Computation of Power Loss in Utility Scale Solar PV Projects due to Power Limitation and Controls

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Abstract

With more and more renewables being integrated into conventional grids, the grid codes and connectivity requirements are becoming stringent for the distributed sources of generation. As installed solar capacities are increasing, the pressure to overcome the intermittent nature and emphasis to behave like a fixed load power plant is also increasing. This has led to the governing of power from wind and solar plants by various tools and technologies. In the last few years, asset real time performance monitoring has become the norm and organizations have built prediction models to monitor and evaluate their assets' financial returns. This paper covers the common types of controls used in utility scale solar PV projects and various methodologies used for computation of losses due to the controls at Solar Inverters and at grid interconnection point. The current study also compares the methodology used in PVsyst (solar PV energy simulation software used in industry) and real time loss estimations due to these controls. For analysis and evaluation, data from multiple utility scale solar PV assets in India have been considered.

Keywords: Asset monitoring, Performance evaluation, Inverter power control, Clipping loss, Power curtailment losses, Grid limitation losses, Power plant controller, PVsyst, Inverter loss over nominal inverter power, power governance.

1. Introduction

Solar photovoltaic projects work on the principle of conversion of sunlight to electricity. Earth's rotation around the sun makes day and night. During the day, the sun follows a certain path in the sky and if solar modules can track the sun, they will convert this falling radiation into energy. Most of the solar technologies like Solar Photovoltaic (SPV), Concentrated Solar Power (CSP), Solar Thermal Technology, Solar Water Heating Systems, Solar Air Conditioning, Solar Desalination and Solar Powered Vehicles work on the same principle of harnessing sun's energy.

Main components of a grid connected Solar PV system are:

1. PV Modules
2. Module mounting structures (MMS)
3. Solar Inverter Unit (Inverter) for converting DC to AC
4. Switchgear with protection and control circuits
5. Transformers for transformation of energy at different voltage levels
6. Utility Grid
7. DC, AC cables, earthing system and other miscellaneous items

2. Global Renewable Energy Scenario

As per *Statistical review of world energy 2023*, the world has increased its renewable electricity generation at a rate of 14.7% from 2021 to 2022 (page 53 of the report), while the overall electricity generation increased

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by 2.26% in 2022 (Fig. 1). The integration of variable sources of energy like wind and solar poses new challenges for grid operators and utilities in terms of demand and supply side forecasting.

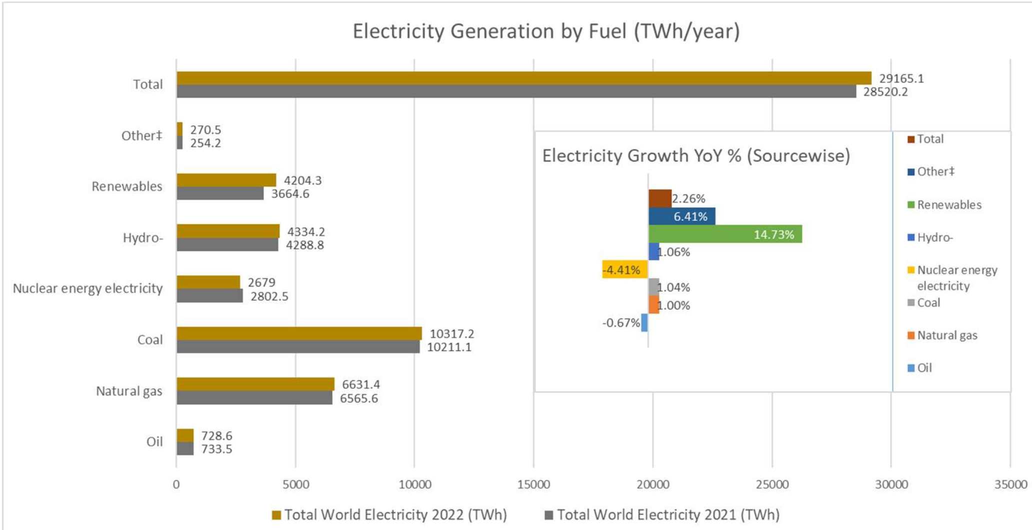

Fig. 1: Electricity Generation across world in Terra Watt Hour/Year in 2021 and 2022. Sub-chart illustrates that renewable sector contribution in energy mix has been growing exponentially YoY in recent years.

With the strong growth in renewable energy sector, the events of power curtailment will also increase in various cases of unbalanced grid and overcapacity in various parts of electric network. *Section 6, Table 1* of this paper covers power governance and control strategies enforced by CEA(Central Electricity Authority), which is the apex body for power sector in India. Utilization of this curtailed energy will be essential for efficient utilization of RE assets. India has started incentivizing new project awards, for round the clock, solar wind hybrid and battery energy storage projects. This will not only help in balancing the grid but also in utilizing this freely available renewable energy in electrifying newer geographies in India.

3. Calculating energy from a Solar Photovoltaic System

Solar system efficiency is dependent on the step efficiency of each system which is a part of the power flow sequence.

$$\mathbf{E_{out} = E_{POA}*(1-L1)*(1-L2)*(1-L3)*(1-L4)*(1-L5)*(1-L6)*(1-L7)} \qquad \textbf{(eq.1)}$$

The solar energy resource received (E_{POA}) and loss factors (Ln) depend on actual site geography, system design factors (electrical, mechanical, civil) and technology used in various conversion processes.

In the above equation,

E_{out} or Energy Output represents energy generated from a solar PV plant (in kWh)

E_{POA} or Energy Received represents solar irradiation falling on module plane of array (in kWh/m^2).

L1 represents the cumulative percentage loss in irradiation due to shading, reflection, soiling etc. before reaching the collector i.e. solar cells

L2 represents the percentage conversion losses in photovoltaic cells
Energy at end of this stage is also known as E_{array} or array nominal energy.
E_{array} = Irradiation received on collector after L1 losses (in kWh/m^2 area)*collector area(in m^2) *module efficiency (in %)

L3 represents cumulative percentage losses in conversion due to actual site geography, design factors above or below the STC lab conditions. This includes thermal loss, electrical shading loss, light induced degradation, DC ohmic wiring loss etc.

L4 represents cumulative percentage loss at Inverter level. This includes conversion efficiency loss, loss over nominal power, loss due to power threshold, night consumption etc.
L5 represents losses in transformers, AC power cables and transmission infrastructure (in percentage)

L6, **L7** can be any other loss parameter which plays a role in power flow (in percentage). These include imports, transmission line loss, auxiliary consumption, loss against reactive power or voltage support to grid etc.

All the above losses can be estimated with software, like PVsyst, to model the energy output from a certain project having fixed DC and AC capacity. In India, utility scale solar projects are allowed to inject a capped and pre-approved AC power. The cost of renewable energy has significantly decreased from 2010 to 2023, thanks in part to the affordability of modules. (*IRENA renewable power generation costs*).

With low-cost modules, it has become an industry norm to install 30% to 50% higher DC capacity than their pre-approved AC capacity, which means overloading inverters on DC side. This philosophy of overloading is a plus for both generating companies and distribution companies/grid controller, as the former can inject more power during early morning and evening hours and simultaneously the latter can rely more on renewables in overall energy mix.

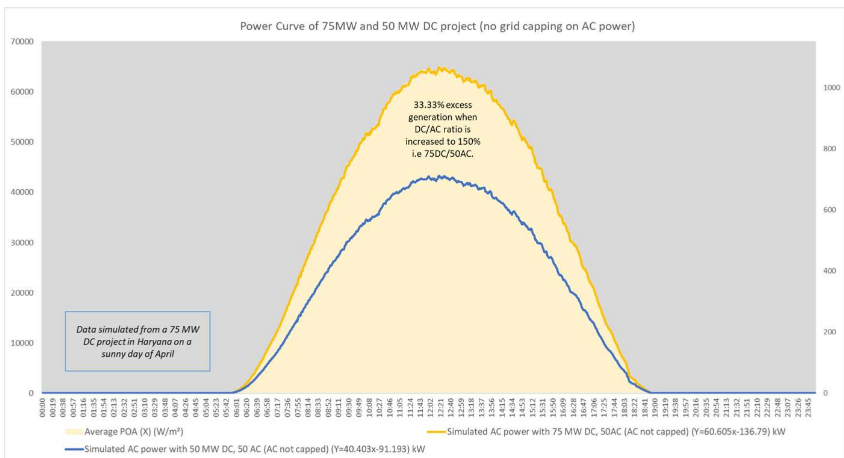

Fig. 2: One day power curve of a 75MW DC and 50 MW DC project without any limitation of evacuation on AC side. The yellow filled area below the line graphs represents Irradiance data on secondary axis.

In an uncapped plant, with higher DC to AC ratio, we can generate up to 33.33% more energy as compared to a system with the same DC to AC rated project. (Fig. 2)

Another key benefit of keeping higher DC to AC ratio can be seen from Fig. 3, where a solar plant with higher DC to AC ratio can pump more power in early hours of the day ($\gamma > \beta > \alpha$). The green curve shows the ideal case, where solar is able to generate at a fixed rated AC capacity from morning till evening. The downward trend in battery prices is resulting in a boosted desirability of the business case of energy storage integration during curtailment hours. (Fig. 3)

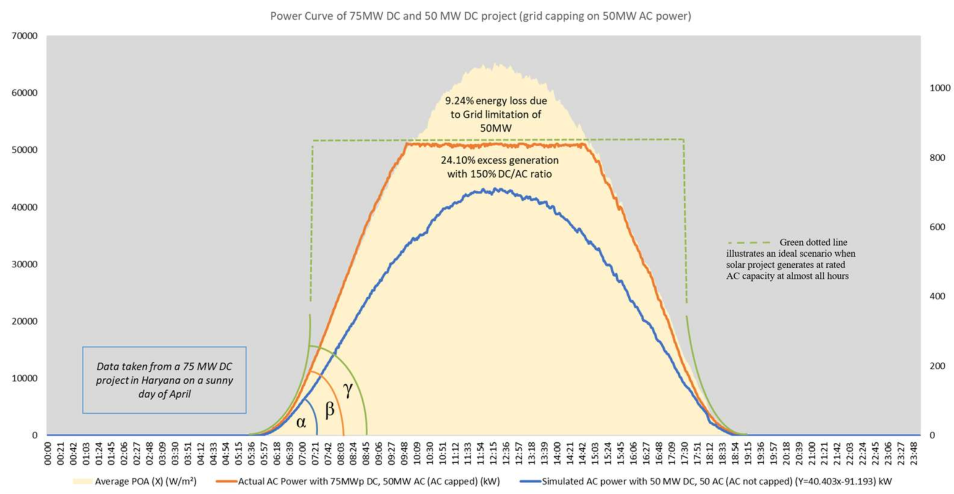

Fig. 3: Power Curve of a fixed 50 MW AC project with 75MW DC (orange curve) and 50 MW DC (blue curve). The yellow filled area below the curves represents Irradiance data.

4. Power governance through Inverters in Solar Projects

In all utility scale grid connected projects, there are stringent requirements to supply power of a desired quality. Power with desired frequency range, voltage range, current range, active-reactive power limits, harmonics and fast dynamic response to various grid events, are few of the requirements as per the grid code of India. These guidelines are enforced by CEA (Central Electricity Authority) through acts or legislation and CERC (Central Electricity Regulatory Commission) through various grid connectivity regulations. Solar Inverter, being the core component of this electricity conversion, is expected to meet all the applicable grid related guidelines.

Typical large scale PV Inverters can operate in three basic operation modes:

a. Voltage control mode: In this mode, the voltage of a reference point is monitored by PPC through inverters and reactive power drawl/ injection is varied accordingly with respect to a voltage set point.

b. Reactive power or Q-control mode: In this mode, the inverter supplies or absorbs a fixed amount of reactive power from the grid.

c. Power Factor control mode: In this mode, the inverters operate at the defined power factors.

There are many inverters which have additional capability to generate and absorb reactive power using a feature known as Night mode or Static VAR generator (SVG) mode. This feature has become a basic requirement in recent times as utilities are becoming increasingly dependent on RE generators for grid stability.

The absorption of reactive power by solar inverters in lean solar period has helped grid operators in reducing requirements of Transmission Line (TL) tripping and TL line isolations at many sub-stations in southern grid of India. As shown in Fig. 4, the PQ (active-reactive) capability curve of inverter showcases the range of reactive power support which can be given by each inverter in case of grid requirement. During the generation period, the energy from PV field is regulated by control algorithms of the inverter to govern the output power.

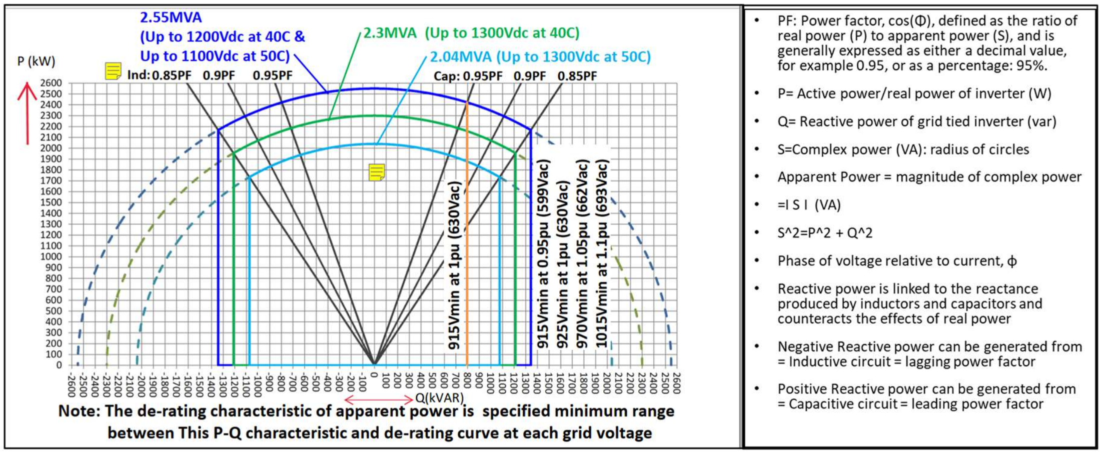

Fig. 4: P-Q curve of 2.55MW TMEIC Solar Inverter with Active/ Reactive power generation capability. The curve shows the various range of operations possible with TMEIC solar central inverter.

In Fig.4, Solar inverter nameplates mention 2.55MVA as its rated power. This rated power can be obtained when the Q value (on x-axis) is zero. With increased reactive power in output, the active power will be reduced by a certain percentage, thereby de-rating the inverter from its peak active power capacity. The above inverter has the capability to generate power with (-0.85) lagging Power Factor (PF) to (+0.85) leading PF, thereby supporting the grid whenever required.

5. Computation of Power loss in Solar PV Projects

For the accurate evaluation of real time energy loss in solar inverters, following parameters must be known:

a. DC capacity of inverter unit

b. Inverter power curve

c. Real time irradiance data

d. Performance Ratio of the inverters or complete power plant

e. AC Set Point conditions at Inverters and real time set point value through Power Plant Controller (PPC)

f. Real time data of inverter power output and grid limitation set point for complete plant

Curtailment at the inverter level can be calculated by evaluating lost irradiation for which solar array was not able to generate electricity. In any utility solar project there are ground based sensors to measure irradiation resource, typically at one minute interval. For electrical equipment, there are metering devices at various levels of solar power flow sequence to measure various parameters for control, monitoring, metering, and protection of equipment and for compliance to grid code.

Methodology of calculating expected power from a solar PV project

The energy generated from a solar PV field can be calculated from measured parameters by the following formula:

$$\mathbf{E_{out} = DC\ capacity*POA*PR} \qquad \textbf{(eq. 2)}$$

where,

E_{out} or Energy Output is the energy generated from a solar PV plant (in kWh)

DC capacity represents the rated capacity of modules installed in the solar project (in kWp)

POA or Plane of array irradiation is the total solar energy received on plane of array per m^2 of area, typically measured by pyranometers (in kWh/m^2).

POA or Peak sun hours (PSH) refers to the equivalent number of hours during a day when the solar irradiance (the amount of sunlight) received at a specific location is equal to an average value known as the "standard solar irradiance of 1000W/m^2." This is a calculated parameter for easy understanding of the irradiation quantum received at any specific location.

PR represents a measure to tell how effectively the power plant can convert sunlight collected by the PV panels into AC energy, which then gets delivered to the grid. It is a relative measure of electricity conversion with respect to what was expected from the plant nameplate rating in DC or kWp. This PR metric quantifies the overall effect of losses due to inverter inefficiency, wiring, cell mismatch, elevated PV module temperature, reflection from the module front surface, soiling, system down-time, shading, and component failures (as per *IEC 61724-1*).

For calculating the curtailment loss, we will utilize the same formula (eq. 2) with certain thresholds and boundary conditions as follows:

In Microsoft Excel data tables, the current methodology calculates curtailed energy with below conditions on DateTime data, Power data and Irradiation data. The power will be considered as curtailed when these conditions (steps 1-3) are qualified.

Step 1. Time shall be >04:00 and < 20:00

Step 2. Inverter power >= 100% or Inverter power >= set maximum power at which inverter is operating

Step 3. Minimum Radiation value threshold at which each inverter reached peak AC power. This is calculated by using relational condition or lookup function of excel. Record and note down each minimum irradiance value (from complete irradiance data of the day) where value of individual inverter active power reached >2500 kW or >set peak power point.

Step 4. Now, compute the Count of instances, where the active power of inverter has reached the peak power. At all these instances, Inverter AC power (kW) >= 2500kW AC.
For e.g. Count the number of instances when the orange data bars of power have hit the flat line as in Fig. 5.

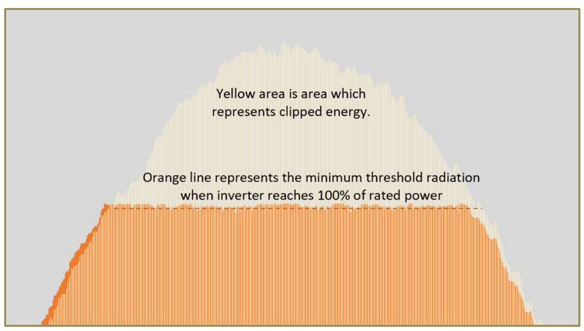

Fig. 5: Bar graph of minute wise Inverter Output Power trend (orange) and Irradiance trend (pale yellow)

Step 5. At all instances captured in step 4, we compute the excess radiation, when all above conditions are met. We do this by subtracting each real time radiation data point from the value calculated in Step 3 above. With this, we will be left with only radiation values which are above the minimum radiation at which clipping starts at each inverter. In other words, we will be left with all the bars which are above the dotted straight orange line as in Fig. 5. This is called as “excess radiation” or “clipped irradiation” which could not be converted into real power.

After computation of excess irradiation, we can replace the POA factor in eq. 2 with cumulative lost radiation (calculated in Step 5) for that day or period of measurement. Inverter level PR for that day or period shall be used in eq. 2 for calculating the clipped energy in that period.
Note: To compute irradiation in kWh/m^2 from irradiance data in W/m^2, one can multiply sum of irradiance values with time interval (1 min in our case) and divide by 1000 to get irradiance value in kW/m^2 and again divide by 60 to get Irradiation in kWh/m^2.

The results from eq. 2 give us the kWh lost due to curtailment. This curtailment can be because of any reason specified in *Section 6 Table 1* below.

Note: For the PV projects which have installed PPC, the data record of set point command values given to each inverter, at every minute interval, shall be used to decide inverter AC set points. In absence of this data, accurately computing the inverter level clipping loss becomes very difficult because minimum irradiance value required at clipping time will vary a lot, with dynamic power set points given by PPC every few minutes. With PPC controlling the inverter AC set points, power curtailment will not be a straight line for all inverters, and one cannot tell with certainty that inverter is generating less power due to any set point/soiling factors/reactive power/voltage control mode or mix of reasons thereof.

6. Power Governance and Control Techniques in Indian context

With the increasing share of non-conventional energy sources, the need for governance of power through integrated resource planning has increased significantly. It includes demand forecasting, generation resource adequacy planning and transmission resource adequacy assessment etc.

In context of Indian grid, RE plants are given must run status by The Indian Electricity Grid Code, 2010 (IEGC) in Regulation 5.2(u), which casts a statutory duty on the SLDC (State Load Dispatch Center)/RLDCs (Regional Load Dispatch Center) to make all efforts to evacuate available solar and wind power. As per IEGC, RE generation is considered as "Must Run", subject to the grid security, the security of personnel and equipment and ensuring that Curtailment of RE generation is avoided.

As per the grid-code, "Curtailment" means a reduction in the output of a generator from what it could otherwise produce with the given available resources, typically on an involuntary basis. The term curtailment is broadly used to refer to the use of less wind or solar power than is potentially available at that time. Below are a few critical scenarios where power is governed by generators as per the guidelines issued by Central Electricity Bodies (CERC, CEA) or SLDC which is a Government State Electricity Body. In India, as per the working committee of *Forum of Regulators Report* on *"Model Guidelines for Management of RE Curtailment for Wind and Solar Generation November 2022"* and CERC Regulations *"Indian Electricity Grid Code 2023"*, Renewable Energy curtailment can happen in below cases:

Table 1: Curtailment Scenarios of Renewable Energy Projects

Curtailment scenarios of Renewable Power	Power governance and control philosophy
System design overloading: Interconnecting transformer (ICT) loading limits, Solar Inverter Ratings, Turbine ratings etc.	Onsite Curtailment at plant level: Curtailment is done by switching off equipment (wind turbines) or by controlling output power of Solar Inverters through Power Plant Controllers
System Wide Oversupply: Intra-state or Interstate Underdrawal or Over-supply	Underdrawal by State at state periphery outside the range of 250 MW for two or more successive time- blocks will initiate power controls at State transmission Utility/SLDC level. In lean or high renewable seasons, the variation of energy cannot be dynamically absorbed by grid. In such cases, curtailment instructions are executed at generator level to ensure their supply is within the demand band or forecasted power levels.
Transmission constraints: Planned or Unplanned Grid unavailability or Thermal limit of transmission lines as per CEA *(Manual of transmission planning criteria, 2022)*	In cases of grid infrastructure limitations, the RE projects are required to curtail at plant level and not inject scheduled power to grid.

Grid Stability and System security requirements: 1. Guideline of Isolation and Islanding as per CEA guidelines 2. Ramp up or Ramp down of power 3. Install AVR (Automatic Voltage regulator), PSSs (Power system Stabilizers), VAR (Volt amp reactive or Voltage Controller devices), and PPC (Power Plant Controller) 4. Install UFRs (under freq. relays), have frequency controls and reserves. 5. System Protection scheme as finalized by regional power committee or SLDC/RLDC. 6. Operating in steady state voltage range as specified by CEA Grid standards.	In Events of grid voltage issues, frequency disturbances, both demand side management and supply side management controls become effective. For e.g. All Discoms and STUs shall have UFR (under frequency relays) for load shedding in case of frequency decline which could result in grid failure. On supply side, as primary responses, generators shall have ramp up and ramp down capability of +/-5% to +/-10% of their MCR (Max. Continuous Rating), as the case may be. When the frequency falls/rises suddenly, generator can provide this primary response. Voltage Control reserves: Voltage Control reserves shall be deployed for controlling the voltage at a bus or sub-system through reactive power injection or withdrawal.
Operating Frequency band: National Reference Frequency is 50.000 Hz. Allowable operating band: 49.900-50.050 Hz	When average frequency for two or more successive time-blocks exceeds 50.050 Hz or falls below 49.900, then NLDC, RLDC, SLDC shall utilize the controls through various available primary/secondary/tertiary control reserves as specified in *Indian Electricity Grid Code 2023*
Inadequate grid availability or infra-deficit in RE rich states – leading to curtailments	Commands are given to different generators when there is no evacuation infrastructure to cater to the extra generation in peak resource season i.e. high wind or high sun seasons
Commercial interest of discoms (coal power related fixed charges and procuring cheaper electricity) and Maintaining Technical minimum margin for Thermal Power Stations (TPS)	In times of excess renewable energy, discoms cannot purchase all the low cost renewable power as there are minimum plant load factor commitments (55% for intra-state thermal as per state grid code) and fixed price PPAs for conventional power generating projects. In these cases, excess renewable is curtailed.

The above table lists some of the scenarios wherein RE generators can be asked to curtail power. There are other mechanisms like Deviation Settlement Mechanism (DSM), time of day tariffs etc. to discourage generators from supplying excess or infirm power into the grid. *Indian Electricity Grid Code 2023,* related to power sector in India published by CERC captures all mechanisms of governance of conventional and RE power.

7. Utilizing Curtailed Energy

The energy not evacuated into the grid due to reasons attributed to power limitation factors can be utilized in other forms by advanced power management and control systems. The excess generation at the plant level can be utilized in various other applications as below:

- Battery storage and other storage technologies
- Green hydrogen production
- Selling in Real time market (RTM)
- Demand balancing by reducing loads, time of day pricing
- E-mobility sector (charging energy banks)
- Ancillary services and support to grid

All these services will not only improve the returns from the existing assets but will also help the grid in supplying electricity in non-generation hours. The current reverse auctions in Indian solar markets emphasize on providing round the clock energy from renewable sources with integrated storage technologies.

8. Conclusion

With renewable capacities growing at exponential rates across major geographies, the need for advanced energy management systems is also increasing. Energy management systems at project level and grid level along with the help of advanced machine learning models will help in balancing the intricacies of supply and demand side. Government bodies across the globe shall develop policies which support renewable sector by low-cost financing and other policy instruments. Amidst the ever-changing political landscapes, different international bodies shall jointly build a knowledge base of solutions to tackle the new challenges of this sector. The current paper highlights the pace of deployment of RE projects and policies which are also changing with the needs of a stable grid and electric infrastructure as electricity will be the basic right of the next generation. In this paper, computation of losses in RE due to governance of power at various levels have been quantified. The potential commercial advantages of strategies to utilize this unused energy of the system has also been highlighted. This will help policy makers, power plant operators, and the research communities in understanding the nuances of a solar plant and grid related system criteria and developing strategies to tackle new challenges of the RE sector.

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