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Technical and economic comparison of battery energy storage system and molten salts thermal energy storage for heat and electricity decarbonization by 2035

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Abstract:

This paper compares Battery Energy Storage Systems (BESS) and Molten Salts Thermal Energy Storage (MSTES) for the decarbonization of industrial electricity and heat by 2035. The comparison is structured around four families of Key Performance Indicators (KPIs): technical and operational, project and integration, economic, and environmental. BESS, represented by Lithium Iron Phosphate (LFP) systems, is naturally suited to electricity-oriented applications because of its high round-trip efficiency, compact footprint and fast response time. MSTES is better aligned with heat-oriented applications because of high thermal efficiency, long discharge duration, large storage capacity and favourable environmental performance per unit of useful heat. The methodology combines KPI screening with an optimisation workflow implemented in OptimHYSe, an internal mixed-integer linear programming tool used to size photovoltaic generation, conversion equipment and storage under operational constraints. Six configurations are assessed for a conceptual study of large project in the Middle East, covering electricity-only, heat-only and mixed heat-and-power delivery, each forced either to BESS or to MSTES. Results show that BESS remains preferred for electricity-only cases and MSTES for heat-only cases through 2035. For mixed supply, competitiveness is governed by renewable penetration and the ratio of electricity in the delivered energy mix, which defines practical decision abacuses for technology selection.

Keywords:

Battery Energy Storage System; Decarbonization; Hybrid energy systems; Molten Salts Thermal Energy Storage; Optimization.

1. Introduction

Industrial decarbonization requires storage solutions able to absorb renewable intermittency while serving both electricity and process-heat demand. In parallel with the large-scale deployment of lithium-ion batteries, molten salts thermal energy storage has reached commercial maturity in Concentrated Solar Power (CSP) plant and is increasingly considered for hybrid renewable systems. The question addressed in this paper is therefore not whether storage is needed, but which storage route should be preferred according to the energy vector to be supplied, the market context and the project horizon to 2035.

2. Technologies BESS & TES

2.1. Battery energy storage system

The BESS route considered in this study is based on lithium-ion batteries, with a practical focus on Lithium Iron Phosphate (LFP) chemistry because of its strong market position in stationary storage, good thermal stability, low degradation, favourable safety profile and competitive cost. A typical BESS plant includes battery containers, a Battery Management System, Power Conversion System, transformers, an Energy Management

System and auxiliary safety and thermal management equipment. The technology offers high electrochemical round-trip efficiency, compact layout and response times in the millisecond range, which makes it naturally adapted to electricity-oriented services and dynamic operational control.

2.2. Molten salts thermal energy storage

MSTES stores energy as sensible heat in nitrate salts, typically with a two-tank configuration comprising a cold tank around 290°C and a hot tank up to 390°C or 565°C depending on the architecture. Energy can be charged by solar thermal input or by electrical heaters supplied by electricity from renewables, then recovered either as useful heat through heat exchangers or as electricity through a steam generation system and turbine. The main strengths of MSTES are long discharge duration (typically > 8 hours), large-scale storage capacity, straightforward integration with heat demand and a favourable environmental footprint for useful thermal output. The main constraints are linked to high-temperature materials, heat tracing, civil works and slower dynamic response than batteries.

At a first level, the two technologies address different dominant applications. BESS is a direct electricity-storage route with high efficiency for power-to-power services, whereas MSTES is a heat-native storage solution that can also deliver electricity through a thermal power block. This distinction in the energy-conversion chain is central to the comparison: when the final product is heat, MSTES benefits from direct thermal delivery; when the final product is electricity, BESS avoids the conversion penalty associated with heat-to-power generation. Figure 1 provides an annotated aerial view of the MSTES central block based on the Andasol 1 reference layout and highlights the main functional subsystems involved in indirect molten-salt thermal storage integration, namely the TES area, Heat Transfer Fluid (HTF)/salt heat exchangers, HTF management section, steam-generation area and condenser/power-block section [9].

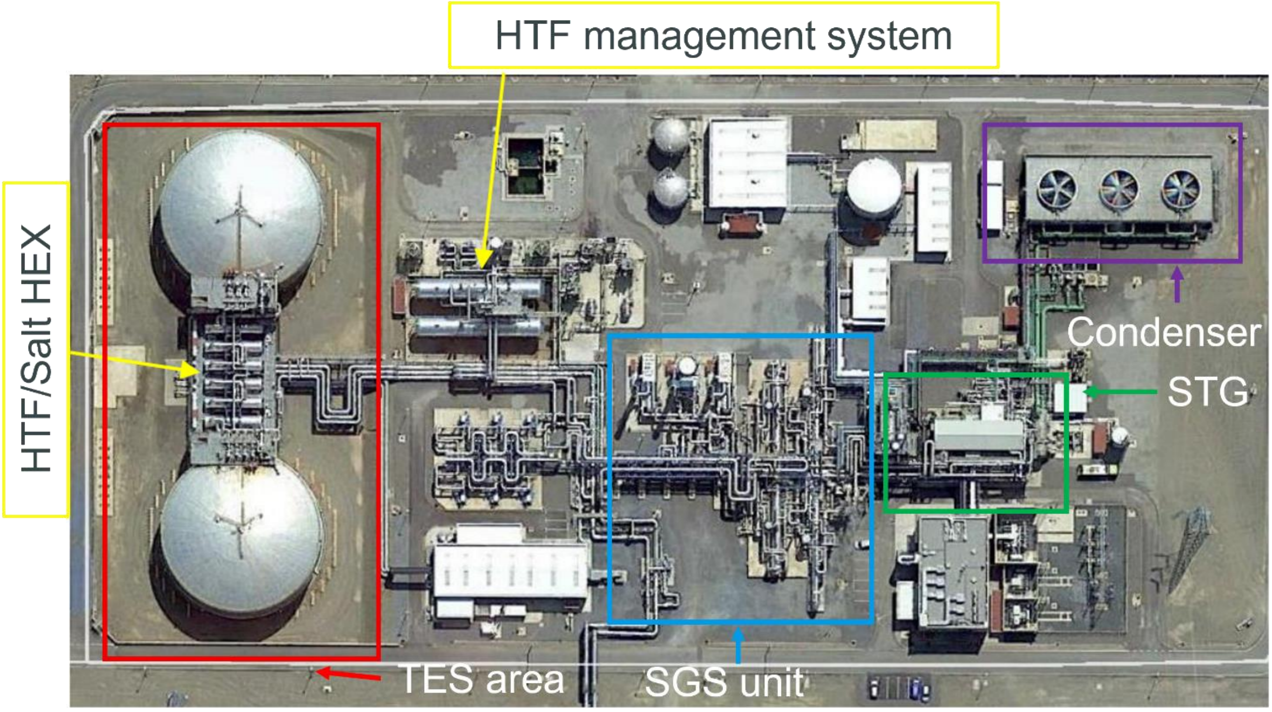

Figure 1. *MSTES annotated aerial view of an indirect molten-salt thermal energy storage (MSTES) central block illustrated from the Andasol 1 reference layout, highlighting the TES area, HTF/salt heat exchangers, HTF management system, steam-generation section (SGS) and condenser/power-block area. STG: Steam Turbine Generator. Adapted from Liberatore (2022), SFERA-III training material [9]; additional annotations by the authors.*

3. Overall comparison

3.1. KPI

The comparison framework is organised around four KPI families used consistently across the source material: (i) technical and operational KPIs, (ii) project and integration KPIs, (iii) economic KPIs, and (iv) environmental KPIs. This structure allows the study to move beyond a single cost metric and to capture the trade-offs between efficiency, duration, cycle life, footprint, execution constraints, cost and environmental performance.

The KPI comparison suggests a clear first-order reading. BESS is structurally advantaged for electricity output because it stores electricity directly and responds rapidly. MSTES is structurally advantaged for heat because it stores heat directly, scales efficiently to large capacities and exhibits a strong environmental profile for useful thermal output.

Data are presented in Table 1. Technical data are derived from technical sheets. The footprint is an estimation from project. CAPEX assumptions for BESS were derived from recent public procurement outcomes and public benchmark studies, distinguishing competitive tender outcomes from conservative benchmark values in both China and non-China markets [1–6]. For molten-salt thermal energy storage, recent public engineering studies in non-Chinese markets suggest practical CAPEX values, while a broader public European range supports the use of a more conservative envelope. The Chinese MSTES value retained in the manuscript remains an internal assumption pending stronger public project-cost evidence

Table 1. *Selected KPI comparison between BESS and MSTES (2025)*

KPI	BESS	MSTES	Unit / note
RTE	≈87%	≈98% for heat-to-heat ≈40% for heat-to-power	%
Storage duration	≤ 8h	>6h	Hours
Cycle life	> 3000*	> 10000**	Cycles
Project life	20-25	20-30	Years
CAPEX (2025)	**China:** L1: 59 $/kWh [1] L2: 84 $/kWh [2] L3:137 $/kWh [3–4] **Global out of China** L4:120 $/kWh [5] L5: 334 $/kWh [6]	**China:** **25–45 $/kWhth** **Global out of China:** 25 – 65 $/kWht [7] [8].	Public Source assumptions
OPEX	1.5%	1%	% of CAPEX
GHG indicator	33 - 440 gCO_2eq/kWh_e [19- 21]	9.8 - 31 gCO_{2eq}/kWh_e or 4 – 12.4 gCO_{2eq}/kWh_{th} [22-23]	Output basis dependent

For China, three levels are considered: a competitive lower bound L1 [1], a conservative market benchmark L2 [2], and a high conservative sensitivity L3 [3–4]. For non-China markets, two levels are considered: a competitive all-in project benchmark L4 [5] and a conservative full-system benchmark L5 [6]. For MSTES CAPEX in non-China markets, the retained values 25 – 65 $/kWh_{th}$ combine a practical engineering-based benchmark of 26–33 $/kWh_{th}$ [7] and a broader conservative public envelope extending up to 45–65 $/kWh_{th}$ [8]. Conservative values were considered for the study to demonstrate the methodology of long-term competitiveness comparison between BESS and TES.

Regarding GreenHouse Gas (GHG) parameter, for BESS, stationary-storage, Lifecycle Assessment Analysis (LCA) from National Renewable Energy Laboratory (NREL) reports a harmonized median around 33 gCO_2eq/kWh_e, although broader BESS literature shows substantially higher values under some assumptions and system boundaries, including reported ranges up to 185–440 gCO2eq/kWh [19 - 21]. For molten-salt TES/CSP, public electricity-basis values are typically in the range of about 9.8–31 $gCO_2eq/kWhe$, with a harmonized median around 28 gCO_2eq/kWh_e [22–23]. The values for heat applications are derived from the electricity basis values with a conversion factor power to heat of 40%.

3.2. Cost outlook: roadmap & markets

The cost outlook differentiates Chinese and non-Chinese markets for both BESS and MSTES. For BESS, the 2025 cost basis is anchored in recent system-cost benchmarks and in public learning-curve evidence showing lithium-ion learning rates around 20% per cumulative doubling of market size, together with a projected 40% global average cost decline from 2023 to 2030; public utility-scale projections further imply a medium-term decline envelope of roughly 3–7%/yr, so the study retains a central assumption close to 5%/yr over 2025–2035. [10–12].

This trajectory is consistent with manufacturing scale-up, especially in the electric-vehicle sector, which dominates battery demand and underpins industrial capacity expansion, while Chinese systems remain structurally cheaper than non-Chinese systems. [11,13]

For MSTES, two trajectories are retained. Hypothesis H1 is a conservative author assumption that applies only modest annual cost erosion (about 2–3%/yr) to a mature tank-based molten-salt storage technology; this assumption is consistent with public literature describing molten-salt TES as a mature commercial option in CSP and with public conservative to moderate CSP scenarios ranging from flat costs to gradual reductions under continued deployment and learning. [14–15]

Hypothesis H2 applies only to China and extrapolates the stronger cost compression already observed in the Chinese CSP sector, where public materials citing the China Solar Thermal Alliance report a 45.6% CAPEX decline for 100 MW tower-type CSP projects between 2018 and 2025, supported by a >90% localized supply chain and a multi-gigawatt project pipeline. [16–18].

On this basis, the paper retains an aggressive China-only MSTES learning path, corresponding to an estimated cost reduction of about 50% by 2030 and 57% by 2035 relative to the base value, while explicitly treating these latter figures as scenario extrapolations rather than direct published benchmarks. [16–18].

Figures 2 & 3 represent the cost evolution for heat and electricity applications respectively with moderate hypothesis of cost reduction for MS TES, and conservative CAPEX for both China and Non-China market at 45 $\$/kWh_{th}$. As a result, Chinese MSTES might remain structurally cost-competitive for heat applications across the time horizons considered, while BESS narrows the gap mainly in electricity-oriented applications. [2–3,7–9]. Other projections have been made according to the scenarios of cost reduction roadmap but not presented in this paper on methodology for cost projection and storage technology selection.

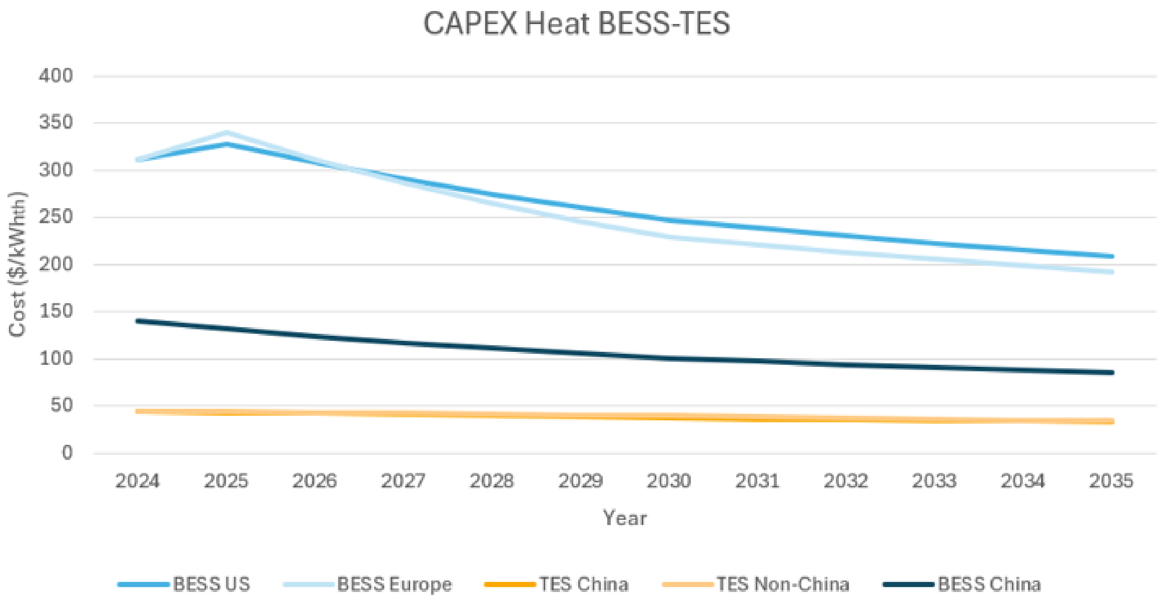

Figure 2. *BESS & MSTES CAPEX evolution if there are used to produce heat using hypothesis 1 for TES [\$/kWh$_{th}$]*

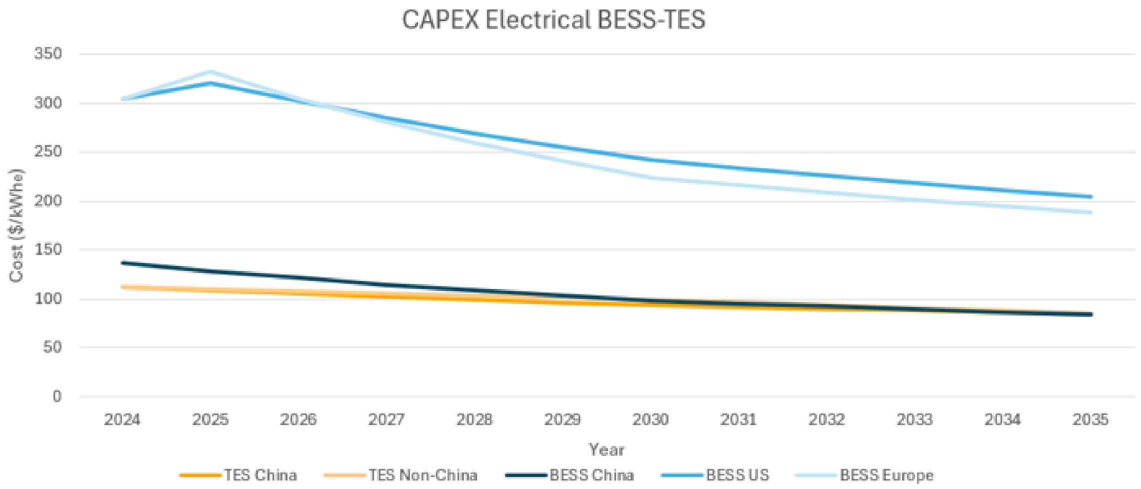

Figure 3. *BESS & MSTES CAPEX if there are used to produce electricity using hypothesis 1 for TES*

4. Methodology

4.1. Optimisation approach

The study relies on an internal tool dedicated to the optimization of the design and operation of multi energy systems[1]. In the present work, a mixed-integer linear programming formulation is used to co-size photovoltaic generation, storage capacity and electrical heater under demand and operational constraints. The objective function is to minimize total cost while meeting the targeted renewable share. The simulation is carried out at an hourly time step over one year, without considering degradation of any equipment.

4.2. Use case and sensitivity plan

The case study corresponds to a large project in the Middle East with approximately 170 MW$_e$ and 205 MW$_{th}$ of demand, day and night, and considered constant over project's lifetime. The heat demand is comprised between 180°C and 140°C. Six configurations are assessed: two electricity-only cases (A1 & B1), two heat-

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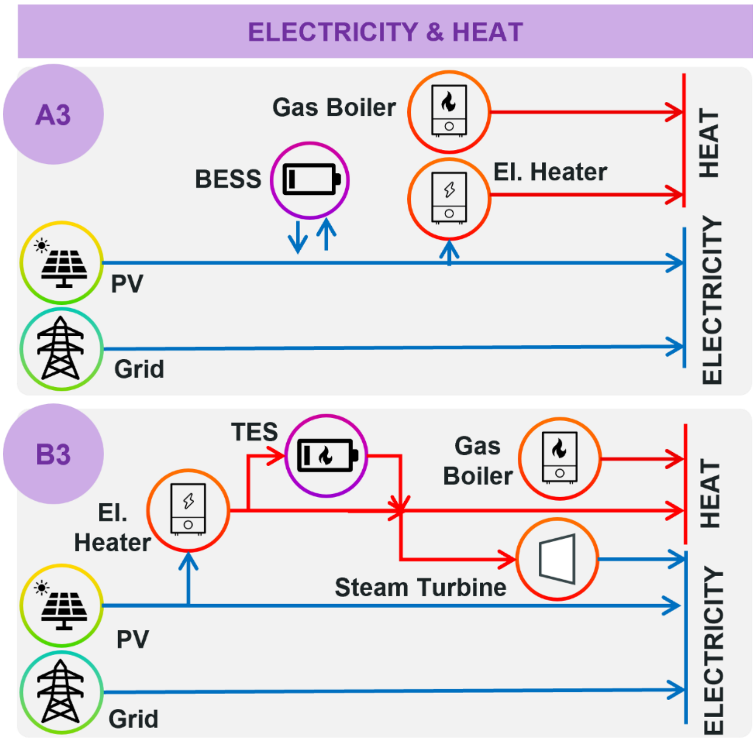
[1] TotalEnergies. Sustainability & Climate 2026 Progress Report. p.68

only cases (A2 & B2), and two mixed heat-and-electricity cases (A3 & B3) where the model is forced either to BESS (A) or to MSTES (B) (Table 2).

Table 2. *Naming of the six configurations*

Energy Demand	ELECTRICITY	HEAT	ELECTRICITY & HEAT
BESS	A1	A2	A3
MSTES	B1	B2	B3



As presented in Figure 4 and

Figure 5, PV is considered as the renewable energy resource. The back-up energy is provided either by the grid for the electricity or by gas boilers for the heat. Those two sources are considered as non-renewable energies and without any cost in the model.

An electric heater ensures the transformation of electricity into heat and a steam turbine is considered to transform heat to electricity.

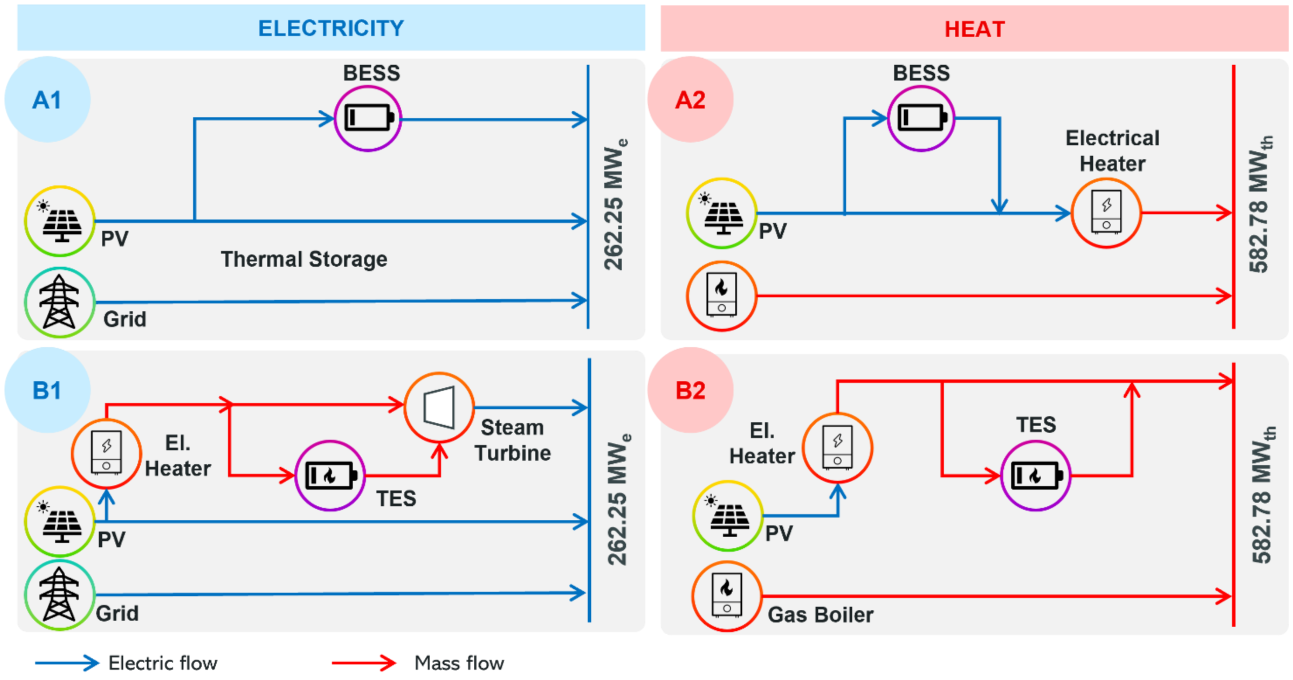


Figure 4. *Configurations A1 to B2 and associated power demand*

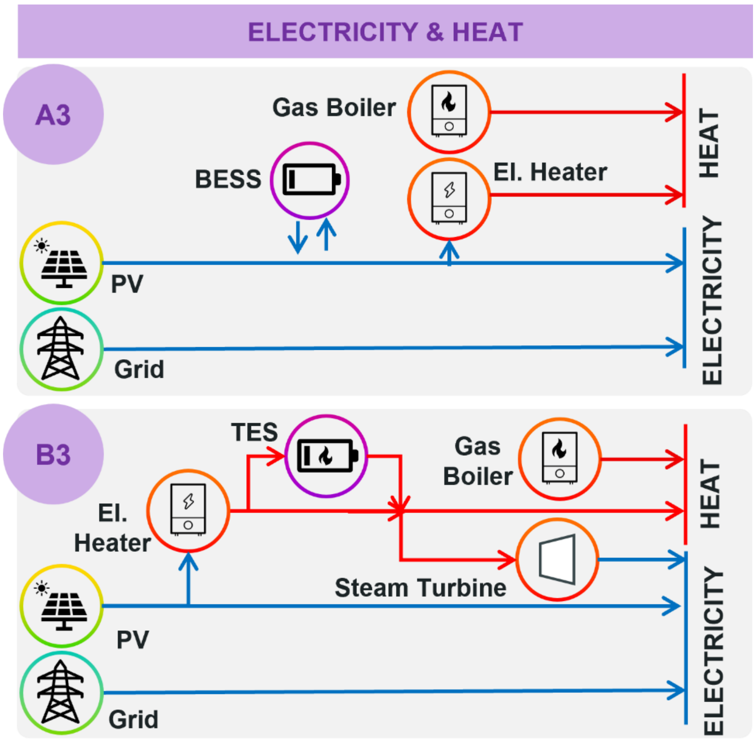


Figure 5. *Configurations A3 and B3*

A sensitivity analysis is conducted regarding the 3 following aspects:

- **Renewable penetration (RENP)**

For the 6 configurations, a sensitivity, from 40% to 100% of renewable share is realized where the renewable share is defined by Eq. (1).

$$RENP\ [\%] = \frac{Renewable\ electricity\ supplied\ [MWh_e] + Renewable\ heat\ supplied\ [MWh_{th}]}{Electricity\ demand\ [MWh_e] + Heat\ demand\ \ [MWh_{th}]} \quad (1)$$

- **Ratio of Electricity (RoE)**

For the mixed cases (A3 & B3), the sensitivity plan also varies the Ratio of Electricity (ROE in the delivered energy mix from 0% to 100%.
Equation (2) defines the ratio of electricity

$$RoE\ [\%] = \frac{P_{electricity}[MW_e]}{(P_{electricity}[MW_e] + P_{heat}[MW_{th}] \times \eta_{Heat\_to\_electricity}[\%])} \quad (2)$$

$\eta_{heat\_to\_electricity}$ corresponds to the conversion factor to go from heat to electricity.
$P_{electricity}$ corresponds to the electricity demand
P_{heat} corresponds to the heat demand

For this study, 45% is considered to reflect the efficiency of a steam turbine power block. Table 3 shows the details of the electricity and heat demand considered for each case.

Table 3. *Electricity and heat demand considered according to RoE*

	RoE, %	ELECTRICITY, MW_e	HEAT, MW_{th}
A1/ B1	100%	262.25	-
A2/ B2	0%	-	582.78
A3/ B3	30%	79	408
	50%	131	291
	65%	170	205
	90%	236	58

- **BESS and MSTES CAPEX**

For the CAPEX three time horizons are considered: 2025, 2030 and 2035, and 2 market assumptions: China and Non-China as presented in Table 4.

Table 4. *CAPEX sensitivity (\$/kWh$_e$ for BESS and \$/kWh$_{th}$ for MSTES) normalized to the Non-China 2025 configuration.*

	China 2025	Non-China 2025	China 2030	Non-China 2030	China 2035	Non-China 2035
BESS	47	100	36	69	31	57
TES	16	16	8	15	7	13

The size of the steam turbine is fixed for a given RoE (%) whatever the RENP (%). It is determined according to the electricity demand.

For the electric heater, its size is fixed and it is determined according to the heat demand for architectures A2 and A3. For architectures B1, B2 and B3, the electric heater size is a variable in the model.

The C-rate of the BESS is fixed for all the simulations to 4h.

4.3. Evaluation criteria

To evaluate the sizing, two KPI were contemplated: LCOS (Eq. (3)) and LCOE (Eq. (4)).

Levelized Cost of Storage defines the additional costs of sending electricity through a storage system.

$$LCOS\ [\$/MWh] = \frac{CAPEX_{Storage}+\sum_{t=1}^{n} OPEX_{Storage,t}+\sum_{t=1}^{n} Charging\ Cost_t}{\sum_{t=1}^{n} E_{Discharged}\,[MWh]_t} \quad (3)$$

Due to the difficulty in defining clear system boundaries for storage-related equipment (e.g. electric heaters) and in distinguishing between the respective energy flows delivered as heat to supply production and heat for storage, the use of LCOE was preferred to LCOS. Some equipment has a dual function.

LCOE (Eq. (4))evaluates the overall levelized cost of the hybrid plant excluding backup boiler and grid supply. Actualization isn’t considered.

$$LCOE\ [\$/MWh] = \frac{\sum CAPEX_{Global}+\sum_{t=1}^{n} OPEX_{Global}}{\sum_{t=1}^{n} E_{REN\ Delivered}\,[MWh_e+MWh_{th}]_t} \quad (4)$$

Where:

$$\sum CAPEX_{Global} = CAPEX_{PV} + CAPEX_{MSTES} + CAPEX_{BESS} + CAPEX_{EHT} + CAPEX_{STG}$$

$$\sum_{t=1}^{n} OPEX_{Global} = OPEX_{PV} + OPEX_{MSTES} + OPEX_{BESS} + OPEX_{EHT} + OPEX_{STG}$$

5. Results

5.1. Pure electricity and pure heat cases

For each renewable penetration target, a sizing is found by the model. A LCOE vs renewable penetration rate graph is used for the analysis of the results. Figure. 6 and Figure. 7 shows the results for the 100% Electricity case and 100% heat case, respectively.

The results confirm the qualitative screening. For electricity-only supply, BESS is the preferred technology across almost all market conditions and time horizons considered, with only limited high-renewable-penetration exceptions in non-China 2025 cases. For heat-only supply, MSTES remains preferred for all renewable penetration levels and all market assumptions through 2035. These two boundary cases establish a robust anchor for interpreting the mixed-production results.

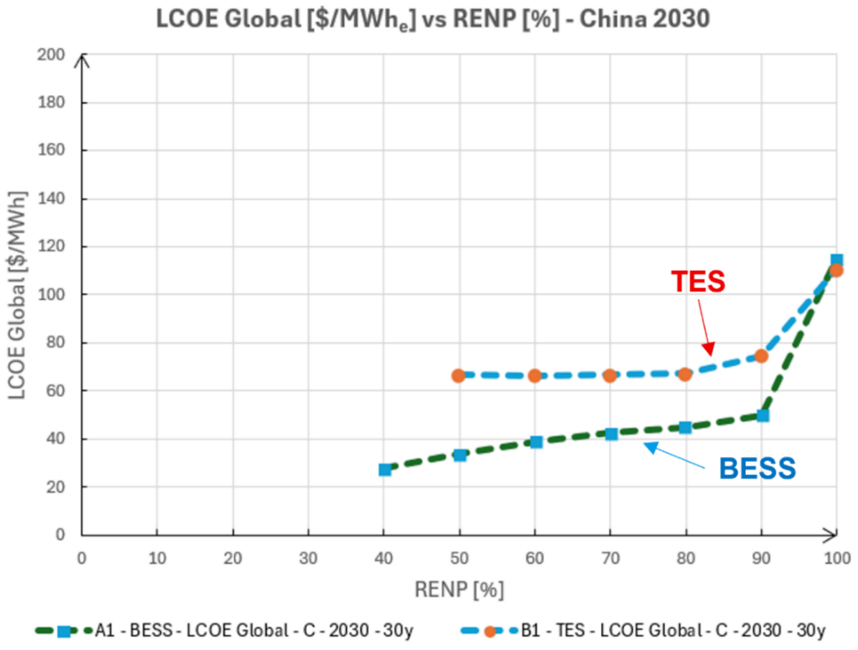


Figure 6. *LCOE [\$/MWh$_e$] vs RENP for A1 and B1 (RoE=100%) for China market in the horizon 2030*

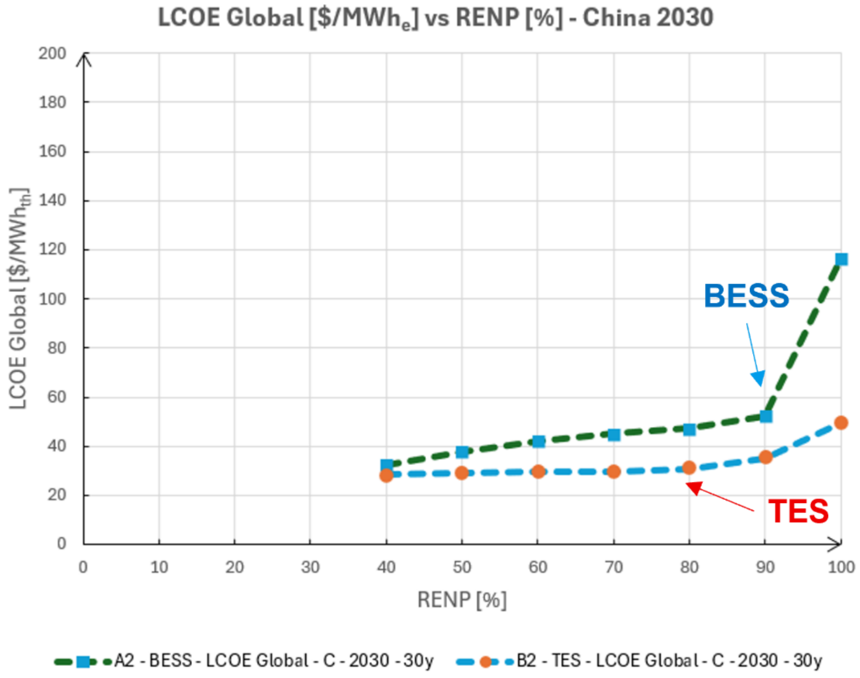


Figure 7. *LCOE [\$/MWh$_{th}$] vs RENP for A2 and B2 (RoE=0%) for China market in the horizon 2030*

5.2. Mixed heat-and-power results

The mixed-production configurations are the most decision-relevant because they capture the combined heat and electricity demand of the reference project. Results are synthesized through renewable-penetration versus ratio-of-electricity abacuses that identify the dominance regions of each technology (see Table 5 and Table 6). Two threshold variables structure the results:

- **Critical renewable penetration**, RENP$_{crit}$, which corresponds to the value of RENP separating two areas where competitiveness BESS vs TES evolves differently.
- **Critical ratio of electricity**, RoE$_{crit}$, which corresponds to the value of RoE separating two areas where one takes over the other technology for every RENP higher than RENP$_{crit}$.

Illustration of the methodology is done for two cases among six, reference case China 2025 in Table 5 and landing zone China 2035 in Table 6.

Table 5. *Abacus – LCOE – scenario China 2025*

RENP RoE	40%	50%	60%	70%	80%	90%
0%	TES	TES	TES	TES	TES	TES
30%	TES	TES	TES	TES	TES	TES
50%	BESS	TES	TES	TES	TES	TES
65%	BESS	BESS	BESS/TES	TES	TES	TES
90%	BESS	BESS	BESS	BESS	BESS	BESS
100%	BESS	BESS	BESS	BESS	BESS	BESS

Table 6. *Abacus – LCOE – scenario China 2035*

RENP RoE	40%	50%	60%	70%	80%	90%
0%	BESS/TES	TES	TES	TES	TES	TES

30%	BESS	BESS/TES	TES	TES	TES	TES
50%	BESS	BESS	BESS/TES	TES	TES	TES
65%	BESS	BESS	BESS	BESS/TES	BESS/TES	BESS/TES
90%	BESS	BESS	BESS	BESS	BESS	BESS
100%	BESS	BESS	BESS	BESS	BESS	BESS

Across the analysed cases, $\text{RENP}_{\text{crit}}$ remains relatively stable around 60–70% on an LCOE Global basis, whereas RoE_{crit} decreases over time as BESS costs fall. In non-Chinese markets, the decrease is more pronounced, with the TES-advantage frontier moving down by roughly 20 percentage points between 2025 and 2035. In China, the shift is more limited, around 5 percentage points, because MSTES also benefits from a favorable cost trajectory within this market. The resulting interpretation is operational: BESS gains competitiveness as renewable penetration decreases or as the electricity share of delivered energy increases; MSTES remains advantageous when a material share of heat must be supplied, especially at high renewable penetration. **Table 7** summarizes the results.

Table 7. *Summary of critical thresholds for mixed heat-and-power cases based on LCOE*

Market	**Year**	**$\text{RENP}_{\text{crit}}$**	**RoE_{crit}**
Non-China	2025	60-70%	90-100%
Non-China	2030	60-70%	85-90%
Non-China	2035	60-70%	65%-75%
China	2025	60-70%	65%-75%
China	2030	60-70%	65%
China	2035	60-70%	65%

5.2. Interpretation and limitations

The use of abacuses is one of the main outputs of the study because it translates detailed optimisation results into a project-screening tool. However, the current analysis remains subject to several limitations already highlighted in the source material. First, the sampling of renewable penetration and ratio of electricity could be refined near critical values. Second, only BESS and MSTES costs were varied; future work should also capture cost evolution for photovoltaic systems, electrical heaters and power blocks.. Finally, the environmental dimension has not yet been integrated directly into the optimisation-based ranking.

5. Conclusion

This paper confirms that BESS and MSTES should not be seen as substitutes with a single universal winner. They answer different dominant needs. Through 2035, BESS remains the preferred route for electricity-only applications, while MSTES remains the preferred route for heat-only applications. For mixed heat-and-power projects, the decision is governed by renewable penetration and by the ratio of electricity in the delivered energy mix. The resulting abacuses provide a practical decision aid for early project screening.

The comparison also shows that cost decline alone does not remove the structural advantages of each technology. Rapid battery learning improves BESS competitiveness, especially in non-Chinese markets, but thermal storage remains difficult to displace when significant heat demand is present. The next development steps should therefore focus on densifying the sensitivity grid, refining cost assumptions for the balance of plant, clarifying LCOS boundaries, and extending the analysis toward life-cycle assessment and broader application cases.

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Nomenclature

BESS	Battery Energy Storage System
BMS	Battery Management System
CAPEX	CAPital EXpenditure
CSP	Concentrated Solar Power
GHG	GreenHouse Gas
HTF	Heat Transfer Fluid
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCOE	Levelised Cost Of Energy
LCOS	Levelised Cost Of Storage
LFP	Lithium iron Phosphate
MSTES	Molten Salts Thermal Energy Storage
MILP	Mixed-Integer Linear Programming
NREL	National Renewable Energy Laboratory
RENP	RENewable Penetration
RoE	Ratio of Electricity
SGS	Steam Generation System
STG	Steam Turbine Generator
TES	Thermal Energy Storage

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