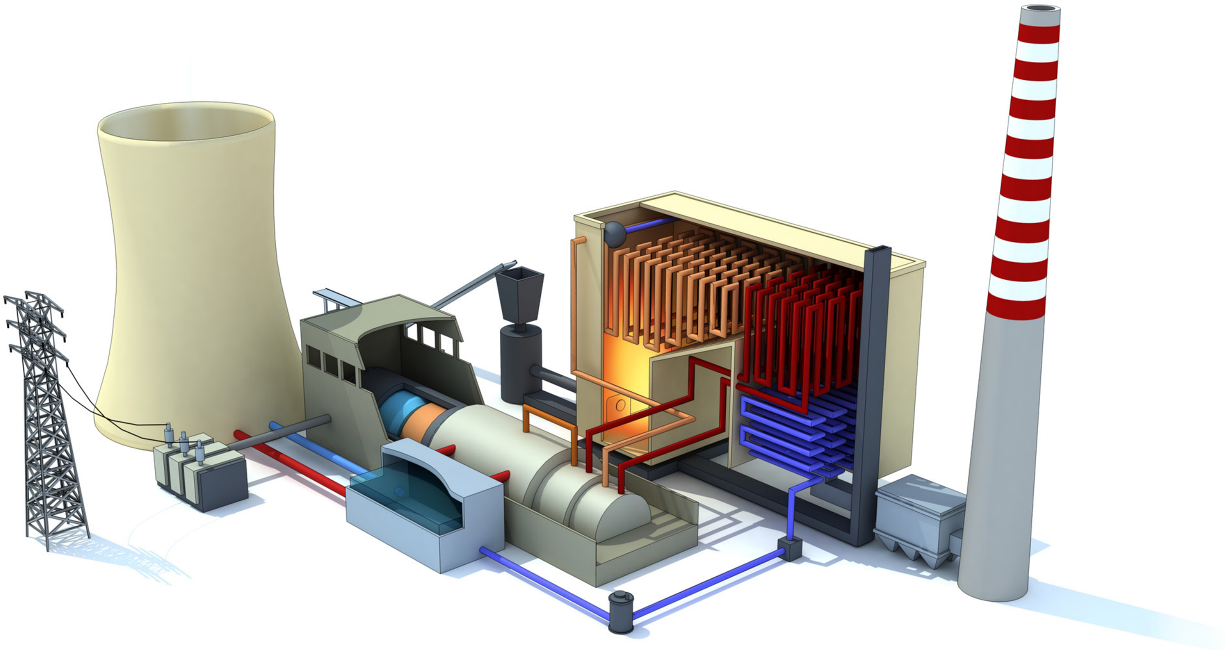

Thermal Electricity Storage in India

Retrofitting Potential for Coal-Fired Power Plants in India

October 2021

This study was conducted and funded as a project of the Indo-German Energy Forum

Indo-German Energy Forum

Federal Ministry for Economic Affairs and Climate Action

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1 Background

This study is conducted under the auspices of the Indo-German Energy Forum (IGEF). The IGEF was founded in 2006 in order to intensify and deepen the strategic political dialogue about the ongoing energy transition in Germany and India. Since then, it has served as a communication platform for networking research institutions, political decision-makers, banks and the private sector in both countries. Many strategic co-operation projects have been initiated between German and Indian partners.

To ensure the power supply in the country, India needs to double its electricity production capacity by 2030. The Indian government has also set ambitious goals for the expansion of renewables – 100 GW for solar PV and 60 GW for wind should be installed by 2022. According to Prime Minister Modi this goal will be expanded to 450 GW in 2030. Currently the renewable capacity excluding hydro accounts for 99 GW. These developments mark a huge change in the Indian energy system, as currently around 61 percent of the installed capacity (387 GW in total) comes from conventional thermal power plants[1]. In order to accelerate the energy transition in India in a sustainable way, various alternatives for converting coal-fired power plants are being researched.

Thermal storage power plants (TSPP) represent one promising conversion option and would enable the use of existing infrastructure, including some of the major machines and plant equipment. Such a concept can be an efficient alternative to a complete shutdown, as valuable assets can be repurposed, jobs can be preserved and emissions can be drastically reduced.

[1] Central Electricity Authority (CEA), Installed Capacity in India as of 31 July 2021: https://cea.nic.in/installed-capacity-report/?lang=en, retrieved on 30 August 2021

2 Scope of the Study

The study provides an overview of the international state of the art with regards to TSPP and the conversion potential for existing coal-fired power plants in India. The technology assessment focuses on the following issues:

- Advantages and disadvantages of available TSPP technology options
- Assessment of the Technology Readiness Level (TRL)
- List of existing and, as far as possible, planned projects

In a next step, necessary conversion measures for the most promising TSPP approaches should be listed and described. This should include:

- Determination of the technical (not economic) conversion potential in India
- Assessment of the technical feasibility of molten salt storage facilities at Indian coal-fired power plants
- Rough estimate of the individual components of the investment costs (CapEx) of at least one promising technology, and of possible operating costs (OpEx)
- Rough estimate of levelized cost of electricity (LCOE) when retrofitting an existing power plant, assuming that technical conversion measures that India does not need to import are usually achievable at 1/3 of what it would cost in Europe

Finally, conclusions, recommendations and next steps for India must be derived.

To do this, it is necessary to consider the international state of the art, as well as the results of the existing DLR (German Aerospace Center) study "Reconversión de centrales a carbón en plantas de almacenamiento térmico con energía renovable en Chile".
For the study,vgbe has partnered with TU Wien's Institute for Energy Systems and Thermodynamics, which is led by Prof. Dr. Markus Haider. Professor Haider is a member of vgbe's Scientific Advisory Board and an acknowledged expert in the field of TSPP.

3 Executive Summary

In view of rising shares of variable renewables and increasing demand for flexibility in the energy system, storage technologies become more and more important. Although battery storage is regarded as a very promising option, thermal electricity storage will play an increasingly important role.

Thermal electricity storage or, respectively, electro-thermal energy storage refers to a concept in which excess electricity is converted into heat – which is the charging process. During discharge, this heat is used to generate electricity with the help of a thermal power process. Such a technology can be used to retrofit and transform coal-based power plants into TSPP. In order to develop economically viable TSPP concepts, pilot projects have been initiated in the US, Europe and Chile. To date, three technology concepts that use three different types of storage material have been selected for these projects: molten salt, rock-based and sand-based heat storage concepts. They each have pros and cons with respect to the technology readiness level, cost and temperature ranges.

However, all these concepts can potentially be used to repurpose parts of the Indian coal fleet. Especially the steady PV supply provides long charging periods, which are beneficial for TSPP. Moreover, many benefits speak for this TSPP concept to be applied in India:

+ **Multi-hour and large-scale electricity storage solution**
+ **Re-use of existing infrastructure, competencies of Indian industry and expertise of existing staff → enabling a smooth transition and structural change process**
+ **Continued provision of valuable system services at critical points in the grid network**
+ **Costs comparable to other storage alternatives (e.g. batteries)**
+ **Provision of heat and process steam in addition to electricity – although heat might not be so important for India, steam can be important for captive power plants**
+ **Savings made on decommissioning costs for retired coal-fired power plant**

A rough estimate of the quantitative potential in India shows that almost 70GW of the installed coal capacity could be repurposed into TSPP. These mainly subcritical plants are now 8 to 15 years old and have a sufficient remaining lifetime – as the steam turbine part will remain. It is proposed to further investigate the TSPP potential at two reference plants, with a unit capacity of 200 MW and 500 MW. This in-depth feasibility study will provide further transparency on technology and cost.

Currently the energy related CapEx associated with the repurposing is in the range of €100 to €150/kWh-e. The according levelized costs of storage (LCOS/LCOE) are in the range of €65 to €105/MWh (based on power purchase cost of €30/MWh-e). Taking Indian cost levels into account it is estimated that the CapEx reduction potential is in the range of 40 to 45 % and for LCOS in the range of 10 to 15 %. The cost of the charging electricity is main lever for the LCOS.

Key Recommendations:

(1) Consider thermal storage power plants as a large-scale storage solution for the Indian power sector

(2) Take into account the most promising technology options: molten salt, rock-based and sand-based concepts

(3) Conduct a feasibility study at two existing power plant sites

(4) Select a 200 MW and a 500 MW plant with operating ages of between 8 and 15 years as reference plants for the study – one plant should be a captive power plant

(5) Consider the expertise of different international stakeholders when executing the study

(6) Develop a TSPP roadmap based on the results of the feasibility study

(7) Initiate and promote the knowledge transfer about TSPP concepts

4 Overview of Thermal Power Storage Technologies

TSPP belong to the group of technologies referred to as “electro-thermal energy storage” (ETES). Over the years, several names have been used, the most prominent being “pumped thermal electricity storage” (PTES), “pumped heat electricity storage” (PHES), “Carnot batteries” (CB) and “electro-thermal energy storage” (ETES).

ETES is the broadest and most clearly defined term, given that pumped hydro is also an electricity storage technology (causing confusion in abbreviations) and that the name Carnot refers to the person rather than to the Carnot cycle, which is based on isothermal heat transfer. ETES technologies have the following in common:

- electricity is stored as thermal energy (TES)
- the technology is site-independent,
- depending on the temperature levels, one or two thermal reservoirs are needed,
- in general, two reverse thermodynamic cycles are needed (heat pump cycle for charge and power cycle for discharge)

The thermal storage temperature levels may be above or below ambient temperature. In the case that the ambient temperature is chosen for the lower temperature, only one thermal storage for high temperature is needed. In a simple set-up, electrical resistance heating (instead of a heat pump cycle) charges the high-temperature storage. The combination of a water-steam based Rankine cycle – which is the basis of coal based power plants – with electric heating and thermal energy storage (TES) yields the special case of a TSPP.

4.1 Classification according to Thermodynamic Cycle and Machinery

4.1.1 Rankine, Brayton and Kapitza Cycle

Figure 1 shows, on the left, the general process diagram, where the red arrows and letters (C for compressor and E for expander) represent the charge process, while the green arrows and letters represent the discharge case. It reflects a thermodynamic cycle, which functions as an electricity generator in discharging mode and as a heat pump in charging mode.

The two temperature/entropy (T-s) diagrams in **Figure 2** show four of the five cycles used in current ETES technology concepts. The blue and red cycles show the simple sub-critical and transcritical Rankine cycles. The transcritical cycle is possible with both H_2O and CO_2 as working fluids. The yellow cycle represents concepts with ideal gases as working fluids (mainly air, but also argon or nitrogen) in a Brayton cycle. The black cycle on the right represents a concept working with an organic Rankine working fluid, such as butane.

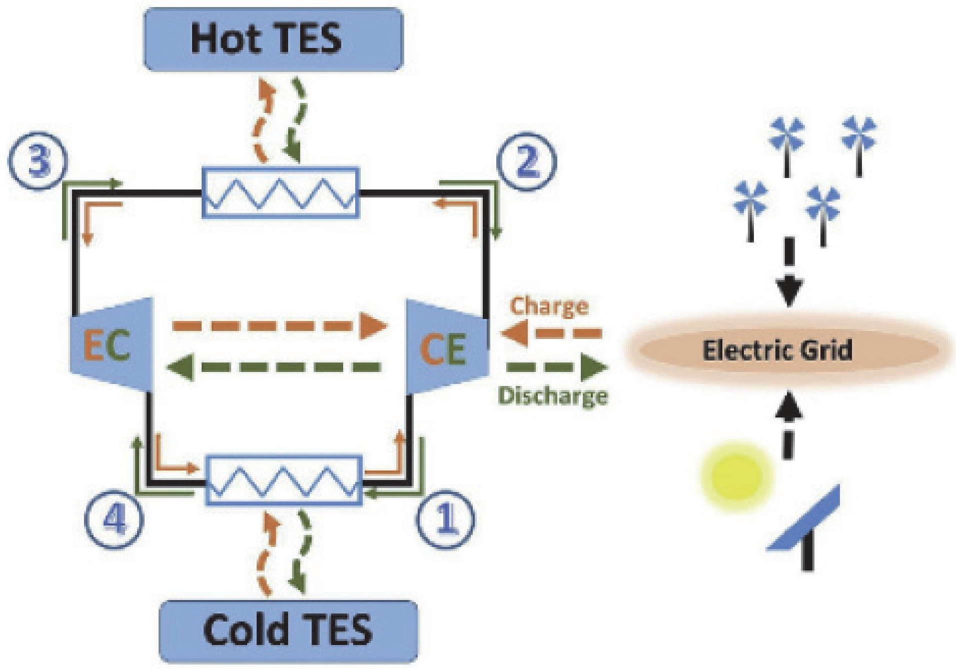


Figure 1: The principle of electro-thermal energy storage.
Source: Abarr et al.[2]

[2] M. Abarr, B. Geels, J. Hertzberg, and L. D. Montoya, Pumped thermal energy storage and bottoming system part a: Concept and model, Energy, vol. 120, pp. 320–331, 2017

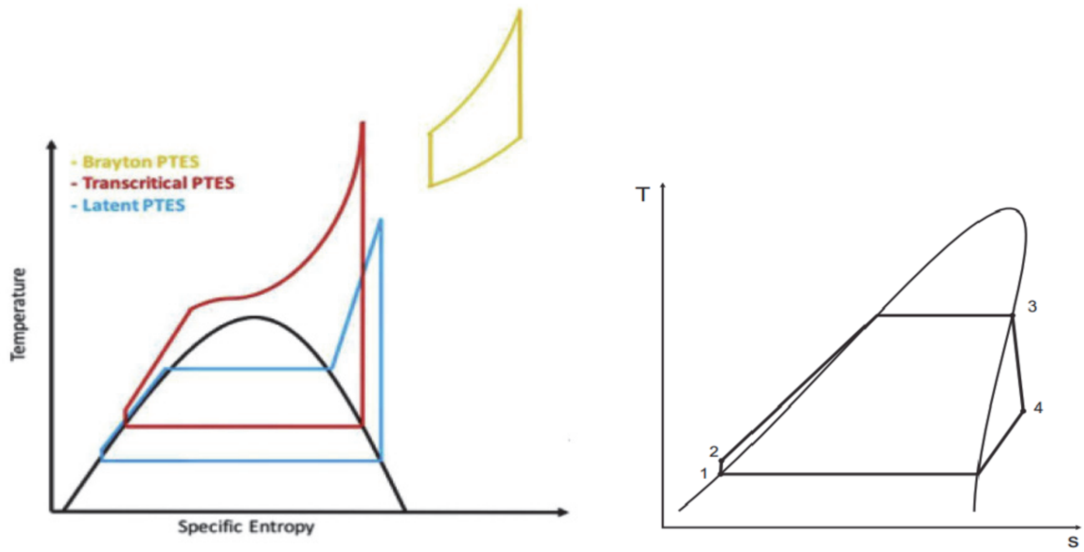


Figure 2: Temperature/entropy diagrams for different thermodynamic cycles
Source: Abarr et al. [3]

A further concept, which still is within the perimeter of ETES, is the so-called liquid air energy storage (LAES). It is based on the Kapitza cycle for air liquefaction and its particularity is that, besides sensible thermal storages for both heat and cold, it uses the working fluid as a latent low temperature (cryogenic) storage medium.

LAES is not the only concept with low temperature thermal storage: Ideal gas Brayton cycle concepts such as that of Malta Inc.[4] have the low temperature storage reservoir at approx. -50 °C, and MAN and Echogen have transcritical CO_2 concepts that work with ice storage.

The choice of a thermodynamic cycle triggers different needs for machinery and thermal storage technology. The efficiencies of the compression and expansion machines are of high importance, given that four compression/expansion steps act upon the working fluid within a charge-discharge cycle. For this reason, some of the Brayton cycle concepts (e.g. Isentropic Ltd) use piston engines, which can achieve isentropic section efficiencies of close to 100 % (compared to turbomachinery, which achieves isentropic efficiencies of 85 – 92 %).

[3] M. Abarr, B. Geels, J. Hertzberg, and L. D. Montoya, Pumped thermal energy storage and bottoming system part a: Concept and model, Energy, vol. 120, pp. 320–331, 2017
4 https://x.company/projects/malta/ retrieved on 21 September 2021

High temperature concepts with only one high temperature thermal reservoir may eventually use electrical heating instead of a heat pump. For coal power plant conversion into TSPP, the thermodynamic ETES concepts are either **supercritical or subcritical reheat water/steam Rankine cycles. The ambient is the lower temperature level**. For these systems, several concepts are presented below.

Because this study focusses on the repurposing of existing steam power plants, the power cycle is considered as a given. Consequently, the upper and lower cycle temperatures also directly result from the existing power plant configuration. The high temperature storage consists of one of the following concepts:

› **two-tank molten salt**
› **two-tank sand**
› **packed bed of crushed rock, quartz pebbles or structured ceramic elements**
› **steel elements**
› **concrete**

The first two concepts (molten salt and sand) also use the storage medium as a heat transfer medium, while the fixed bed systems of rocks, steel or concrete need air as an auxiliary fluid.

4.2 Classification according to the Storage Material

4.2.1 Molten Salt

DLR has proposed a TSPP concept based on molten salts[5]. This approach is based on the thermal storage concepts known from the current state of the art in the concentrating solar power (CSP) industry. A eutectic mixture of 60 % sodium nitrate ($NaNO_{3}$) and 40 % potassium nitrate (KNO_{3}, the so-called “solar salt”) is molten during the commissioning phase in dedicated heaters fired by oil or gas burners and stored in two well-insulated and heatable liquid tanks.
During charge (i.e. periods of electricity surplus in the grid), molten salt from the low temperature tank (typically 280 to 300 °C) is pumped over an array of electric resistance heaters, heated up to approximately 560 °C and stored in the high temperature tank. (Note: in CSP plants, this step of the process takes place in the receiver of a solar power tower). During discharge, the hot molten salt is pumped over a dedicated molten salt steam generator, feeding the existing steam cycle.

[5] https://www.dlr.de/content/de/dossiers/2019/third-life-kohlekraftwerk.html retrieved on 21 September 2021

Figure 3 shows a picture of a CSP plant, a picture of a state-of-the-art molten salt sub-critical steam generator and a system diagram for a molten salt TSPP.

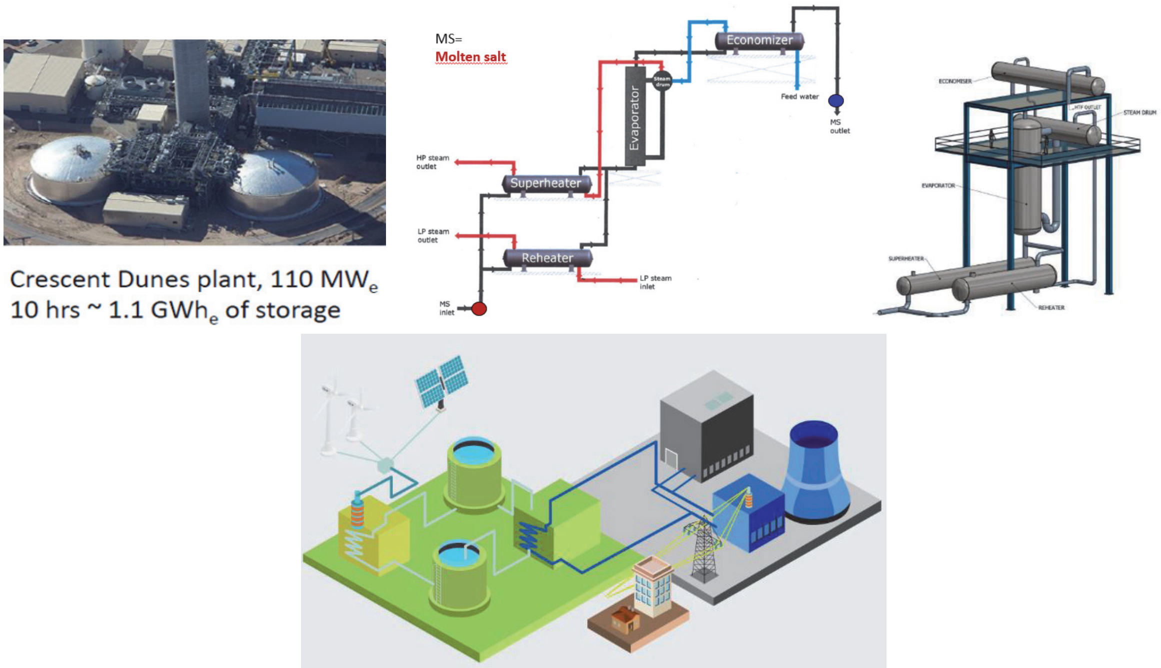


Figure 3: Elements of molten salt storage technology.
Sources: Solar Reserve, Aalborg, DLR

The molten salt approach has the following strengths and weaknesses:

- <u>Strengths (pros):</u> The most important benefit of this approach is that the technology is commercially proven and therefore has the highest technology readiness level (TLR) of all considered technologies (TRL 7.5 for TSPP, TRL 9 for CSP). Probably least commercially proven (at scale) are the high capacity electric heaters for molten salt. The system is simple, and liquid circuits need less volume and material than gas circuits. This compactness and simplicity may to some extent outweigh the cost of the storage material, which at €700 – €1000/t is far higher than the cost of basalt rock, concrete or sand.
- <u>Weaknesses (cons)</u>: The maximum and minimum temperatures of the working/storage material are limited by chemical stability and by solidification. The upper limit of the heat storage will result in a cycle downgrading need and efficiency loss – if applied in modern coal power plants (which have live steam temperatures above 540 °C). Due to the freezing risk (molten salt solidification at 240 °C), the operating range is limited to less than 300 K, which – for the same energy –

will require up to twice the mass needed for systems based on solid materials – as they can operate with lower temperatures. Last but not least, molten salt is more expensive than basalt rock or sand. Although molten salt could be produced in a synthetic route, the present market is dominated by imports from Chile (company SQM).

4.2.2 Sand-Based

TU Wien has developed a sand-based storage system, which operates in a two-tank concept similar to molten salt. Sand is, of course, only one particulate material of choice, alternatives being bauxite, etc. Particle-based storage cycles are currently one of the preferred technology vectors for the next generation of CSP power plants. The US Department of Energy (DOE) announced recently (in spring 2021) that Sandia National Laboratories got the main award of the GEN3 CSP initiative, with a funding volume of $ 23 million for particle-based storage.

In operational terms, the main differences between sand and molten salt are as follows:

a) Sand needs fluidization by auxiliary air for heat exchange (electrodes or water/steam). The mass flow of auxiliary air is approximately 3 % of sand mass flow, and the sensible heat in exhaust air is recuperated.

b) Sand cannot be pumped and needs conveying equipment such as bucket conveyors.

The basic operating principle can be seen in **Figure 4** and is described in Steiner et al.[6].

The concept was demonstrated from 2016 to 2018 at TU Wien, at a scale of 200 kWt / 600 kWht, using plain tubes (sandTES1.0). Based on the pilot results for heat transfer, as well as on additional lab-scale research, the developers decided to switch to fin tube technology (sandTES 2.0)[7]. Parts of the TU Wien test rig have been transferred to Akron, Ohio, where a sandTES 2.0 system with 200 kWt will be tested in a CO_2-ETES system of Echogen Power Systems in spring 2022.

[6] P. Steiner, K. Schwaiger, H. Walter, M. Haider, Active fluidized bed technology used for thermal energy storage, Proc. ASME 2016 10th Int. Conf. Energy Sustainability, ES2016-59053

[7] S. Thanheiser, M. Haider, P. Schwarzmayr: Experimental Investigation of the Heat Transfer between Finned Tubes and a Bubbling Fluidized Bed with Horizontal Sand Mass Flow, subm. to Energies, 2021

In parallel, TU Wien has teamed up with EPRI, CDM Smith and Southern in a 3-stage DOE funding opportunity (FO) for coal power plant reconversion to TSPP. In the case of a positive funding decision by DOE, the concept will be demonstrated in 2024 at a scale of 2.5 MWt – 25 MWht in a US coal power plant (scale-up factor 12). The developers and the industrial partners consider that, assuming a successful demonstration at 2.5 MWth, the concept would be ready for demonstration at commercial scale.

A parallel route to TSPP is a US demonstration program for ETES systems, where Echogen is targeting a 25 MWe CO2 ETES based on sandTES storage.

The sandTES approach has the following strengths and weaknesses:

- Strengths (pros): Sand benefits from a high working range (0 to 800 °C); sand is abundantly available, cheap (€40/t) and environmentally benign.
- Weaknesses (cons): The main challenge is the (not yet commercial) TRL in the range of 4 to 5 (TRL 4.5).
- Cost Considerations: The system cost (heat exchangers, auxiliary and conveying equipment) is higher than comparable systems for molten salt. Analysis carried out in projects in which TU Wien participated showed that the break-even between molten salt and sand is at a storage duration of 2.5 hours.
  - For 2.5 hours, the two systems are expected to have a comparable CapEx, while for 10 hours, sandTES should be 80 % cheaper.
  - Compared to packed bed systems (rocks), sandTES should be about 20 % cheaper.

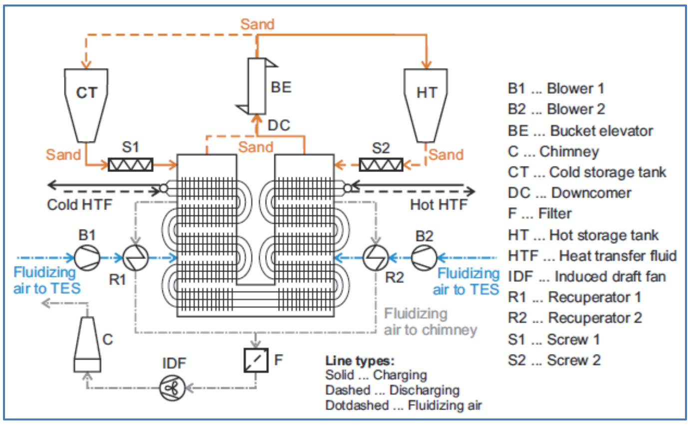


Figure 4: Elements of sandTES technology
Source: TU Wien

4.2.3 Rock-Based

Siemens Gamesa has developed an ETES concept based on crushed basalt[8]. Starting with the development and validation of the first models in 2012, the concept of ETES has achieved 95 % heat storage efficiency at 700 kW charging power, and 5 MWh storage capacity has been tested since 2014 [8]. A collaborative nationally-funded, 24-hour ETES project was undertaken by Siemens Gamesa, Hamburg Energie and the Hamburg University of Technology. The storage facility, commissioned in Hamburg (**Figure 5**) in 2019, achieved a thermal storage capacity of 130 MWht at temperatures of 750 °C provided by 1,000 tons of rock, and generated power at about 1.5 MW, thereby accomplishing a round-trip efficiency of 27.7 % [8].

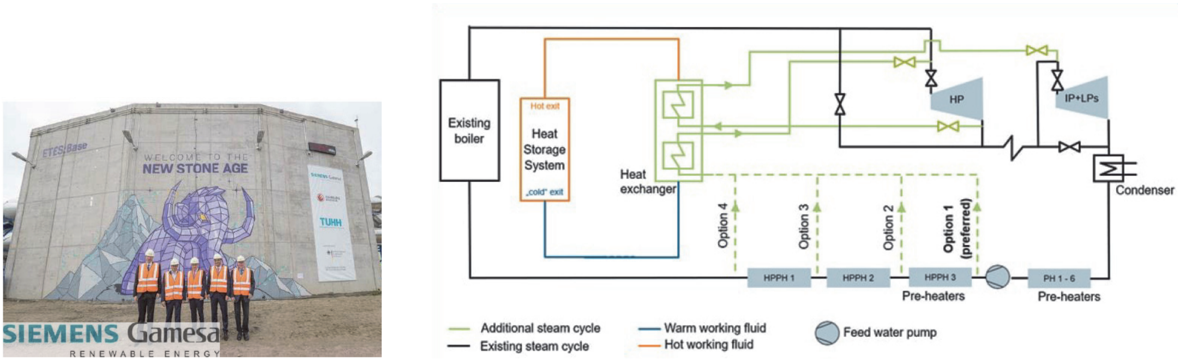


Figure 5: Elements of Siemens Gamesa packed bed technology
Source: Siemens Gamesa

Siemens Gamesa proposes a GWh-scale application named **ETES:Base.** The main components are:

- air blower,
- high-capacity / high-temperature electric heater,
- a horizontal plug flow, above ground volcanic rock packed bed sensible TES,
- high volumetric flow insulated air ducting and valves/dampers,
- air-driven heat recovery steam generator (HRSG).

During charging, the electric heater converts excess power from the grid to heat, which is transferred to the working fluid: air. The blower drives the air across the electric heaters and the packed bed of volcanic stones. The hot air heats up the stones to temperatures between 650 °C and 800 °C.

[8] https://www.siemensgamesa.com/products-and-services/hybrid-and-storage/thermal-energy-storage-with-etes retrieved on 21 September 2021

During discharging, the air blowers convey air at atmospheric pressure flows across the packed bed in reverse direction, and the air is heated up by direct contact to the stones. The hot air transfers its sensible heat to the water/steam in the HRSG. (reheat Rankine cycle).

The principle is not only applicable to conventional power plants (i.e. all types of coal power plants), but also to steam turbine cycles in combined cycle power plants, solar and biomass power plants. Siemens Gamesa has named these applications ETES:Add and ETES:Switch.

The concept of **ETES:Add** is a hybrid power plant facility consisting of both fossil fuel and thermal storage. Charging the heat storage can be accomplished by using power either from the grid at peak demand times or from the generator of the conventional power plant. With the **ETES:Switch** application, the existing coal boiler is dismantled and the conventional power plant transformed completely into emission-free storage plant.

S. de Roo et al.[9] performed an assessment to find the best integration position of the storage system into the water-steam cycle. The integration point of storage cycle into the water-steam cycle has been selected considering an overall economic optimum. If only the thermal optimum is considered, the integration point determining the average temperature of heat entry into the water-steam cycle would have an opposite effect on the efficiency of the storage and the discharge cycle [9]. With a higher temperature level, the efficiency of the discharge cycle increases, whereas the efficiency of the storage cycle decreases due to the increase of the storage size to store the same amount of heat and the increase of the power consumption of the blower [9].

Siemens Gamesa came to the conclusion that the lowest possible inlet temperature into the storage cycle is beneficial, as it enables the greatest discharge of thermal energy from the storage, and a cost-effective design of the components at the inlet to the storage cycle (because of the lower temperatures) [9].

[9] S. de Roo, K. Lawrenz, and D. Schlehuber, Second life of fossil power plants with large-scale thermal energy storage, Siemens Gamesa Renewable Energy S.A, Tech. Rep., 2020.

According to [9], a round-trip efficiency comparable to the current efficiency of coal power plants (45 %) has been achieved with relatively low cost owing to the following facts:

(i) storage cycle doesn't exhibit any losses

(ii) own consumption of the storage cycle is lower because several consumers such as the fuel and flue gas handling are no longer part of the system,

(iii) the energy consumption of the blower dissipating into heat increases the degree of energy utilization, and the power consumption of the blower is almost wholly recovered as heat during charging and discharging.

More efficient components (hence higher investment costs) and a more complex integration between the storage and discharge cycle would improve the round-trip efficiency to values beyond the current efficiency of the existing power plants.

While Siemens Gamesa has widely published the overall concept, the technological details remain somewhat scarce. Our discussion below is based on thermal engineering expertise and knowledge of Siemens' patent applications.

- Strengths (pros): Advantages of the system comprise the potentially low investment cost, the potential to have up to 100 % of Indian value chain contribution coupled with a reasonable TRL of currently 6.5.
- Weaknesses (cons): The air piping has a high external surface and, hence, potentially high thermal loss. Large-scale systems will need a high number of gas dampers, which themselves have leakage potential. Any packed bed system is subject to the issue of thermal ratcheting, which limits unitary size. Packed bed systems with horizontal flow are subject to the danger of self-discharge and, in addition, thermal hysteresis is more difficult to manage.

4.2.4 Metal-Based

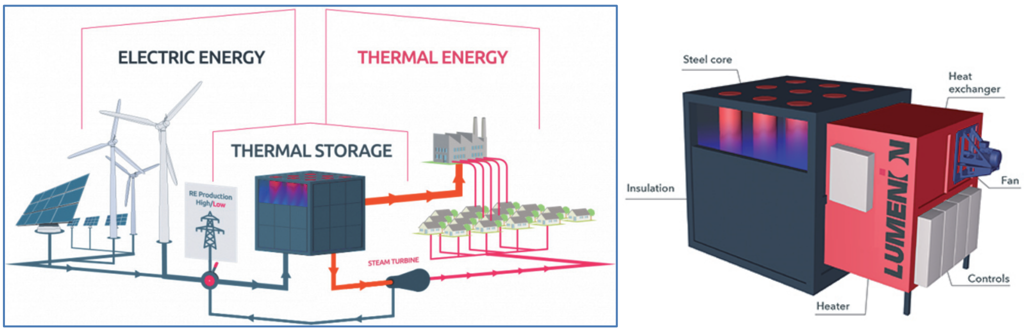


Figure 6: Elements of Lumenion steel based sensible heat storage technology
Source: www.lumenion.com

Swiss company Lumenion AG has presented a concept (**Figure 6**) for the capacity range of 0.2 to 20 MW. The process also uses electric heating of the working fluid air. The process fluid air then transfers its sensible heat to cylindrical steel elements at temperatures up to 650 °C. The stored energy is extracted as process steam and heat as required.

For larger plants, a conversion to electricity is also possible. The thermal output of the current concept is in the range between 0.2 and 20 MW.

- Strengths (pros): The modularity and compactness of sensible heat steel storage.
- Weaknesses (cons): The limited upper temperature and the cost of the storage material steel. Lumenion mentions that the steel could be reused at the end of the operating lifetime of the storage installation. This may be applicable to small and medium-sized industrial plants, but the concept may be challenging for large-scale plants.

4.2.5 Concrete-Based

Several companies around the world have developed concrete storages for sensible heat. One prominent approach from the solar thermal community (CSP) is the technology developed by Norwegian company EnergyNest. Energy in the form of heat at high temperature is transferred to the so-called thermal battery using a heat transfer fluid (HTF) inside pipes cast into the thermal battery elements.

EnergyNest has resolved some of the issues encountered in earlier projects with concrete (**Figure 7**).

- The HEATCRETE® storage material is designed to have a similar coefficient of thermal expansion to that of the cast-in carbon steel tubes.
- The modular approach allows repair in case of quality issues.
- The storage material HEATCRETE® has been tested up to 550 °C, and is guaranteed to perform as intended up to 450 °C.
- Thermal losses are less than 2 % over 24hrs for large-scale projects.
- There is no direct contact between the heat transfer fluid and HEATCRETE®. Steel piping is compatible with water/steam, which enable straightforward integration within a wide range of applications.
- Due to the fixed ratio of energy to power, any additional MWh of storage will require additional pressure parts
- Due to inertia and limited conductivity of the concrete, the EnergyNest thermal battery is not recommended for short-term cycles of less than 30 minutes.

Figure 7: Elements of EnergyNest concrete based sensible heat storage technology
Source: www.energy-nest.com

The maximum temperature is supposed to be determined by a quartz phase change process, which occurs in the concrete at 570 °C, thereby introducing a risk of cracking. The question of why the supplier only guarantees performance to 450 °C would have to be analysed.

In the US, Bright Energy (now Storworks), in collaboration with EPRI and Sothern company, won a $5 million DOE award for demonstration of its proprietary concrete storage technology (**Figure 8**). In comparison to EnergyNest, Storworks seems to work with stainless steel spiral tubes.

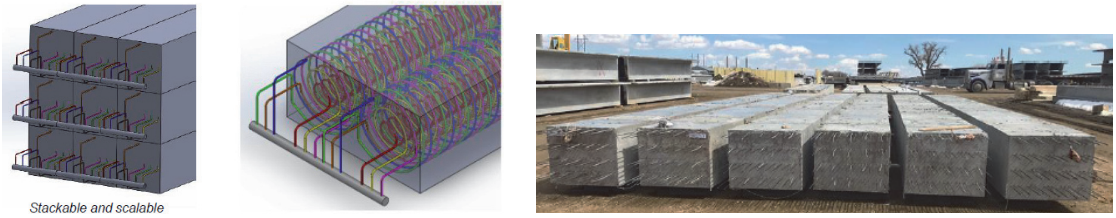


Figure 8: Elements of Storworks concrete based sensible heat storage technology
Source: https://netl.doe.gov/sites/default/files/netl-file/21TPG_Hume_0.pdf

- Strengths (pros): Compact modular system, reasonable TRL (Storworks will have TRL6 by 2022)
- Weaknesses (cons): Temperature limitation, fixed ratio of energy to power, no economies of scale

4.3 Comparison of Technology Options

The following **Table 1** provides an overview of the different technology options.

Type	TRL	Temp. Level [°C]	Unitary Capacity [MW-t]	Storage Mat. Cost (€/t)	Pros	Cons
Molten Salt	8	280–560	HEX: 100MWt RESERVOIRS: 1GWh (Crescent Dunes, Ouarzazate)	700-1000	Highest TRL simple	Limited temperature range, cost of storage material Lower local content
Sand-based	4.5	50–800	HEX: 80MWt (FB HEX size and conveyor capacity) RESERVOIRS: 2GWh	40	Lowest system cost, Highest reservoir capacity, Low storage material cost, High local content	TRL still low (can be 6 by 2024), Conveying equipment, higher complexity than molten salt
Rock-based	6	50–800	Estimation: HEX 200MWt; RESERVOIRS: 500MWh; Limited by thermo-mechanical stress (thermal ratcheting)	40	Low CapEx (slightly above sandTES) High local content	Thermal ratcheting, self -discharge, thermal losses, air ducting
Metal-based	6	50–650	20 (according to Lumenion)	6000	Simple and compact, High local content	High material cost, temperature limitation
Concrete-based	6 by 2022	50–450/550	Modules of few MWh	65	Modular and simple	Maximum temperature not yet fully validated (450°C according to EnergyNest, 600°C according to Storworks)

Table 1: Overview of the different storage technology options

The preceding chapter included an overview of the storage technologies, which in principle can be retrofitted into existing coal power plants. In order to derive the levelized costs of stored electricity, it is necessary to understand and to consider the complete integration concept.

This will be done in the next chapter. In this preliminary comparison, only the TRL, the feasible temperature range of the storage system, the maximum unitary capacity (beyond this capacity, parallel lines have to be considered) and the pros and cons were considered.

4.4 Thermal Storage Projects Worldwide

ETES systems are a rather novel technology and demonstration projects are on the verge of commencing. In terms of **TSPP**, there are only two known projects:

a) Siemens' **130 MWh-t rock** based TSPP system in Germany has been operating since 2019.

b) The **30 MWh-t concrete based system of EPRI + Storworks** at Alabama Power's E.C. Gaston Steam Plant in Wilsonville, Alabama, US, funded by DOE, is under construction and is expected to be commissioned by the end of 2021.

A **25 MWh-t sandTES system by EPRI, TUW + others** is currently in Phase 1 funding by the US DOE and is expected to be demonstrated by 2024 at the Gaston site (Phase 3 funding not yet achieved).

Under the auspices of the energy cooperation between Chile and Germany, a TSPP concept for repurposing a 250 MW coal based power plant is currently in the execution planning phase. The project is driven by US-based operator AES and supported by DLR – applying a molten salt concept. The detailed case study shows that expected CapEx is in the range of $ 200 to $ 450 million[10] – depending on the technology concept. The levelized cost of electricity (LCOE) is in the range of $ 85 to $115/MWh-e. This calculated LCOE assumes an average cost of $ 30/MWh-e for the charged electricity. Given that the expected round-trip efficiency is in the range of 40 % - 45 % (i.e. 55 % – 60 % of the charged electricity is lost), approximately 50 % – 60 % of the LCOE stems from the cost of the purchased charging electricity. The remainder is split by CapEx amortization (financial cost) and O&M costs.

Several other non-steam cycle ETES initiatives are in the process of being authorized or under construction in the US and in Europe:

a) In 2021, Highview Power announced the start of construction of a 50 MWe **LAES** demonstration plant in the UK.[11]

b) In September 2021, Stiesdal announced the construction of a 'hot rocks' **Brayton cycle packed bed ETES** demonstration on the Danish island of Lolland (10 MWh)[12]

[10] Dr. Michael Geyer et.al., Repurposing of existing coal-fired power plants into Thermal Storage Plants for renewable power in Chile, DLR-GIZ presentation from 20 September 2020
[11] https://highviewpower.com/news_announcement/world-first-liquid-air-energy-storage-plant/ retrieved on 4 October 2021
[12] Aarhus University, https://scitechdaily.com/gridscale-storing-renewable-energy-in-stones-instead-of-lithium-batteries/ published on 6 May 2021, retrieved on 21 September 2021

c) MAN and Echogen are working intensively on **trans-critical CO_2 ETES** projects for commercial scale demonstration either in the US or in Europe (start in 2022 is plausible)

d) Malta Inc. is working intensively towards commercial scale demonstration of **Brayton cycle molten salt ETES** in the US (start in 2022 is plausible)

5 Conversion of Coal-Fired Power Plants

5.1 System Integration concepts for Retrofitting Measures

Starting with the storage technologies introduced in the preceding chapters, there are different options for integration into power plant cycles:

a) TES integration can be either **electrical** or **steam based**. While storage via electrodes (power to heat to power) allows storing power originating from PV at a round-trip efficiency in the order of 45 %, steam-based storage of power stemming from the combustion of fuel (heat to heat to power) can be achieved at a far higher round-trip efficiency (RTE) of 80 %.

   Some hybrid concepts enable both modes of power storage.

b) TES integration or the extent of retrofit can be **hybrid** or **total**. (ETES:Add or ETES:Switch, according to Siemens Gamesa)

c) In a total retrofit, the coal fired steam generator is decommissioned.

d) In a hybrid system, the coal fired steam generator can continue to operate. The TES system allows the power produced by the steam cycle to be uncoupled from the power transmitted to the electric grid

Types of electric heaters:
Depending on the storage medium and, in particular, the process fluid, the electric heaters operate at varying levels of power density and, hence, varying costs. The heat transfer coefficients are low for air, medium for sand fluidized beds and molten salt and high for water/steam evaporators and super-heaters.

› In molten salt TES, the electric heaters heat the storage medium molten salt
› In sand TES, the electric heaters heat the storage medium sand in a fluidized bed
› In rock-based TES, the electric heaters heat the auxiliary fluid air
› In metal-based TES, the electric heaters heat the auxiliary fluid air
› In concrete-based TES, the electric heaters directly heat, evaporate and superheat water.

Currently, electric heaters for air or molten salt have a maximum unitary capacity in the range of 5 MW. A considerable upscaling effort will be needed for the concepts in ETES/TSPP. In any case, this technology does not promise relevant economies of scale.

Feedwater Preheating:

The feedwater systems of the steam turbine cycles differ according to the type of TES:

- In all solid storage media TES, it seems to be techno-economically advantageous to deactivate the feedwater preheating during TES discharge. This approach makes it possible to maximize the temperature difference between the hot and cold TES material temperatures. The storage density is maximized and the mass flows of air or sand are minimized.
- In molten salt-based TES, feedwater preheating during discharge is obligatory to avoid solidification of the molten salt. The advantage here is that the steam cycle operates nearer to the design point. The disadvantage is that far more storage material is needed.

Process Flow Diagrams:

The following figures give an overview of the integration options. **Figure 9** shows the three arrangements for electric (only) charging. **Figure 10** shows some hybrid arrangements.

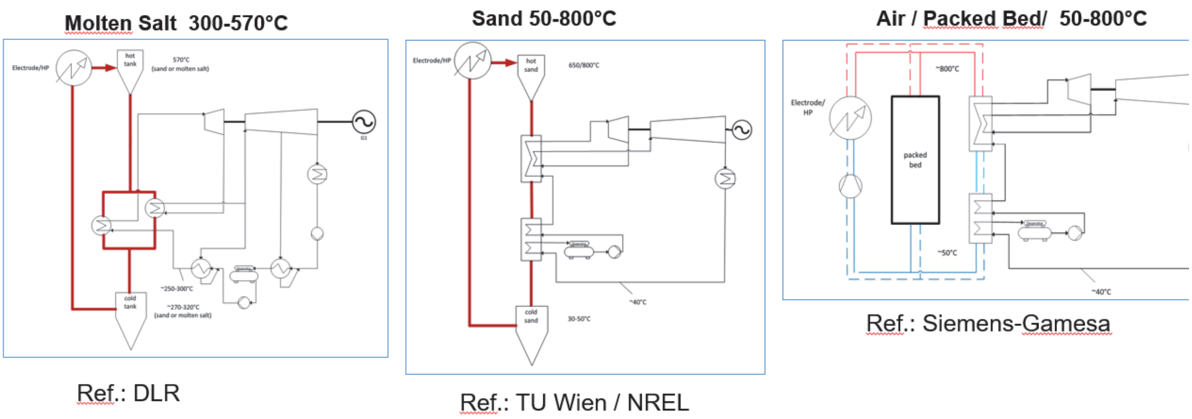


Figure 9: Electrode TSPP system integration – Molten salt, sand or air is heated electrically.
Source: TU Wien

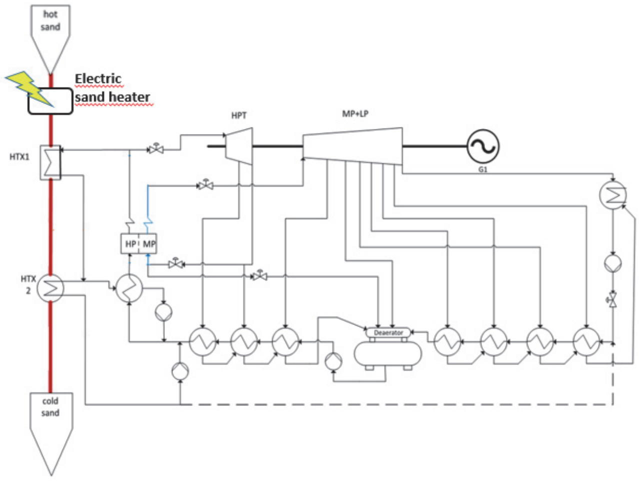


Figure 10: Hybrid Electrode/steam based TSPP system integration options
Sand is heated either electrically or by a combination of steam from the coal steam generator and electric power
Source: TU Wien

Potential for further thermodynamic improvement:
The TSPP based on reheat Rankine cycle and electric heating can achieve electric round-trip efficiencies (RTE) of up to 10 % higher compared to the fuel-to-power efficiency of the retrofitted coal power plant. As the storage cycle approach is not affected by the exhaust loss and auxiliary power requirement of the steam generator, RTE of almost 50 % is feasible.

It is possible to go further if, at a later stage, the electric heating is partly replaced by a heat pump cycle. Given that the lower temperature level of the steam cycle is at ambient temperature, a heat pump cycle based on transcritical CO_2 seems to be the most appropriate approach.

Advantages of TSPP

The advantages of repurposing existing coal-fired power plants into TSPP can be summarized as follows:

+ **Multi-hour and large-scale electricity storage solution**
+ **Re-use of existing infrastructure, competencies of Indian industry and expertise of existing staff**
  → enable a smooth transition and structural change process
+ **Continue to provide valuable system services at critical points of the grid network**

+ **Costs are comparable to other storage alternatives (e.g. batteries)**
+ **Provision of heat and process steam in addition to electricity – the latter is particular important for captive power plants**
+ **Savings on decommissioning costs for retired coal-fired power plant**

5.2 Cost Factors

The costs of retrofitting a coal power plant to become a TSPP can be broken down into the following categories:

- 1-Project management (PM), engineering, procurement and construction (EPC)
- 2-Water/steam, electric and controls connection between existing steam cycle and storage system
- 3-Electric heaters (cost varies, depending on the heat transfer coefficients and on corrosion protection)
- 4a-TES system civil works
- 4b-TES system equipment (heat exchangers, blowers, pumps, etc.)
- 4c-TES system piping, ducts, conveying equipment
- 4d-TES system reservoirs
- 4e-TES system storage material
- 5-TES steam generator

The cost of dismantling a decommissioned coal boiler may be part of the project, but it is not considered in the context of the TSPP.

The following numbers and considerations are based on cost information from a GIZ study[13], as well as on information received from Siemens Gamesa and on the results of projects in which TU Wien has participated.

- **Costs (1+ 4a)** make up approximately 25 % to 45 % of total CapEx
- **Cost (2)** is in the range of a few percent (3 % to 4 % of total CapEx)

[13] GIZ study: Reconversión de centrales a carbón en plantas de almacenamiento té-rmico con energía renovable en Chile, August 2020

- **Cost (3)** for electrode heating represents the CapEx side of the charging cost. It does not allow for economies of scale and is in the range of €40 to €90/kW. Given that electrode heating has a non-negligible cost, it seems advantageous to plan for a charging time of 10 to 12 hours.
- **Cost (4)** is a function of storage size and of storage material. As a result of storage material cost, the technologies with solid materials (rocks or sand) have a lower marginal cost than molten salt systems.
- **Cost (5)** is a fixed cost in all cases, as its capacity is related to the existing steam cycle.

Currently the energy related CapEx associated with the repurposing is in the range of €100 to €150/kWh-e. The according levelized cost of storage (LCOS/LCOE) is in the range of €65 to €105/MWh (based on a power purchase cost of €30/MWh-e). **It has to be emphasized that, for TSPPs, the cost of purchased power plays a substantial part in the LCOS**. For an average cost of €30/MWhe, the charging electricity cost will represent between 50 % and 60 % of LCOS.

Indian context
If it is assumed that in India the cost for non-imported equipment and services are 1/3 of the European level the following cost reduction potential can be derived. The Indian content mainly contributes to the cost factors 1+4a and 5 which account for almost 66 % of the CapEx. Hence, 2/3 cost reduction results in an overall cost CapEx reduction of up to 45 % for Indian conditions which corresponds with €55 to €85/MWh.

As the CapEx accounts for 1/3 of the LCOE/LCOS, this would refer to a reduction of about 10 to 15 % LCOE reduction. Here, it is very important to reflect that the LCOE are very much dependent on the cost of the charging electricity.

6 Repurposing Potential in India

6.1 Overview of Installed Coal Based Capacity in India

As of 31 July 2021, the total installed capacity for electricity generation in India (**Figure 11**) added up to 386.9 GW. The share of coal is about 52 %.[14] The operators in India come from the central, state or private sectors.

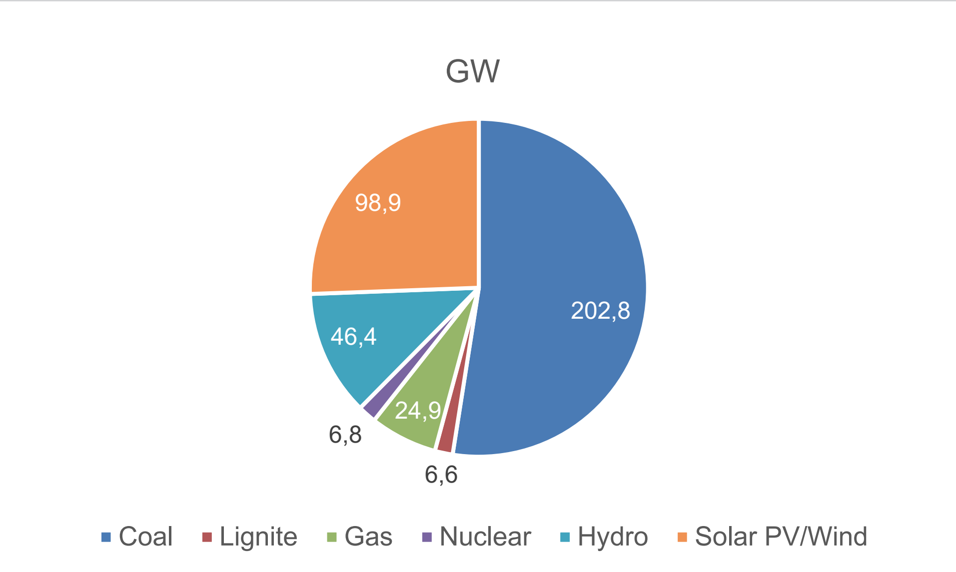


Figure 11: Indian electricity mix as of 31 July 2021
Source of data: CEA

In 2020, subcritical power plants accounted for almost three quarters of the coal capacity (**Figure 12**). That means that they operated with steam parameters below the critical point of water – which corresponds to 374 °C and 221 bar. According to a study from the previous year, the majority of subcritical plants are operated by state-owned companies, whereas 55 % of the supercritical capacity is operated by companies in the private sector.[15] Source applies for the rest of this chapter.

[14] CEA, Installed Capacity in India as of 31 July 2021: https://cea.nic.in/installed-capacity-report/?lang=en, retrieved on 30 August 2021

[15] India Infrastructure Research, Coal Based Power Generation in India 2020, provided by GIZ for study purposes only

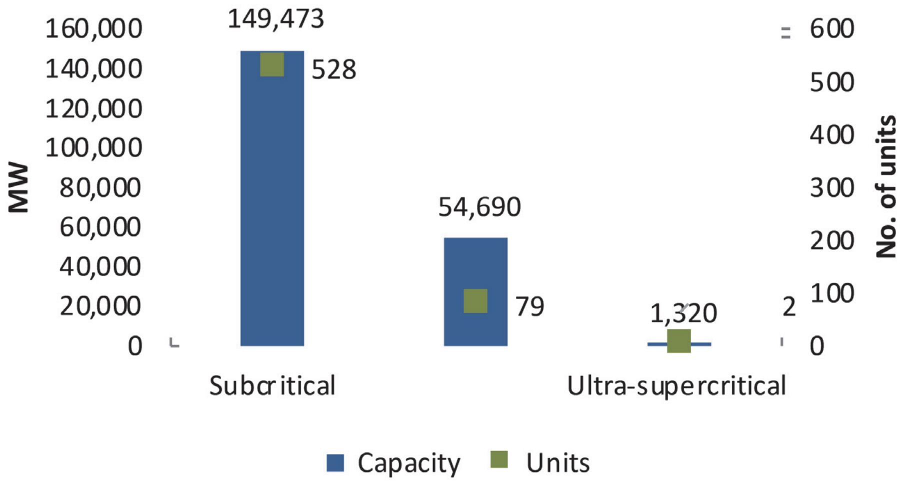


Figure 12: Distribution of installed capacity by technology as of 2020 (middle column: supercritical), Source: India Infrastructure Research

Furthermore, the study states that the majority of the 609 coal units – approximately 40 % of the overall capacity and 200 of 609 units – are between five and ten years old (**Figure 13**).

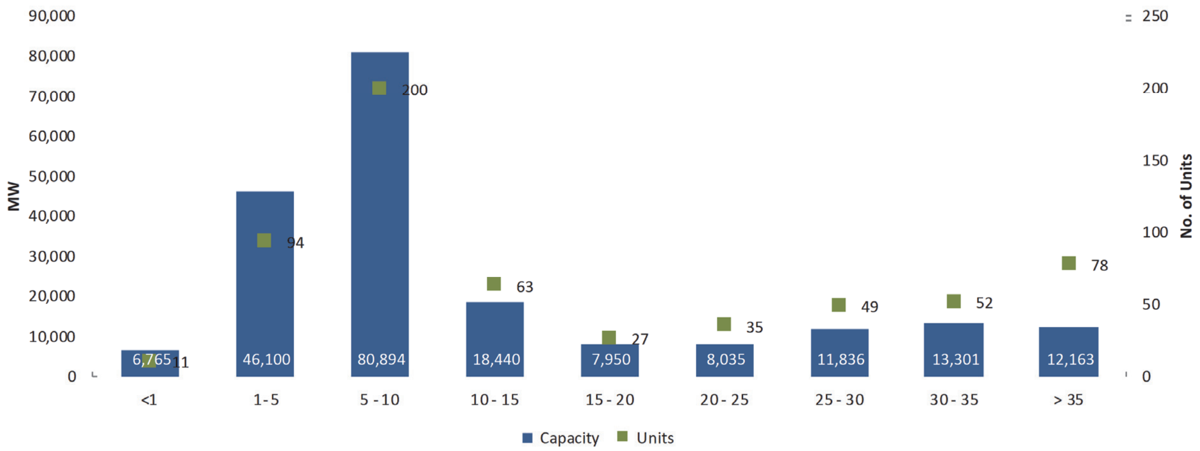
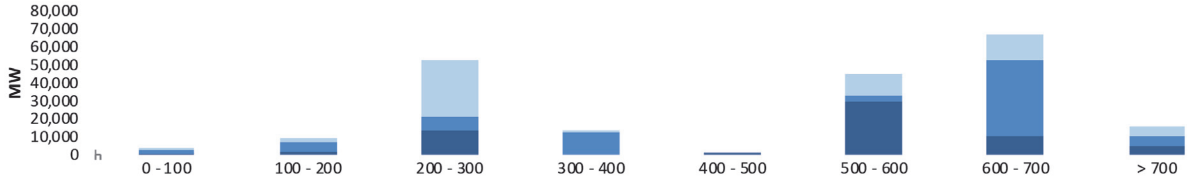


Figure 13: Distribution of installed capacity by age as of 2020 Source: India Infrastructure Research

Another important consideration is the size of the units (**Figure 14**). In 2020, more than 230 units had a capacity of 200 to 300 MW (subcritical). They account for one quarter of the installed capacity. Capacities of 200 MW, 210 MW and 250 MW are most common in this range, which is dominated by Russian/LMZ design. The next largest group, comprising 105 units, was in the supercritical 600 to 700 MW range – mainly with a capacity of 660 MW. This category represents 32 % of the installed capacity.



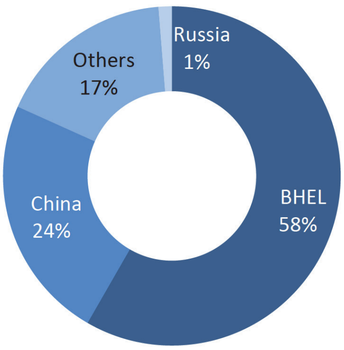
	0 - 100	100 - 200	200 - 300	300 - 400	400 - 500	500 - 600	600 - 700	> 700
State	567	1,675	31,010	1,500	-	12,000	14,400	5,500
Private	1,594	5,187	7,300	12,260	-	2,590	41,870	5,400
Central	540	1,930	13,940	-	980	30,000	10,440	4,800

Note: Based on data of 191 coal/lignite based plants (above 25 MW capacity) aggregating to 205.5 GW, as of March 2020.
Source: CEA, India Infrastructure Research

Figure 14: Distribution of coal units by size and sector as of 2020
Source: India Infrastructure Research

The majority of main plant equipment was manufactured in India. The Indian supplier Bharat Heavy Electricals Limited (BHEL) delivered almost 60 % of the boilers and turbines – see next **Figure 15** which shows the supplier distribution for boilers.

Distribution of Installed Capacity by Boiler-make



Boiler Make	Capacity (MW)	No. of Units
BHEL	119,862	376
China	48,014	119
Others	35,008	96
Russia	2,600	18
Total	**205,484**	**609**

Figure 15: Distribution of installed capacity by boiler supplier
Source: India Infrastructure Research

6.2 Retrofitting Potential and Cost Estimation

The usual lifetime of a power plant is about 35 to 40 years. The TSPP retrofit mainly focuses on repurposing of the steam turbine and related systems, such as the cooling and steam piping system. Therefore, the lifetime of the steam turbine is an important parameter to estimate the retrofitting potential. The steam turbine lifetime is in the range of 200,000 operating hours. After expiration of this time the turbine rotor and blades usually need to be changed – very cost-intensive maintenance measures.

Repurposing Potential of 67 GW
Therefore, power plants with an operating time of about 8 to 15 years are appropriate candidates for a TSPP retrofit within the next five to eight years. Taking the age of India's power plant fleet into account (**Figure 13**) and assuming an equal distribution of ages, approximately 67 GW capacity is potentially suitable for TSPP repurposing.

The capacity of units with an age of 5 to 10 years is about 80.9 GW; the capacity of units with an age of 10 to 15 years is about 18.4 GW. The capacity for units aged 8 to 10 years is (80.9 GW/5 x 3) which is 48.5 GW. This value needs to be added to 18.4 GW, which results in 67 GW. Subcritical plants account for most of this capacity. This is not an issue for the repurposing into a TSPP as the steam parameters which (currently) can be achieved by the different technologies are subcritical anyway.

6.3 Recommendations

TSPP should definitely be considered as a large-scale storage solution for the Indian power sector for the following reasons:

- Costs are comparable to batteries.
- It simplifies the structural change of existing coal based power plant sites.
- It provides mulit-hour storage capacity.
- Due to multiple benefits (e.g. provision of process steam), it is especially beneficial for captive power plants.
- There is an enormous retrofitting capacity of about 67 GW.

There are different technologies availabe – the most promising options seem to be molten salt, rock-based and sand-based solutions. Molten salt offers the highest TRL. The solid-based concepts can score with the significant lower costs of the storage material. Therefore, it is recommended that feasibility studies be conducted at one or two power plant sites. The retrofit potential should be investigated in detail, considering different technology options. Taking the ages and unit sizes into account, it is recommended that a 200 MW plant is selected in a first step and a 500 MW plant in a second step. For both plants, retrofitting options should be elaborated. The inclusion of world-wide expertise on the three technologies is required to ensure a holistic and objective analysis.

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