Novel Solution to Mitigate Thermal Plant Flexibilization Issues along with Meeting Peak Demand by Integrating Thermal Energy Storage System with Thermal Power Plant: A Comprehensive Review and Analysis

Pankaj Kumar Gupta[1], Dipankar Halder[2], Sankardas K[3]

Energy Transition and Policy Research, Engineering Division, NTPC Limited, Noida

Abstract: ***The rapid increase in renewable energy penetration forces thermal plants to operate in a more flexible mode, with thermal power plants assuming a pivotal role in meeting peak demand and supplementing periods of low RE generation. In flexible operation, thermal power plants will face more load variation from high load to load far below design limit and faster ramping rates. This flexible operation, particularly low load operation of thermal power plants, have severe detrimental effects in boilers. This aggressive operation result in heightened thermal and mechanical stresses in the boiler and its downstream equipment, potentially leading to irreversible damage and reduced life span. Indian boilers, inherently larger due to lower Gross Calorific Value (GCV) and higher ash content of indigenous coal, face added complexity at lower load operation of boiler such as flame instability leading to forced outage, reduced efficiency, increased auxiliary power consumption, heightened slugging and fouling in addition to most detrimental effect of reduction of equipment life. Innovative solution of Thermal Energy Storage system integrated with thermal power plant can help in avoiding both low load and severe cyclic operation of steam generator, thereby addressing the challenges associated with flexible plant operation. This solution can also be used to supply additional power to balance demand supply gap during the peak hours using existing thermal plant infrastructure without additional thermal power capacity addition. In this paper, a detailed study on Thermal Energy storage integration with thermal power unit along with case studies for an Indian 500MW unit is presented. This paper analyses various options of charging & discharging strategies. Further, details with respect to design factors to determine TESS Integration Strategies & Role of Charging Steam, Selection of Compatible and Efficient Charging Options and TESS Discharging Options for different use cases is also deliberated. This paper describes distinctive Advantages of TESS which make it well - suited for Integration with TPP.***

Keywords: Thermal Energy Storage System, Renewable Energy Integration, Thermal Power Plant, Flexibilization, Peak Demand

1. Introduction

The global push towards achieving net zero emissions has spurred a rapid increase in the adoption of renewable energy sources. Embracing renewables offers a pathway to decarbonizing our energy systems and mitigating the impacts of climate change, driving us closer to a sustainable, “net zero” future.

The increasing penetration of renewable energy into Indian grid has brought its own challenges to our predominantly fossil fuel - dependent Power sector. The rapid increase in renewable energy (RE) penetration has necessitated a shift towards more flexible operation of thermal power plants. With renewables like solar and wind contributing an increasing share to the energy mix, thermal power plants are now required to provide balancing power to manage grid stability effectively. In this evolving landscape, thermal power plants play a crucial role in supplying peaking power during periods of high demand or when renewable generation is low. However, this has resulted in several operational challenges for thermal power plants, requiring them to adapt their generation schedules and ramp rates to accommodate fluctuations in renewable energy output, ensuring grid stability and reliability while integrating a higher share of renewables into the energy mix.

In flexible operation, thermal power plants will face more frequent start - ups and shut - downs, load variation from high load to load far below design limit and faster ramping rates in order to balance the grid. This flexible operation, particularly low load operation of thermal power plants has severe detrimental effects in boilers. This aggressive operation will cause larger and more periodic thermal and mechanical stresses in the equipment of thermal power plants, which may lead to irreversible damage if the maximum stress limits of the material are exceeded. Creep and fatigue are the main damage mechanism that grows cracks in highly loaded condition even if proper control strategies are followed, which ultimately leads to lack of reliability of the equipment and plant. Large boiler size exacerbates issues during lower load operation below Technical Minimum load. Indian boilers, inherently large due to lower Gross Calorific Value (GCV) and higher ash content of indigenous coal, face added complexity. Lower load operation of boiler leads to severe detrimental effects such as flame instability leading to forced outage, variation and deterioration of steam quality resulting in direct impact on downstream equipment like TG set, decreasing efficiency, increasing auxiliary power consumption, heightened slugging and fouling in addition to most detrimental effect of reduction of equipment life.

Considering the above challenges being faced in the operation of thermal power plants, it becomes mandatory to adopt innovative and effective strategies to save thermal power plants from these issues. NTPC being the largest Power

Producer in India, is at the forefront of efforts to enhance the reliability and resilience of thermal power plants in the face of these evolving energy landscapes and it is explored that installation of Thermal Energy Storage Systems (TESS) integrated with thermal power plants is one such step which can help in avoiding the low load and severe cyclic operation of steam generator.

Further, India being a fastest growing economy, energy demand is expected to be grown in multifold. At country level, demand profile of India is unique. A significant gap between average power demand and peak demand persists, which is expected to be widened further with due time with the growth of the power sector. This typical characteristic of Indian Power supply system demanded massive capacity addition of thermal plant just to meet the projected peak demand during non - solar hours. As a result, these additional capacity addition with huge capital investment will be underutilized. The above innovative solution of TESS integrating with Thermal power units can also be used for additional power generation during peak hours by discharging TESS energy using a new set of Turbine - Generator set. This unique way of TESS integration can be proved as a solution to meet growing peak demand by using existing Thermal plant infrastructure and resolve the challenges being faced for massive thermal power capacity addition.

1) Thermal Energy Storage System (TESS)

Figure 1: Thermal Energy Storage System

Thermal energy storage systems (TESS) have distinctive characteristics. It can be charged using both heat and electricity as well as discharge energy in the form of heat energy and electricity. This ability of Thermal energy storage makes it unique from other types of Energy storage and it gives flexibility in wide application especially for the case where requirement of charging is using heat energy and discharge is also as heat energy. Advancement of this technology, involving use of static type storage medium such as crushed rock, graphite, concrete, etc. make it more efficient, compact. It can be designed to extract a major part of heat including latent heat while charging with steam. Similarly, during discharge, it can convert water into superheated steam which can either be used for electricity generation or in process Industry.

2) Innovative solution of TESS Integration with Thermal power plant

Due to its unique ability as discussed above, Thermal energy storage (TES) systems can be efficiently integrated with thermal power plants to mitigate the challenges associated with the flexible operation as well as used to generate additional power during peak hours.

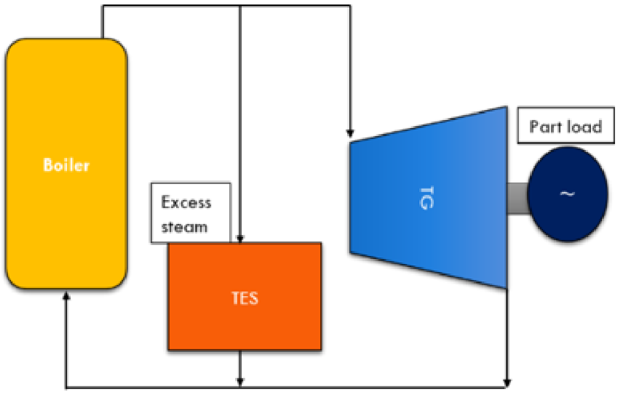

Figure 2: TESS Charging Scheme from TPP

During low demand from the Thermal plant, the boiler is maintained at, or above technical minimum load and the surplus steam is utilized to charge the storage medium. This is done by circulating superheated steam generated by the boiler through storage medium. As the superheated steam pass through the block, they transfer thermal energy to the storage medium, raising its temperature and condensate generated from Thermal Energy Storage System is further fed to Thermal plant feed water cycle by integrating with condensate line of Thermal power unit. Basic charging scheme of TESS from thermal Plant is shown at Figure 2. The storage block acts as a thermal battery, storing the heat energy until it is needed. This helps in ensuring boiler operation above technical minimum load while TG load is adjusted as per the grid demand. This also helps in avoiding frequent cyclic operation of boiler thereby reducing the impact of Thermal stress and fatigue.

When electricity demand increases, the stored thermal energy can be used in two ways. One way is, it can be retrieved by circulating feed water from feed water cycle of thermal plant through the storage block to generate superheated steam which is then integrated to a suitable point into the power cycle to generate electricity, allowing the power plant to operate more flexibly and efficiently while meeting fluctuating demand patterns and grid requirements. Another way is stored energy can also be used using a separate turbine generator set with independent power block to generate additional power to meet peak hour requirements. Basic Discharging scheme of TESS showing both options are shown at Figure 3.

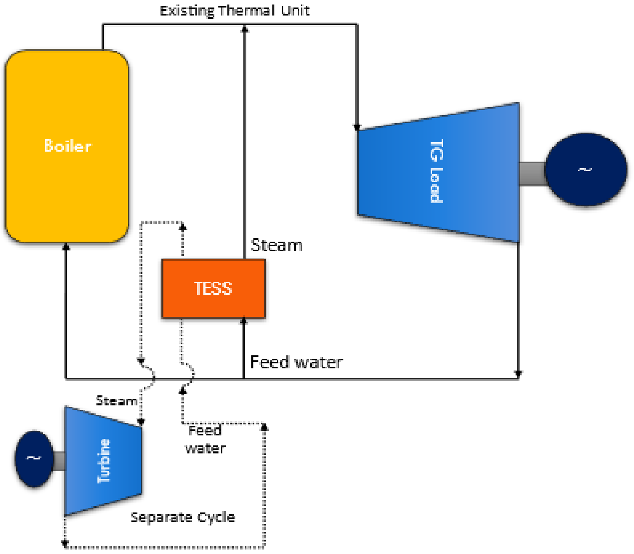

Figure 3: TESS Discharging Cycle scheme

3) Design Factors to Determine TESS Integration Strategies & Role of Charging Steam

Charging TESS with steam from thermal power plants can be done during part load operations, providing a valuable opportunity to optimize energy utilization and balance supply and demand dynamics. Designing the charging strategy of the TESS with steam from Thermal power plant involves multiple factors.

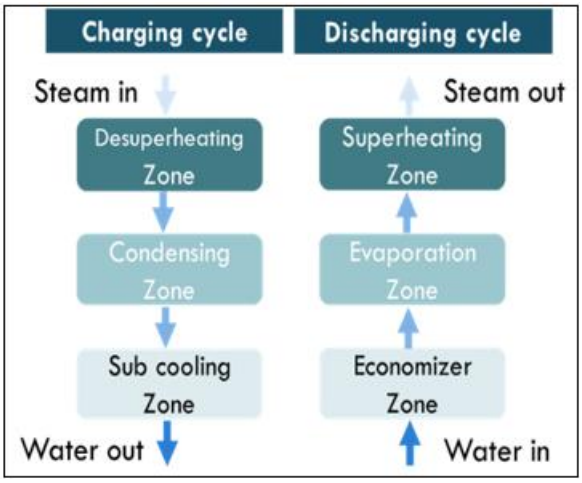

Figure 4: Zones of TESS charging & Discharging

- The steam used for charging the steam should be at high temperatures and pressures so that the energy per unit volume is high. The high energy density allows for the storage of large amounts of thermal energy in a relatively small volume, thereby reducing the size of the TESS unit. Further, high - energy steam can rapidly charge thermal energy storage systems, enhancing the flexibility and reliability of energy storage systems.

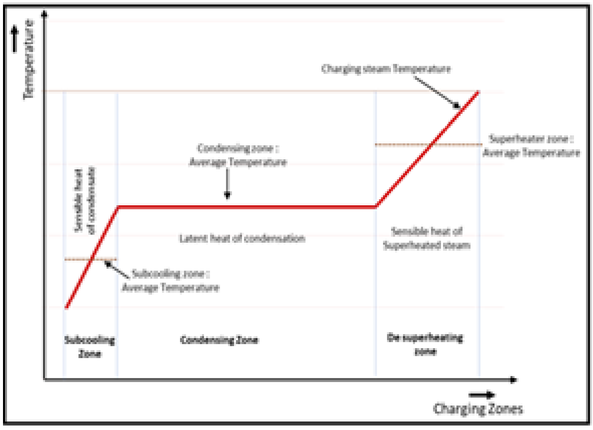

Figure 5: Charging steam profile at TESS Zones

- The charging of TESS is to be designed in such a way that maximum thermal energy of the steam is transferred to the storage medium in order to achieve maximum overall efficiency of the system. In addition to this, it is to be ensured that the charging steam condenses completely into liquid medium to ensure seamless integration back into the condensate cycle of the thermal plant. Accordingly, the extraction of thermal energy from charging steam should be ensured through three distinct stages. Sensible heat of superheated steam, latent heat of condensation, which accounts for nearly 60% of the energy content is captured, and finally the sensible heat from the sub - cooled condensate, stored in superheated zone, condensing zone, and sub - cooling zone respectively of Thermal Energy Storage block. These three zones will act as Superheater, Evaporator and Economizer respectively during the discharging cycle as shown in Figure 4.

- The temperature and the pressure of the charging steam plays a crucial role in determining the steam characteristics of the discharge cycle. Higher the differential pressure between charging steam and required discharge steam, more will be the differential temperature between stored energy at evaporator zone and saturated temperature of discharge steam (as shown in Figure 6), which interns will help to extract maximum heat from storage media and will make the storage block of lower size and hence more efficient and economical. Moreover, this higher differential temperature allows it to attain the required output temperature at a faster rate, and the system will be able to maintain the required output temperature for a longer duration which is essentially required for integration with thermal power unit. Also, high charging temperature allows to generate steam of higher temperature during discharge. However, a constraint arises when output pressure is lowered beyond a certain limit. Since the TESS discharge steam needs to integrate back into the power cycle, there must be a point where the TESS discharge steam parameters match those of the power cycle. So, as the discharge pressure is reduced beyond a certain value, it may not be feasible to integrate the same into the power cycle. Moreover, in case of discharge cycle for generating additional power using independent Turbine Generator set, steam at low pressure and temperature will make the system inefficient and increase the capacity of TESS.

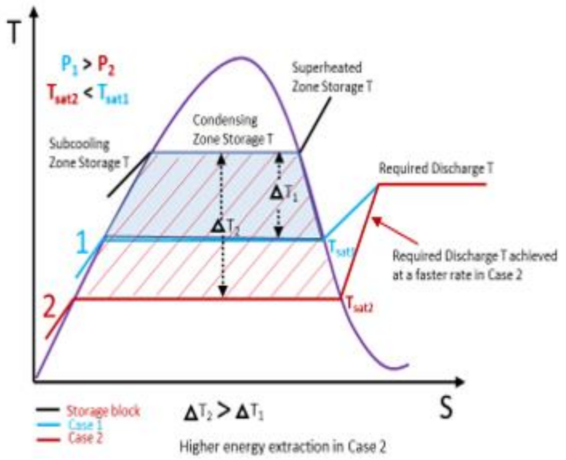

Figure 6: TESS Discharging Cycle

Conversely, if the pressure of the feed water is increased during discharge cycle, the saturation temperature also increases, which, in turn reduce differential temperature of storage media at evaporator section and saturation temperature of discharge steam, resulting in increased size of the TESS unit.

4) Selection of Compatible and Efficient Charging Options (A case Study for 500 MW)

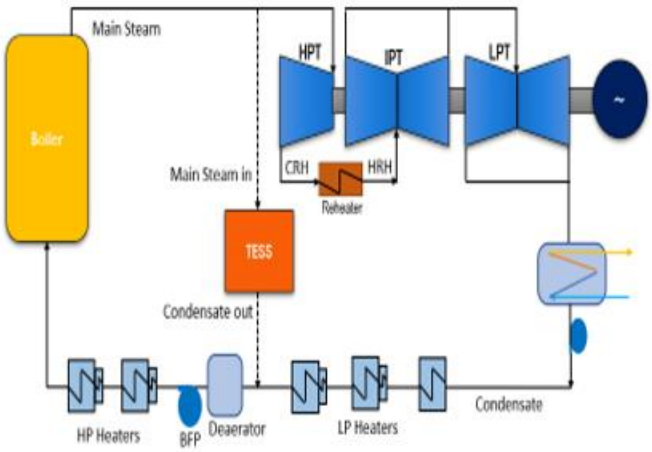

Figure 7: TESS Charging with Main Steam of TPP

For analyzing the integration of TESS with the Thermal power plant, case of a typical 500 MW Thermal power unit is considered. There are mainly three points in the steam circuit from where high energy steam can be extracted for charging the TESS block. The Main steam line, Cold Reheat line and the Hot Reheat line.

a) Charging with Main Steam:

Charging of the TES is done during periods of low demand from Thermal plant. Under such conditions, Thermal plant output shall be maintained as per grid demand whereas the boiler shall be maintained at a loading of 50% or above. Steam extraction from the Main Steam line (103 KSC/537^{0}C) is utilized for charging the TESS. The superheated steam interfaces with the TES blocks, thereby charging the TESS. Following the heat transfer process, the resultant condensate is connected back into the feed water cycle after appropriate pressure reduction mechanisms for a seamless integration at the inlet of the deaerator.

This approach offers several advantages. As the steam tapping is from the Main steam line, the energy density is high enabling rapid charging and efficient storage of thermal energy. Further, as the tapping is before any of the Turbine modules. There shall be no load unbalance among the HP, IP and LP Turbine modules. Since the charging steam pressure is 103 KSC (corresponding Saturation Temperature of 312^{o}C), it will be possible to generate steam during TESS discharge with a reasonably high saturation temperature and pressure so that it can be seamlessly integrated with the power cycle. For example, if we analyze a case of discharge steam with saturation temperature of say, 265 ^{o}C (below the saturation temperature of Charging steam), this corresponds to a pressure of 52 KSC. This saturated steam can be further superheated in the superheater section of the TESS block to the required temperature and can be discharged (during full load conditions) into the Power cycle at CRH after matching the steam parameters. As the charging steam temperature is higher (537^{o}C), discharge steam of high temperature (approx.440 - 450^{o}C) is possible to generate. Due to the possibility of generating steam of high pressure and temperature, this charging option is the most efficient option for the case of generating additional power using independent Turbine Generator set during discharging.

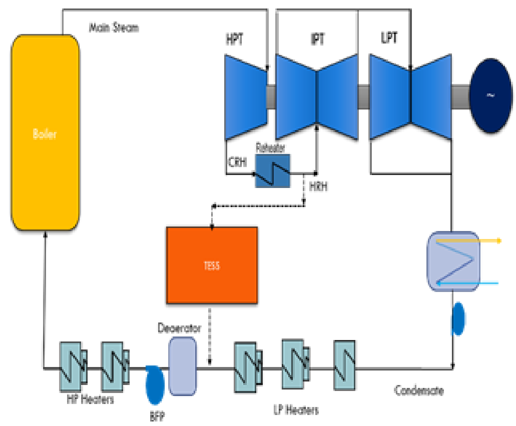

Figure 8: TESS Charging with HRH of Thermal Power Unit

b) Charging with Hot Reheat Steam

Another option of charging the TESS is from the Hot Reheat line of the Thermal unit. The advantage of this charging route is that the Energy density of the HRH steam is higher and hence facilitates efficient charging of the TESS. However, on the flip side, this charging method can cause load distribution unbalance among different Turbine modules. Also, the lower pressure of the charging steam (20 KSC at 50% load) restricts the pressure of the discharge cycle well below this value. This makes it impossible for integrating the steam during the discharge cycle to the power cycle (During full load). Moreover, due to its inability to generate steam of high pressure, it makes the discharge cycle inefficient and hence increases the size of TESS for the case of generating additional power using independent Turbine Generator set during discharge.

c) Charging with Cold Reheat Steam

A third option for charging the TESS is by using the steam extracted from Cold Reheat line.

But this option may not be suitable as the energy content of the steam is already on the lower side and this extraction can

Paper ID: SR24612093926 DOI: https://dx.doi.org/10.21275/SR24612093926

cause disturbance in loading of the Turbine modules as well as unbalance in boiler heat duty. Also, the low - pressure steam used for

charging (23 KSC) will cap the discharge pressure to further lower values rendering it impossible to integrate back into the cycle. Moreover, low charging steam temperature (310°C) limits discharge steam temperature to a very low temperature (Approx.220 - 230°) which may not even be suitable for power generating option also.

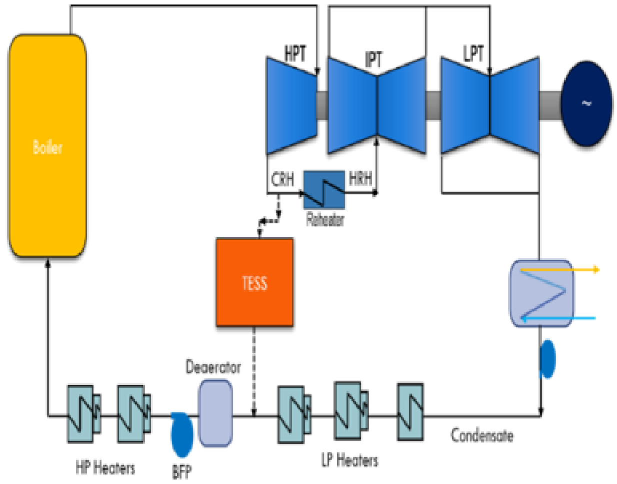

Figure 9: TESS Charging with CRH of TPP

Considering all the factors as elaborated and as summarized in Table 1 below, it may be concluded that charging with Main Steam is most suitable and efficient option for both the cases i. e discharge cycle integration with thermal cycle and generating additional power using independent Turbine Generator set during discharging.

Table 1: Comparison of Charging Options

Options	Steam Tapping Point	Pressure (KSc)	Temperature (Deg C)	Issue	Remark
Charging with Main Steam	MS	103	537	High pressure steam connection required.	Best suited solution
Charging with Hot Reheat Steam	HRH	20	565	Pressure difference while discharging is not available.	Not economic solution as it will require higher size of TESS.
Charging with Cold Reheat Steam	CRH	23	310	Major energy available at 220 deg C	Not Suitable for integration

5) TESS Discharging Options for Different Use case

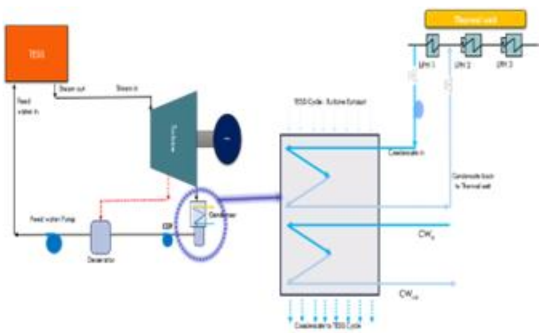

Figure 10: Discharging to same Power Cycle

Depending upon the requirement, discharge cycle can either be integrated with thermal power unit itself or an independent power block, consisting of new set of Turbine generator, may be used to generate power using generated steam from TESS.

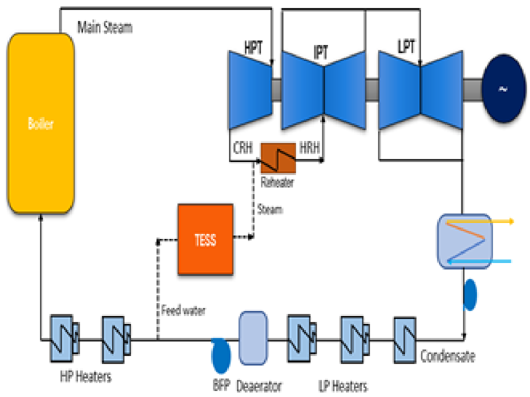

Figure 21: Discharging in separate power cycle

a) Discharging to CRH line

One way of discharging the TESS is by generating superheated steam using the energy in TESS and integrating back into the power cycle as shown in Figure 10. For this, feed water is taken from the feed water system of the thermal unit (during full load conditions) and is passed through TESS where it is converted to superheated steam. Subsequently, the superheated steam is integrated back to the power cycle at a suitable point after matching the TESS discharge steam parameters with that of the Power cycle.

A probable scheme is shown here. Feed water is taken from the discharge of the BFP and after required pressure reduction, it is passed through the TESS. Feed water absorbs the heat energy in the TESS and gets converted to superheated steam which is then connected to the CRH line in the power cycle**.** This option is found most feasible while integrating with the existing steam cycle of thermal power unit during discharge and it will be applicable for the case when no additional power supply beyond thermal power capacity is required during peak hours.

b) Discharging in a separate cycle for additional Power
As discussed, considering Indian future power demand scenario where a significant gap is expected between peak demand and average demand, alternate way of TESS integration with thermal plant for supplying additional power during peak hour will be more relevant.

In this option the energy stored in TESS is discharged in a separate independent power cycle as shown in Figure 11. Here, the TESS is used for generating superheated steam which is then passed onto a new Turbine Generator set in a separate cycle to generate power. This method enables the operator to generate additional power over and above the unit capacity which can be utilized during peak demand hours. This option will benefit in two ways, first to mitigate issues that arises due to flexibilization of Thermal Plant and secondly, it can supply additional power to balance demand supply gap during the peak hours using existing thermal plant infrastructure without additional thermal power capacity addition. This unique way of use TESS is most relevant and innovative option in India's perspective.

Innovative solution to enhance efficiency:
Overall efficiency of integrated Thermal energy storage can further be enhanced by introducing an innovative scheme of utilizing waste heat of turbine exhaust. In this scheme Condensate from Condensate Extraction Pump outlet of Thermal power unit is diverted and used as condenser cooling water for new power block. The latent heat of new turbine exhaust will heat the existing unit condensate and raise its temperature reasonably. This heat addition from external source to condensate cycle of the thermal power unit will improve the heat rate of existing unit which interns will enhance the overall efficiency of integrated Thermal energy storage system.

Distinctive Advantages of TESS Make Well - suited for Integration with TPP
Use of Thermal Energy Storage for the discussed innovative solution to mitigate flexibilization issue of thermal power plant has several advantages over the other options. TES systems are inherently compatible with the thermal processes involved in power generation. They can easily integrate into existing thermal power plant infrastructure, such as boilers and steam turbines, without significant modifications. This makes them a convenient and cost - effective option for enhancing the flexibility and efficiency of thermal power plants. TES for heat - to - heat application i. e charging with heat energy and discharging as heat energy, is the most efficient option which can offer efficiency more than even 95%. TES systems have high energy densities and can store thermal energy for long durations. This is advantageous for thermal power plants, as it allows them to store excess heat generated during off - peak hours and use it to generate electricity during periods of high demand, improving overall plant efficiency and grid stability. TES systems can be more cost - effective compared to other storage solutions for this application, especially for large - scale integration with thermal power plants. The materials used in TES systems, such as graphite or crushed rock, are often abundant and relatively inexpensive, making them economically viable for energy storage applications. TES systems are known for their durability and reliability, with long lifecycles and minimal maintenance requirements. This ensures continuous and reliable operation when integrated with thermal power plants, reducing downtime and operational costs.

Overall, the distinctive advantages of thermal energy storage systems make them well - suited for integration with thermal power plants, offering opportunities to improve efficiency, grid stability, and overall performance while reducing costs and environmental impact.

2. Conclusion and Way Forward

This novel solution of TESS integration with thermal power plants will play crucial role to mitigate all the major challenges being faced/ will face in future due to RE Integration and increase peak demand in the operation of thermal plant and balance supply demand gap during transition period of India. It will prevent boiler operation below Technical Minimum Load, ensuring optimal and safe operation. This solution will mitigate the occurrence of frequent cyclic operations, both during ramp down and ramp up. TESS can act as an effective buffer for storing surplus heat during ramp down and as a thermal reserve during ramp up. This minimizes major boiler issues such as heavy creep fatigue interaction, stress impact. TESS integration facilitates smoother control over ramping operations, enabling more precise adjustments in power generation levels while maintaining system stability. TESS contributes to efficiency enhancements within thermal power plants, optimizing energy utilization during varying demand cycles. Most importantly, this solution can be utilized for generating additional power which comes useful particularly during peak demand hours and hence helps to avoid requirement of additional thermal plant capacity addition just to meet peak demand.

India's perspective where thermal power plant is and will remain of critical component of energy mix, at least for next few decades to assure energy security of the country and supply affordable and reliable power, this innovative solution of TESS integration will open a new door to solve the most burning issues of coal plant operation i. e., flexibilization with an added advantage of supplying additional power during peak hours. This solution will help seamless integration of increased RE penetration.

References

[1] Report on optimal generation capacity mix for 2029 - 30. Version 2.0, April 2023, CEA, MoP, Govt of India
[2] https: //e2s - power. com/
[3] https: //bren - energy. com/
[4] Figure 1: Source: https: //advanceseng. com/sulfurtes - next - generation - thermal - energy - storage/

Author Profile

Pankaj Kumar Gupta, General Manager, Energy Transition and Policy Research, NTPC Engineering Office Complex, Noida. He has more than 30 years' experience in thermal power plants in engineering and Operation & maintenance of Steam Generator. Out of which, more than 24 years of experience in Engineering and design of subcritical and supercritical Steam generator & its auxiliaries, Electrostatic Precipitator (ESP) and other Environmental systems like FGD & De - NOx system.

Dipankar Halder, Addl. General Manager, Energy Transition and Policy Research, NTPC Engineering Office Complex, Noida. He has more than 23 years' experience in thermal power plants in all areas of plant in engineering, engineering services and operation & maintenance. Out of which he worked 17 + years in engineering and design of CHP, Turbine, Ash handling, FGD, Boiler, system engineering, ACC, FOH and Layout. He was key engineering member of NTPC team for NTPC's only international project in Bangladesh where widened his experience in almost all the area of engineering. In O&M, he headed mechanical maintenance team and has experience in O&M of CHP.

Sankardas K, Manager, Energy Transition and Policy Research, NTPC Intelligent Office, Hyderabad. He has more than 12 years' experience in thermal power plants in operation & maintenance. He has worked in CHP operations and Maintenance planning sections. His present portfolios include long duration energy storage, Biomass cofiring in boilers and waste to energy.

List of Abbreviations

RE……………Renewable Energy
GCV…………Gross Calorific Value
TG……………Turbine Generator
TESS…………Thermal Energy Storage System
TES………… Thermal Energy Storage
MW………… Mega Watt
HPT………… High Pressure Turbine
IPT…………… Intermediate Pressure Turbine
LPT……………Low Pressure Turbine
MS…………… Main Steam
CRH……………Cold Reheat
HRH…………… Hot Reheat
BFP……………. Boiler Feed Pump
LPH……………. Low Pressure Heater