by different sources like coal hydro, nuclear, solar and wind in 2029–30. Both CEA and IEA have carried out detailed modelling of supply and demand on an hourly basis, and have come to the conclusion that renewable energy generation may have to be curtailed on some days (Table 5).

The CEA report mentions that one limitation is coal plant operation at 55% of minimum load. With minimum load reduced to 40%, further absorption is possible.

Another important point to note is that both CEA and IEA assume gas-based capacity at 25,000 MW (same as now). India has planned to increase share of gas in energy supply from 6% to 15%. Gas provides highly flexible source and gas capacity can safely aimed to be 40 GW. Gas-based generation can increase from 35 to 60 BU in 2029. This will allow full absorption of all solar and wind generation. Also, solar and wind system inverters themselves will be able to provide many grid functions.

Case studies in Gujarat, 2029–30

IEA has given an interesting example for renewable energy absorption for Gujarat, using detailed modelling. In Gujarat 13% of energy generation is provided by wind and solar, with little curtailment at present.

In 2030, Gujarat plans to have 44 GW of solar and wind energy in the state, and another 20 GW imported from other states. Renewable energy generation would be 40% and curtailment of power would be about 7%.

IEA has suggested the following three steps.

(i) Demand side response: Agriculture accounts for 20% of consumption, mainly during night hours. Agriculture

feeder separation has been done in Gujarat. If agriculture is provided, energy during the daytime using solar curtailment can be reduced to 3%.

(ii) Flexible operation of coal plants: Reducing minimum load to 40% from 50% will allow more renewable energy absorption.

(iii) Provision of 4000 MW of battery: This will allow for better renewable energy absorption. About 40% renewable energy generation on average and 100% on some days is possible in Gujarat.

Concluding remarks

This article discusses various methodologies of integrating renewable resources in grid. Status of energy storage systems is also discussed. Case studies of renewable energy integration from Denmark, Hawaii and South Australia are discussed. High level of renewable energy integration up to 50% can be achieved with the present available technology.

In India solar and wind provide 25% of electricity generation capacity but only 10% of electricity generation, as solar and wind plants that operate intermittently have average capacity factors of 20% compared to 60–80% for conventional generation. In 2029–30, renewable electricity generation capacity may reach 50% of total electricity generation capacity, but will provide 20–25% of total electrical energy generation. In Rajasthan, Gujarat and Tamil Nadu, average renewable electricity generation may reach 30–45% and peak generation 70–80%. GoI has taken major steps for constructing Green Energy Corridors and Renewable Energy Management Centres in all renewable energy-rich states.

Steps for renewable energy integration can be summarized as follows:

Denmark

(i) Strong transmission grids and interconnectors. (ii) International electricity markets—wholesale. (iii) Flexible and controllable generation system. (iv) Specialized forecasting and operational planning tools. (v) Well-known rules and business models.

Hawaii

Flexible thermal generation and large battery storage.

South Australia

(i) Interconnection with larger grid. (ii) Flexible operation of coal plants. (iii) Grid supporting inverter systems. (iv) Demand management.

India and Gujarat

(i) Integrated country-wide grid system, including Green Energy Corridors. (ii) Accurate forecasting for solar and wind. (iii) Flexible operation of coal plants. (iv) Battery storage system. (v) Demand management.

Providing more gas generation will allow integration of 50% renewable energy generation. This is a better option than running coal plants at 40%. Coal will continue to remain an important source for power and energy.

For 100% renewable electricity and 100% renewable energy, further steps are required (Annexure 1).

Annexure 1. Steps planned by Denmark

For 100% renewable electricity supply

- (1) Strong transmission grids and interconnectors.
- (2) International electricity markets – wholesale.
- (3) Flexible and controllable generation system.
- (4) Specialized forecasting and operational planning tools.
- (5) Well-known roles and business mode.

For 100% renewable energy supply

- (1) Coupling of sectors.
- (2) Activation of demand side.
- (3) New market players.
- (4) Data-based business models.
- (5) Temporal integration.

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ACKNOWLEDGEMENTS. Use of library facilities of the Community Science Centre, Vadodara is acknowledged. We thank Mrs Harshangi Yagnik, Community Science Centre, Vadodara for assistance.

Received 10 July 2020; revised accepted 23 March 2021

doi: 10.18520/cs/v120/i12/1827-1832