

Repurposing Coal-Fired Power Plants Integrating the Use of Second-Life Batteries, Flywheels, and High Temperature Molten Salt Storage



M. Esther Rojas, Marcos Lafoz, Margarita M. Rodríguez-García,
Eduardo Rausell, Gustavo Navarro, and M. Rocío Bayón

Abstract The chapter explores the transformation of coal-fired power plants into sustainable energy facilities through the integration of advanced storage systems. Historically, coal-fired plants operated with inflexible schedules and slow response times, making them unsuitable for modern grids reliant on renewable energy. Repurposing these plants into Thermal Storage Power Plants (TSPP) replaces coal-fired combustion with molten salt thermal energy storage, leveraging existing infrastructure to store renewable energy for electricity generation. To enhance flexibility, second-life batteries (SLBs), repurposed from electric vehicles, are integrated. These batteries, despite reduced capacity, provide cost-effective, sustainable energy storage for medium-term demands, extending their lifecycle through optimized conditions. Flywheels are also included, offering instantaneous power output to stabilize the grid while reducing SLB degradation. The resulting Hybrid Energy Storage System (HESS) combines TSPP, SLBs, and flywheels under a centralized control scheme. Flywheels manage short-term fluctuations, SLBs address intermediate demands, and TSPPs provide long-term, stable power. This system improves efficiency, minimizes degradation, and ensures grid stability. Case studies and examples demonstrate the potential of this model, highlighting its economic and environmental benefits. This innovative approach aligns with global decarbonization goals, offering a pathway to modernize energy systems while repurposing obsolete infrastructure effectively.

Keywords Thermal storage power plant · Second-life battery · Flywheel · Sustainable power generation · Hybrid energy storage

M. E. Rojas (✉) · M. R. Bayón
Thermal Energy Storage Unit, CIEMAT, Madrid, Spain
e-mail: esther.rojas@ciemat.es

M. Lafoz · E. Rausell · G. Navarro
Electric Power System Unit, CIEMAT, Madrid, Spain

M. M. Rodríguez-García
Thermal Energy Storage Unit, CIEMAT, Almería, Spain

1 Introduction: Requirements of the New Electric Grids

In the current climate situation, there is a global shift in the way electric power systems are structured. The traditional model, which relies on centralized generation facilities, is being replaced by a distributed approach that utilized renewable energy sources with energy storage solutions to mitigate intermittency.

Historically, thermal power plants have operated according to a fixed daily schedule. In particular, coal-fired power plants are able to provide flexibility services, including: partial load following; non-spinning reserve (meaning that they can be brought online within hours if needed); voltage support, by means of reactive power supply; inertia provision to stabilise the grid; operation at partial load, although it can increase wear and tear on the plant. However, these conventional coal-fired power plants are being shut down due to environmental reasons. Moreover, they have some flexibility limitations due to their slow ramping rate and long start-up time, which are associated with their inherent thermal processes, which are slower than other types of thermal power plants, such as natural gas, as well as hydroelectric plants.

The new paradigm of electricity generation gives rise to new considerations in relation to the operational requirements of power generation plants. These must be met in order to ensure reliability, efficiency, and stability, while also enabling integration with renewable energy sources and compliance with grid codes (Martínez-Lavín et al. 2022). Furthermore, the provision of greater flexibility to the system will result in a more economically viable power plant.

Gas turbines, small hydroelectric plants and energy storage technologies with faster response, such as batteries, flywheels and supercapacitors, are better placed to provide flexibility services. Combining a coal-fired power plant with one or more of these storage options would enhance its flexibility and security.

This chapter explores the potential for repurposing coal-fired power plants by utilising thermal energy storage in place of the coal combustion chamber. Furthermore, an additional energy storage system based on second-life batteries is integrated to provide new auxiliary services, extending the concept of repurposing. Finally, in order to implement the performance characteristics of second-life batteries, extending their lifetime, and achieve even higher system flexibility, a third energy storage technology is considered: a short-term, high-power storage unit based on flywheels.

The system is designed to be a fully integrated hybrid energy storage system, capable of meeting significant power demands through the integration of three distinct storage technologies.

2 Repurposing Coal-Fired Power Plants

Coal-fired power plants worldwide are facing challenges due to low-capacity utilisation levels and environmental concerns. An increasing number of governments have implemented plans to achieve a carbon-free future. To date, over 100 countries have

joined an alliance with the objective of achieving net-zero emissions (Song et al. 2021). A number of countries, including Norway, Finland, Sweden, and Uruguay, have set a target to achieve net-zero emissions by 2030. Other countries, such as UK and Canada, anticipate reaching net zero carbon emissions by 2050, while China is targeting 2060.¹ Furthermore, coal-fired power plants have become unprofitable to utilities and uneconomical to customers (Forbes 2018). As outlined by (Song et al. 2021), countries have implemented mainly two measures to regulate the current coal-fired power plants. One approach is the coal retirement mechanism, which would allow for the elimination of existing coal-fired power plants within 10–15 years, rather than the currently expected 30–40 year to remain operational. The second measure is to replace obsolete coal-fired power plants with an integrated mix of efficiency measures, including, for example energy storage systems or renewable power generation.

Kefford et al. (2018), analysed the impact of **early retirement** of coal-fired power plants on asset owners and communities in four regions, namely, China, India, the European Union, and the United States. Notable examples in USA of Repurposed Coal Fired Power Plants are the following:

- Plant Scherer, Georgia²: Once one of the largest coal-fired power plants in the U. S., Plant Scherer successfully transitioned into a biomass plant.
- Fisk Generating Station, Chicago (see footnote 2): The Fisk Generating Station underwent a remarkable transformation by converting its operation to natural gas-fired power generation.
- Mount Tom Power Plant, Massachusetts³: Currently operated by Mt. Tom Solar LLC, it was commissioned on 2018 as a PV power plant and started energy operation the same year with a peak capacity of 7.6 MW_e.

The conversion to a biomass power plant (first example) allows the power block of the former coal-fired power plant to be still used. In contrast, the transformation to a gas-fired or to a PV power plant (second and third examples) only utilises the land available at the power plant, along with the civil and power transmission system (Thomas and Akhtar 2023).

Reducing the use of fossil fuel consumption in coal-fired power plants, while increasing their peaking capability, is the approach followed by AES Gener in Chile. In 2009, they began replacing the 7 MW_e of coal-fired thermal capacity with 20 min lithium-ion battery capacity. AES Gener deployed a similar strategy at the 554 MW_e Eléctrica Angamos plant in 2012, installing 20 MW_e of 20 min battery capacity, and at the 531 MW_e Cochrane Power Station in 2016, where a comparable volume was installed. Another method for enhancing the flexibility of existing coal-fired power plants is to integrate a thermal storage system within the power block, to be

¹ <https://chinaeucn.com/carbon-neutrality-china/#:~:text=In%20September%202020%2C%20president%20Xi,%E2%80%9Ccarbon%20neutral%E2%80%9D%20by%202060>

² <https://petroedgeasia.net/repurposing-and-recommissioning-coal-fired-power-plants-for-A-sustainable-energy-transition/>

³ <https://database.earth/energy/power-plant/mt-tom-solar-project-hybrid>

charged by the main or reheated steam and discharged to the low-pressure turbine or condenser (Wang et al. 2023; Zhang et al. 2024).

3 Thermal Storage Power Plants

An interesting option for the early retirement of coal-fired power plants is so-called Thermal Storage Plants. This reuses existing equipment such as steam turbine, heat recovery boilers or heat exchangers, but replace the coal combustion chamber by a high-temperature thermal energy storage system, mainly of the type already developed and commercially available for Concentrating Solar Thermal Power (CSTP) plants, which is charged by renewables such as PV or wind, in practice adopting the Carnot Battery concept.

Thermal storage systems for commercial CSTP plants are based on a system known as the double-tank configuration. The storage medium is a non-eutectic mixture of sodium and potassium nitrate salts (solar salt) in the liquid state, stored at high temperature in one of the tanks. When the system is discharged, the thermal energy is transferred to the power block, and the molten salts are stored in another tank, called the cold tank (Fig. 1). The limitation imposed by the maximum size of metal tanks on the amount of energy that can be stored is overcome by using several systems in parallel. Notable CSTP plants with thermal storage systems of large capacity include Noor II and Noor III, which have 200 MW_e/1200 MWh_e (6 h of nominal power output without solar input) and 150 MW_e/1125 MWh_e (7, 5 h of storage capacity), respectively (SENER, 2022a, 2022b), or Atlántica Solana Generating Station, in Arizona, with 250 MW_e/1500 MWh_e (6 h at nearly nominal power, (Atlantica Sustainable Infrastructure PLC)). The current average investment cost for CSTP-TES systems is around 40 €/kWh_e (Crespo 2020).

Fig. 1 Molten salt thermal storage system at MASEN (Morocco)



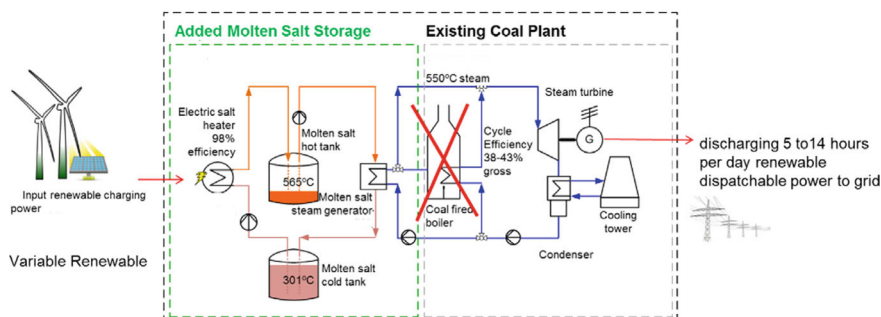


Fig. 2 Scheme of a thermal storage power plant: integration of a two-tank molten salt storage into an existing coal-fired power plant (adapted from Geyer et al. 2020)

In the retrofitted (coal-fired) power plant, the molten salt would be heated using electric resistance heaters or microwaves (Rodríguez-García et al. 2023), powered by renewable electricity. In this way, the excess or curtailed variable power available in the grid from photovoltaic and wind power plants can be stored as thermal energy. The stored thermal energy is then released by pumping the hot salt through a turbine steam generator system. In this process, heat is transferred from the salt to the turbine steam, which is then returned to the cold tank after cooling. The turbine steam is then used by the existing steam cycle of the former coal-fired power station to generate electricity (see Fig. 2). The components of a thermal storage plant are mature technologies, but the combination of technologies represents a novel approach (Geyer et al. 2020).

The concept of Thermal Storage Power plants has been developed since 2018 (Deign 2021), but not such a project has been realized yet. This may change in the near future thanks to the Alba project, which will transform the Angamos coal-fired power plant (560 MW_e), located in Mejillones (northeast Chile), into a thermal storage power plant. The Chilean authorities approved the environmental study submitted by AES Andes in December 2023 (EnerData 2023).

4 Hybrid Energy Storage with Second-Life Batteries

To enhance the flexibility of the Thermal Storage Power Plant, the potential use of batteries, such as lithium-ion, has been explored. The use of batteries in a (thermal energy storage) power plant offers the following advantages (Koike et al. 2018):

- Batteries are able to respond almost instantaneously (within milliseconds to seconds) to frequency deviations. This makes them an ideal solution for primary frequency regulation, fast ramping for load following and other types of fast responses to changes in demand or fluctuations in renewable energy generation.
- Batteries can be precisely tuned to deliver the optimal output power.

The development of electric vehicles (EV) has increased in recent years in line with EU goals to reduce the CO₂ emissions from the transport sector. Batteries are typically discarded after being used in an EV when they have reduced by of 20–30% of their nominal capacity. However, they have some remaining capacity that can be used in other applications, such as stationary energy storage with lower technical requirements. This extends the battery's useful life and contributes to environmental sustainability, enhancing the circular economy (Thakur et al. 2022) and reducing the dependence on critical materials (Wu et al. 2020).

These batteries are referred to as second-life batteries (SLB), also known as repurposed or reused batteries. They offer a promising solution to extend the lifecycle of EV batteries, which represents a significant cost factor (around 40% according to Shahjalal et al. 2021). It is anticipated that by 2025, approximately 3 million discarded EV batteries from vehicles with a total capacity of 953 GWh will still have potential for use as SLB. With regard to battery technology, lithium nickel manganese cobalt (NMC) batteries offer a more circular and environmentally sustainable option to lithium iron phosphate (LFP) batteries, with a Global Warming Potential of 4–6% and an Abiotic Depletion Potential of 13–16% for the minerals used (Picatoste et al. 2024).

The initial decision when considering a battery from an electric vehicle is to either retain those battery cells for a second-life application and extend their operation beyond the original and first intent (SLB), or send them to recycling facilities (Takahashi et al. 2023).

An SLB system comprises a set of battery cells or packs, sourced from different EVs and, each with distinct characteristics. The SLBs are characterized by measuring internal resistance increase and capacity, and repackaged for a second life. They are classified into groups of cells with similar conditions and performance. SLB systems are designed to operate beyond the so-called 'aging knee', which is the threshold where the battery is expected to start degrading rapidly. However, it is possible to halt this process by optimizing the working conditions, thereby achieving a second-life potential of 4000–6000 cycles between 75 and 50% of the State of Health (SoH) (Gao et al. 2024).

It is essential to regulate the maximum electrical current of SLBs in order to maintain the desired level of degradation while ensuring an optimal SoH. This may result in the system being sized to the maximum peak power, which would entail a higher initial investment.

5 The Additional Support of Flywheels

To extend the operational range and to improve the power performance, it is advisable to consider the further hybridisation of the storage system with a technology capable of frequently delivering ultra-fast power peaks without experiencing degradation of SLBs. Thus, in order to enhance the SLB performance, it would be beneficial to consider complementary storage technologies, such as flywheels. This approach

is supported by various research studies, including those by (Lee and Wang 2008; Barelli et al. 2019; Glücker et al. 2021; Arani et al. 2020; Ayodele et al. 2020).

The use of batteries and flywheel combination in a power plant has been referenced in the case of a hydroelectric power plant (Casarin et al. 2023). Flywheels contribute to the flexibility market in two main ways:

1. they can provide high power peaks almost instantaneously (in milliseconds) to grid frequency deviations for primary frequency control and/or support secondary frequency control by providing energy over a few minutes. This makes them ideal for providing fast frequency response (FFR) services.
2. being connected to the grid through power electronic converters, they are able to provide voltage support and reactive power compensation.

In addition to the above, flywheels offer very high round-trip efficiency (85–95%), an almost unlimited number of charge-discharge cycles, a significantly lower environmental impact compared to batteries, and a sustainable manufacturing process that uses basic resources.

Similarly to the use of flywheels, the technology of supercapacitors can be combined with batteries, with a comparable operational profile than flywheels, although with some different features primarily associated with the specific application area. Some references of the use of batteries and supercapacitors operating co-ordinately for grid application are included in (Guo and Sharma 2016; Vaca et al. 2016; Akram and Khalid 2017; Kim et al. 2016).

With regard to the specific operation of the flywheel subsystem, it should be noted that it is composed of a set of parallel connected number of machines. They operate at a common DC voltage, connected to a grid-tie converter. However, they can provide independent power, depending on the system command (Torres et al. 2020).

6 The Complete Hybrid Storage System and Its Control Scheme

This section outlines the description of the hybrid energy storage system (HESS) that integrates a thermal storage power plant (TSPP) with second life batteries (SLB) and flywheels (FW) connected to the grid. The objective is to optimise plant operation for the management of both short-term power fluctuations (fast frequency response) and longer-term energy demands. By combining the rapid response of FW with the medium-term power regulation provided by SLB and the Rankine cycle run by the thermal energy storage system, this approach is set to offer enhanced efficiency, reduced SLB degradation, and improves grid stability.

The system configuration is shown in Fig. 3. It consists of a renewable energy source connected to the grid, where surplus energy from renewables is supplied to the thermal storage power plant or used to recharge SLB and FW. Flywheel and SLB are also implemented to handle short-term frequency and power fluctuations, delivering the rapid response that the thermal storage plant, due to its slower dynamics,

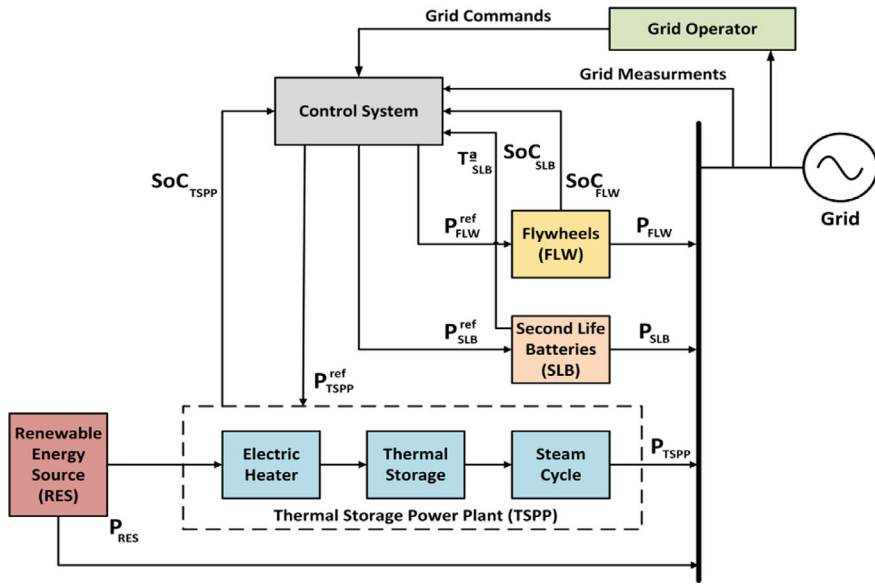


Fig. 3 Hybrid Energy Storage System (HESS) Configuration Scheme

cannot provide. A centralized control system operates the entire system, receiving grid commands and measurements, as well as monitoring the state of charge across all energy storage components.

The respective roles of each subsystem in maintaining optimal power output and grid performance under various operational conditions are described as follows:

1. **Power Request Input (Grid Commands):** The power grid controller sends a command to adjust the power in accordance with grid requirements, such as frequency control or load following. Alternatively, the power command could aim at controlling grid variables according to measurements right at the connection point.
2. **Flywheel Operation (Fast Response):** Due to their rapid response time, the flywheels are ideally suited to providing an immediate high-power output to smooth out short-term fluctuations. However, due to their limited capacity to store energy, they are only able to manage immediate peaks or drops in demand for short periods of time. Once the batteries or the thermal storage power plant are able to meet the required load, the flywheels should be switched off.
3. **SLB Operation (Intermediate Response):** As the flywheels discharge, the batteries respond more slowly to prevent high power spikes and their associated degradation. The maximum batteries power output is regulated by its state of charge (SoC_{SLB}) and temperature (T_{SLB}^a). In the event that the batteries over-heat or have a low charge, the system will reduce the discharge rate in order to extend their lifespan.

4. **Thermal Storage Power Plant Operation (Slow Response):** Due to its slow dynamics, the Rankine cycle is the last to respond. It gradually increases power output to absorb long-term demand, ensuring a steady supply once activated. The thermal plant adjusts its output based on sustained grid demand, reducing reliance on the flywheel and batteries once stable conditions are reached.

The different operation states of the Hybrid Thermal Storage Power Plant (HTSPP) are described in the scheme of Fig. 4. The system considers a certain power P_{RE} , coming from renewable energy sources, and a certain power demand coming directly from the grid operator (TSO) or based on measurements at the connection point, P_{grid} . Based on the difference between them, it is evaluated whether there is a surplus energy from renewables or not. If the grid demand is covered by the renewables (OP1) the HTSPP does not operate.

If there is a surplus on the renewable power, not used by the grid, this power is firstly used to recharge FW (OP2) and SLB (OP3), in case they need to be charged (SoC below the limits). The rest is used to supply the electric heater in order to charge the thermal energy storage system (OP4). Once being at this point, the HTSPP is fully charged (OP5) and further excess power will not be possible to be managed.

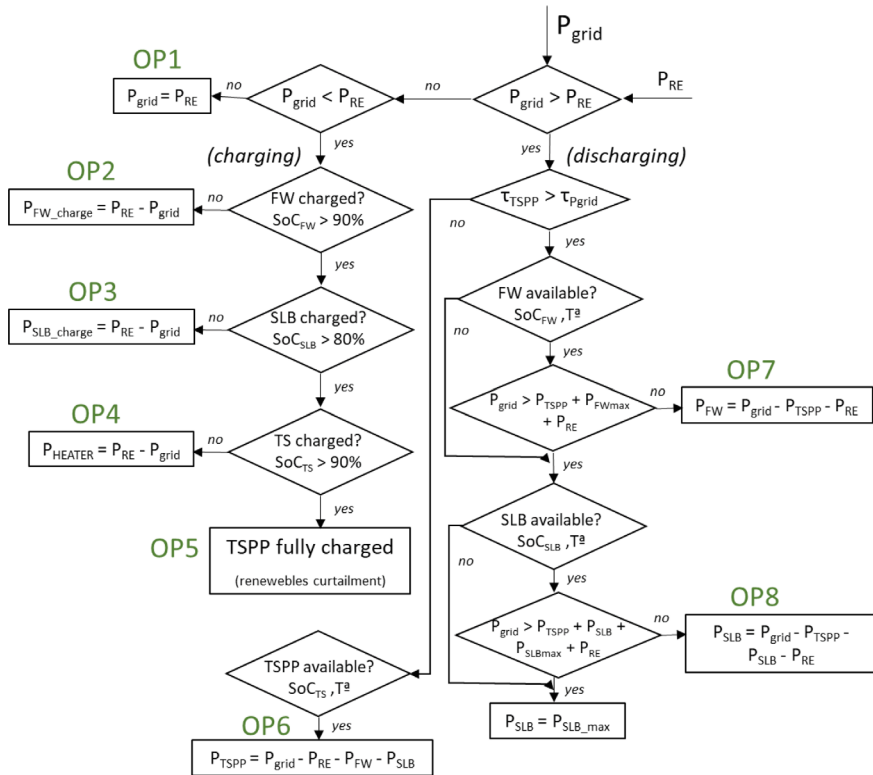


Fig. 4 Flux process diagram for the hybrid energy storage power plant

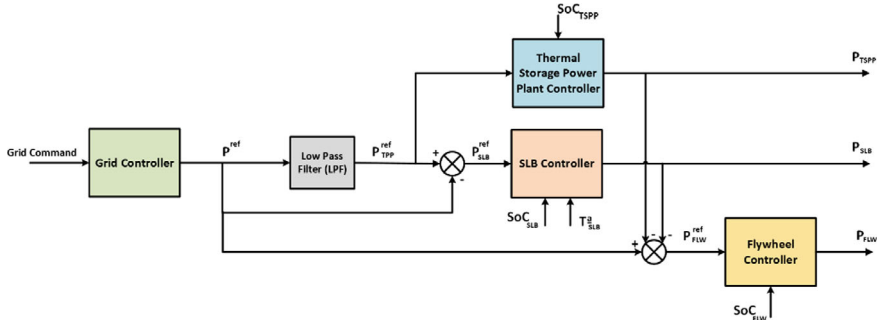


Fig. 5 Control scheme

Considering that the grid requires power beyond the renewable energy supply, the power is provided by the different subsystems of the HTSPP. In the case of rapid oscillations, if the time constant of the power requirements ($\tau_{P_{grid}}$) is lower than the time constant of the thermal power cycle (τ_{TSP}), the FW is firstly in charge of providing the faster response, considering that the TSPP will require a longer time to supply the required power, $P_{FW} = P_{grid} - P_{TSP} - P_{RE}$ (OP7). Once the FW reaches the minimum SoC or maximum power limitation, the SLB contribute to the power, $P_{SLB} = P_{grid} - P_{TSP} - P_{SLB} - P_{RE}$ (OP8). The TSPP will contribute to the required power whenever the response time and the rate value allow to provide it, $P_{TSP} = P_{grid} - P_{RE} - P_{FW} - P_{SLB}$ (OP6).

Coordinated Operation of a Thermal Power Plant with SLB and Flywheels

The coordinated control of the Hybrid Energy Storage System is illustrated in Fig. 5 and described in the following paragraphs.

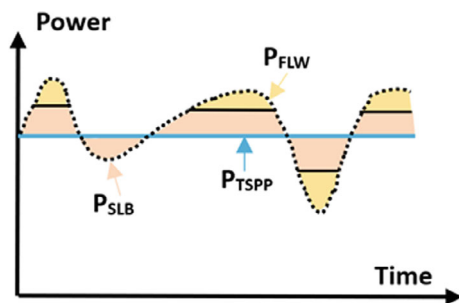
In case of stable power demand stable, with minor fluctuations, the flywheel responds to handle short-term fluctuations. Meanwhile, the battery stays in standby mode if its contribution is not needed, maintaining an optimal SoC and temperature to preserve its lifespan. The thermal power plant operates at a steady output, ensuring the base load power supply.

In case of sudden increase in the power demanded by the grid (P_{grid}) FW switch on immediately to absorb the required power spike, delivering high power for some seconds until it reaches its limited energy capacity. As the energy of the flywheels decreases, the battery activates after a short period, with its power output depending on the following factors:

- Batteries SoC: If the SoC_{SLB} is high ($> 80\%$), it can discharge at full power; if it is low ($< 20\%$), it limits power output to preserve battery health.
- Batteries Temperature, T_{SLB} : If the batteries temperature is high, power output is restricted to prevent thermal degradation.

As shown in Fig. 6, the thermal power plant remains unaffected, as the duration of the spike is too short to trigger its slow ramp-up process. A similar process occurs

Fig. 6 Power demand in time



during a sudden decrease in the power required by the grid, but in this case, flywheels and batteries charge until they reach their SoC limit. SLB handle more of the energy from these fluctuations, while flywheels can provide faster power peaks, reducing the load on SLB to absorb high power demands, which helps minimize their degradation.

On the other hand, when the grid demand increases the power supply for an extended duration, lasting several minutes to hours, the flywheels discharge, but they soon reach its minimum state of charge limit and is kept in a standby state until operating conditions allow them to be recharged. Subsequently, batteries take over to supply intermediate-term power, with their discharge rate adjusted according to SoC_{SLB} and $T^{\text{a}}_{\text{SLB}}$.

As demand persists, the thermal power plant slowly ramps up its output, delivering stable, long-term power to ensure a sustained supply. A similar process occurs during a sudden decrease in power, but in this case, flywheels and batteries charge until the SoC is limited and the thermal power plant ramps down slowly.

In conclusion, the control system prioritizes the flywheel for fast short-term power regulation, followed by the SLB for short and medium-term operation, and finally the thermal storage for long-term, stable power supply.

6.1 How Does This Hybrid Technology Improves the KPIs?

Table 1 describes the different KPIs associated with the three energy storage technologies involved (thermal storage, SLB and flywheels), as well as the KPI improvement from the combined installation and operation of the three technologies as a hybrid thermal storage power plant (HTSPP).

The main advantages of integrating the three technologies are:

1. Temporal complementarity. Thermal plant provides energy supply for many hours, batteries support loads for minutes to hours and flywheels provide power response in the range of milliseconds for grid stabilization.
2. Cost optimization. Thermal storage and SLB have low long-term costs. Flywheels reduce the cycling stress on the SLB, extending their life cycle.

Table 1 KPI analysis associated to the HTSPP

KPI	Description	SLB values	FW values	TES values	Hybrid storage
Energy storage capacity	Maximum energy the system can store, measured in kWh	- Industrial: 50–500 kWh - Grid-scale: > 1 MWh	- Small: 5–50 kWh - Large: Up to 500 kWh	up to GW _e h	Sum of capacities of thermal storage and batteries. FW handle short-term high-power scenarios
Energy density	Energy stored per unit of weight or volume	200–500 kWh/m³ (approximately 70–80% of C_N)	100–400 kWh/m³ for grid applications	26–80 kW_eh/m³	The low energy density of TES is compensated by high energy densities from SLB and FW
Output power	Maximum power the system can deliver	- Industrial: 50–100 kW - Grid-scale: 1–5 MW	- Industrial (e.g., UPS): 10–500 kW - Grid-scale systems: 1–5 MW	10–500 MW	Flywheels provide rapid-response power, while batteries and thermal storage handle sustained and larger-scale loads
Response time	The time taken by the system to respond to changes in load demand	< 1 s (similar to first-life batteries)	< 1 ms for power delivery - Extremely fast ramp-up	Minutes to hours depending on system design	Improved significantly since FW < 1 ms batteries: secs and TES in minutes to hours
Round trip efficiency	Ratio of energy charged to energy discharged (%)	85–95% (depending on the cells' state of health)	- Typical flywheels: 85–95% - Advanced vacuum-sealed systems: Up to 98%	30–40% (considering both the thermal and electric cycles)	Depending on the ratio of usage of the dif. Technologies, 60–80%

(continued)

Table 1 (continued)

KPI	Description	SLB values	FW values	TES values	Hybrid storage
Cycle life and durability	The number of charge-discharge cycles before the system degrades	1000–5000 additional cycles (depending on usage and maintenance)	Commercial systems: 10^5 to 10^6 cycles	5250–10,000 cycles (25–35 years)	FW increase the life cycle of SLB
CapEx and OpEx	CapEx: Initial investment. OpEx: operating and maintaining costs	Installation: 50–150 €/kWh (significantly lower than new batteries)	- Installation cost: 500–1000 €/kWh - Operational cost: \$0.01–\$0.05 per kWh/cycle	Installation: 20–55 €/kWh	CAPEX is increased but OPEX is reduced when using certain patterns
Size and weight	Physical dimensions and weight of the system	Similar to original battery size	- Compact designs: 0.1–0.5 m³ per 100 kWh - Weight: 10–50 kg/kWh	5–15 m ³ per MWh for molten solar salts	Not significantly modified from the initial size and weight since TES is dominant
Carbon footprint (kgCO ₂ eq)	CO ₂ emissions during manufacturing and operation	30–70% reduction compared to manufacturing new batteries	Minimal emissions during operation. Not relevant from fabrication	Minimal emissions during operation. Not relevant from fabrication	Not significantly modified from the initial values
Recyclability and end-of-life Impact	Recycling and disposing of system components	Lithium batteries have not very highly recyclable active materials	Made from recyclable materials (e.g., steel, carbon fiber)	Recyclable materials (e.g., molten solar salts, ceramics)	SLB reduce waste; flywheels and thermal storage use recyclable materials

3. Resilience of the system. Hybrid storage provides flexibility and redundancy to the power system.

References

- Akram U, Khalid M (2017) A coordinated frequency regulation framework based on hybrid battery-ultracapacitor energy storage technologies. *IEEE Access* 6:7310–7320. <https://doi.org/10.1109/access.2017.2786283>
- Arani AAK, Gharehpetian GB, Abedi M (2020) A novel control method based on droop for cooperation of flywheel and battery energy storage systems in Islanded microgrids. *IEEE Sys J* 14(1):1080–1087. <https://doi.org/10.1109/jsyst.2019.2911160>
- Atlantica Sustainable Infrastructure plc (no date) Solana. Available at <https://www.atlantica.com/web/en/company-overview/our-assets/asset/Solana/>. Accessed 28 Sept 2023
- Ayodele TR, Ogunjuyigbe ASO, Oyelowo NO (2020) Hybridisation of battery/flywheel energy storage system to improve ageing of lead-acid batteries in PV-powered applications. *Int J Sustain Eng* 13(5):337–359. <https://doi.org/10.1080/19397038.2020.1725177>
- Barelli L et al (2019) Flywheel hybridization to improve battery life in energy storage systems coupled to RES plants. *Energy* 173:937–950. <https://doi.org/10.1016/j.energy.2019.02.143>
- Casarin S, Cavazzini G, Pérez-Díaz JI (2023) Battery and flywheel hybridization of a reversible pumped-storage hydro power plant for wear and tear reduction. *J Energy Storage* 71:108059. <https://doi.org/10.1016/j.est.2023.108059>
- Crespo L (2020) The double role of CSP plants on the future electrical systems. In: WBG conference ‘Concentrating Solar for Power and Heat’
- Deign J (2021) Latin America’s energy storage leader is getting creative. Canary Media
- EnerData (2023) Chile approves AES Andes’ coal-fired power plant conversion project. Available at <https://www.enerdata.net/publications/daily-energy-news/chile-approves-aes-andes-coal-fired-power-plant-conversion-project.html>. Accessed 17 Sept 2024
- Forbes (2018) Energy innovation: policy and technology. India coal power is about to crash: 65% of existing coal costs more than new wind and solar. *Forbes Newsletter*
- Gao W et al (2024) Comprehensive study of the aging knee and second-life potential of the Nissan Leaf+ batteries. *J Power Sources* 613:234884. <https://doi.org/10.1016/j.jpowsour.2024.234884>
- Geyer M, Trieb F, Giuliano S (2020) Repurposing of existing coal-fired power plants into thermal storage plants for renewable power in Chile. Bonn, Germany
- Glücker Pet al (2021) Prolongation of battery lifetime for electric buses through flywheel integration. *Energies* 14(4):899. <https://doi.org/10.3390/en14040899>
- Guo NF, Sharma R (2016) Hybrid energy storage systems integrating battery and ultracapacitor for the PJM frequency regulation market. *IEEE Power Energy Soc Gen Meet*. <https://doi.org/10.1109/pesgm.2016.7741867>
- Kefford BM et al (2018) The early retirement challenge for fossil fuel power plants: a multi-region analysis of asset stranding and community impact. *Energy Policy* 123:367–379. <https://doi.org/10.1016/j.enpol.2018.08.014>
- Kim Y, Raghunathan V, Raghunathan A (2016) Design and management of battery-supercapacitor hybrid electrical energy storage systems for regulation services. *IEEE Trans Multi-Scale Comp Syst* 3(1):12–24. <https://doi.org/10.1109/tmscs.2016.2627543>
- Koike M et al (2018) Optimal scheduling of battery storage systems and thermal power plants for supply–demand balance. *Control Eng Pract* 77:213–224. <https://doi.org/10.1016/j.conengprac.2018.05.008>
- Lee D, Wang L (2008) Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: time-domain simulations. *IEEE Trans Energy Convers* 23(1):311–320. <https://doi.org/10.1109/tec.2007.914309>

- Martínez-Lavín M et al (2022) Evaluation of the latest Spanish grid code requirements from a PV power plant perspective. *Energy Rep* 8:8589–8604. <https://doi.org/10.1016/j.egy.2022.06.078>
- Picatoste A et al (2024) Comparing the circularity and life cycle environmental performance of batteries for electric vehicles. *Resour Conserv Recycl* 210:107833. <https://doi.org/10.1016/j.resconrec.2024.107833>
- Rodríguez-García MM et al (2023) Experimental and theoretical investigation on using microwaves for storing electricity in a thermal energy storage medium. *AIP Conf Proc* 2815(1):060003. Available at <https://doi.org/10.1063/5.0148703>
- Sener (2022a) Planta termosolar CCP NOOR Ouarzate II. Available at <https://www.group.sener/proyecto/planta-termsolar-ccp-noor-ouarzate-ii/>. Accessed 28 Sept 2023
- Sener (2022b) Planta termosolar de torre central NOOR III, en Ouarzazate (Marruecos). Available at <https://www.group.sener/proyecto/termsolar-torre-nooro-iii-ouarzate/#>. Accessed 28 Sept 2023
- Shahjalal M et al (2021) A review on second-life of Li-ion batteries: prospects, challenges, and issues. *Energy* 241:122881. <https://doi.org/10.1016/j.energy.2021.122881>
- Song F et al (2021) Review of transition paths for coal-fired power plants. *Global Energy Interconnection* 4(4):354–370. Available at <https://doi.org/10.1016/j.gloi.2021.09.007>
- Takahashi A, Allam A, Onori S (2023) Evaluating the feasibility of batteries for second-life applications using machine learning. *iScience* 26(4):106547. <https://doi.org/10.1016/j.isci.2023.106547>
- Thakur J, De Almeida CML, Baskar AG (2022) Electric vehicle batteries for a circular economy: second life batteries as residential stationary storage. *J Clean Prod* 375:134066. <https://doi.org/10.1016/j.jclepro.2022.134066>
- Thomas T, Akhtar K (2023) Repurposing coal-fired power plants: benefits and challenges, Hatch. Available at <https://www.hatch.com/About-Us/Publications/Blogs/2023/03/Repurposing-coal-fired-power-plants-benefits-and-challenges>. Accessed 27 Aug 2024
- Torres J et al (2020) Dimensioning methodology of energy storage systems for power smoothing in a wave energy conversion plant considering efficiency maps and filtering control techniques. *Energies* 13(13):3380. <https://doi.org/10.3390/en13133380>
- Vaca SM, Patsios C, Taylor P (2016) Enhancing frequency response of wind farms using hybrid energy storage systems. In: *IEEE International conference on renewable Energy research and applications (ICRERA)*. <https://doi.org/10.1109/icrera.2016.7884560>
- Wang B et al (2023) Effects of integration mode of the molten salt heat storage system and its hot storage temperature on the flexibility of a subcritical coal-fired power plant. *J Energy Storage* 58:106410. Available at <https://doi.org/10.1016/j.est.2022.106410>
- Wu W et al (2020) Does energy storage provide a profitable second life for electric vehicle batteries? *Energy Econ* 92:105010. <https://doi.org/10.1016/j.eneco.2020.105010>
- Zhang Q et al (2024) Dynamic characteristics and economic analysis of a coal-fired power plant integrated with molten salt thermal energy storage for improving peaking capacity. *Energy* 290:130132. Available at <https://doi.org/10.1016/j.energy.2023.130132>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

