Journal of Energy Storage 166 (2026) 122442

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Short Communication

Framework conditions for multi-service Thermal Storage Power Plants in renewable energy systems

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ARTICLE INFO

Keywords:
Thermal Storage Power Plants
Thermal energy storage
Framework analysis
Energy transition
Residual load
Security of supply
Energy policy

ABSTRACT

Electricity systems with high shares of variable renewable energy increasingly face challenges related to residual load coverage, grid stability, and security of supply as conventional thermal generation declines. While numerous studies address individual technical, system-level, or regulatory aspects of these challenges, integrated assessments that jointly examine these dimensions remain limited. This short communication addresses this gap using Thermal Storage Power Plants (TSPP) as an example of a multi-service technology.

The study combines an illustrative scenario-based energy-system analysis for Germany with a structured review of policy, regulatory and market framework conditions. It examines why TSPP, despite demonstrated technical feasibility and system-level relevance, remain largely absent from current energy transition strategies.

The results indicate that TSPP can provide dispatchable renewable electricity, facilitate higher renewable integration, reduce electricity and fuel imports, and provide grid-stabilizing features and firm capacity through the repurposing of existing thermal power plant infrastructure. At the same time, current funding schemes, and regulatory structures, energy-system modelling approaches, and market structures assess these services largely in isolation, leading to an undervaluation of integrated system benefits and creating structural deployment barriers for multi-service technologies.

The findings of the policy, regulatory and market framework review imply that technology-neutral funding and regulation, holistic energy system models, and target-oriented remuneration for emission reduction, grid stability services, and combined heat and power applications are essential to reflect the full system value of multi-service technologies. Such a framework can enable multi-service technologies to realize cross-sectoral synergies and contribute to a more cost-efficient and resilient energy transition.

1. Introduction

The energy transition is widely debated, considering approaches ranging from systems based on nuclear and fossil fuels with carbon capture to renewable strategies. This study focuses on energy systems with high shares of photovoltaic (PV) and wind energy, as observed in countries like Germany, Spain, Portugal, Australia and Chile. The initial phase of the energy transition was marked by the straightforward integration of variable renewable energies (vRE), where PV and wind capacity could expand without significant curtailment, supported by conventional power plants providing residual load coverage. However, as vRE shares increase, the system enters a more challenging phase, requiring renewables to deliver flexible and secure power on demand to address the gaps left by intermittent generation. This study addresses the second stage, characterised by high vRE penetration and the concurrent phase-out of fossil-fuelled power plants. This leads to a volatile and intermittent residual load [1], resulting in lower efficiency and utilisation of the remaining dispatchable power plants [2,3]. Germany's coal power plants' full load hours reduced in 2024 to 55% relative to 2015 [4]. This leads to higher energy prices for these units [5]. Conversely, variable sources such as PV and wind power have become the cheapest electricity generation technologies available today [6]. Electricity spot markets reflect this phenomenon, showing low prices when vRE is widely available and high prices when the residual load is high [7,8]. As vRE shares continue to rise, curtailment becomes increasingly significant [9–11]. Furthermore, the decommissioning of

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https://doi.org/10.1016/j.est.2026.122442
Received 9 January 2026; Received in revised form 26 March 2026; Accepted 23 April 2026
Available online 1 May 2026

conventional thermal power plants results in a loss of synchronous rotating turbine masses, reducing available physical inertia and making inertial response for grid operation and stabilisation increasingly challenging [12–14]. Consequently, ENTSO-E predicts significant challenges regarding blackout risks in the near and medium future [15]. Additionally, security of supply and the resilience of the energy system are becoming increasingly important issues [16–18]. Conventional solutions, such as short-duration batteries, gas turbines, sector coupling, and retained conventional power plants, provide partial answers to these challenges, but fail to fully address long-duration residual load gaps, synchronous inertia needs, or resilience requirements. Consequently, technologies capable of delivering dispatchable renewable energy, firm capacity, and system services are gaining prominence.

Thermal Storage Power Plants (TSPP) combine multiple energy inputs, long-duration thermal storage and synchronous generation and have been shown to address these challenges from a technical and system perspective. Previous research has demonstrated their feasibility, flexibility and potential role in high-vRE energy systems. However, despite this technological readiness, the deployment of TSPP remains limited.

What has received little attention is how existing market design, regulatory structures and energy system modelling practices influence the valuation and deployment of such multi-service technologies. This short communication contributes to closing this gap by systematically analysing the framework conditions governing the transition of TSPP from technological readiness to market implementation.

2. Previous work and methodology

Previous research has developed and evaluated the TSPP concept at multiple levels (Fig. 1). The initial formulation presented the technical design and its integration into the German energy system [19]. Subsequent work refined the power-plant model, detailing configuration, operating modes and techno-economic parameters [20,21]. Further contributions applied GIS-based methods to assess the potential for converting existing power plant sites into TSPP and to quantify the photovoltaic and bioenergy resources required for such transformations [22,23]. More recent studies assessed the role of TSPP, their integration potential within a sector-coupled energy system and their relevance for a national-scale transition [24].

To position the present study within the broader literature on high-vRE electricity systems, Table 1 compares major research clusters according to four analytical dimensions that become increasingly relevant in renewable-based power systems: residual load coverage, grid stability, security of supply and framework conditions for deployment. In this context, residual load coverage refers to the remaining electricity demand after variable renewable generation, while grid stability includes static and dynamic stability aspects such as frequency control, voltage regulation and inertia provision. Security of supply is used here as an overarching term comprising both resource adequacy under normal system conditions and risk preparedness under extraordinary events. Framework conditions include research and technology funding, policy design, regulatory structures and market conditions relevant for deployment. Because many studies address only selected aspects within these broader categories, the terms are applied here as analytical umbrella concepts.

The taxonomy shows that existing work either extends cost-optimised energy system models towards greater technical robustness, addresses specific technical aspects of grid stability and inertia, or analyses deployment barriers for individual technologies. Integrated framework analyses across these dimensions remain largely absent.

The present short communication therefore links the multi-service characteristics of TSPP with policy, regulatory, modelling and market conditions relevant for deployment. The scientific research presented focused on adopting a qualitative–analytical methodology to examine structural barriers and enabling factors arising from the interaction of technology maturity, regulatory design, market structures and modelling practices.

The methodological approach combined two elements. First, an illustrative energy-system scenario analysis established a system-level

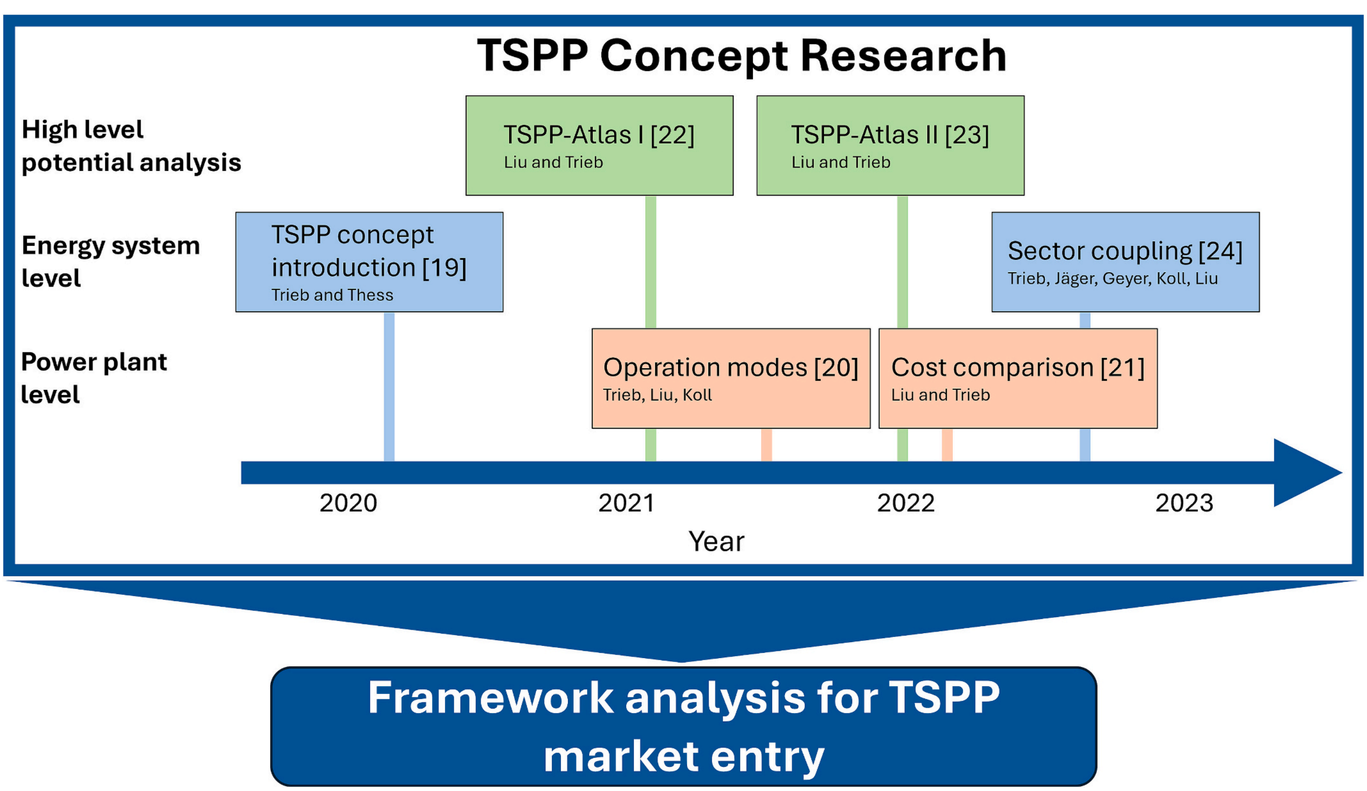

Fig. 1. Research on the TSPP Concept and scientific publications since 2020.

Table 1
Positioning of this short communication within major literature clusters addressing key challenges of high-vRE power systems, including residual load coverage, grid stability, security of supply and framework conditions for deployment.

Research cluster/main analytical focus	Representative studies	Residual load coverage	Grid stability	Security of supply	Framework conditions	Main limitations
Cost-optimised long-term energy system models and robustness extensions	[25–29] [16,30–33] [34–37]	✓	X	X	X	Cost-optimised energy system models for residual load coverage, but grid stability, security of supply and institutional deployment barriers are not represented. Extensions improve robustness through climatic variability, societal factors and availability of critical materials.
Grid stability-integrated energy system modelling	[38]	✓	✓	X	X	Introduces a reliability indicator related to the kinetic reserve, but security of supply, deployment barriers and institutional framework conditions remain outside the analytical scope.
Grid stability and inertia studies	[39–42]	X	✓	X	X	Focus mainly on virtual or synthetic inertia concepts, while multi-service generation technologies combining dispatchability, grid stability and firm capacity are not assessed.
Technology-specific framework studies	[43–45]	Partial [44]	Partial [45]	X	✓	Focus on individual technologies and selectively address deployment conditions; system integration aspects such as grid stability are only marginally considered, while security of supply is generally not assessed.
Previous TSPP research	[19–24]	✓	✓	✓	X	Demonstrates technical feasibility and system contribution of a multi-service technology, but does not examine institutional and regulatory framework conditions for deployment.
This study	Present work	✓	✓	✓	✓	Integrates multi-service technology characteristics with policy, regulatory, modelling and market conditions affecting deployment.

reference for electricity systems with high shares of variable renewable energy. The scenarios presented in Section 3 were not intended as an extensive scenario exercise, but served to identify key requirements of future high-vRE energy systems.

Second, a structured framework analysis was conducted across three dimensions: (i) research and technology development, (ii) policies and regulations, and (iii) market conditions. For each dimension, the current status quo was assessed based on publicly available data, policy documents and existing literature. Barriers to technology deployment were identified by analysing mismatches between system requirements and existing institutional arrangements. Based on this assessment, implications for an enabling framework that supports residual load coverage, resilience and decarbonisation were derived.

This combined approach bridged the gap between technical system potential and real-world deployment conditions, explaining why technologies such as TSPP remain underrepresented despite their system-

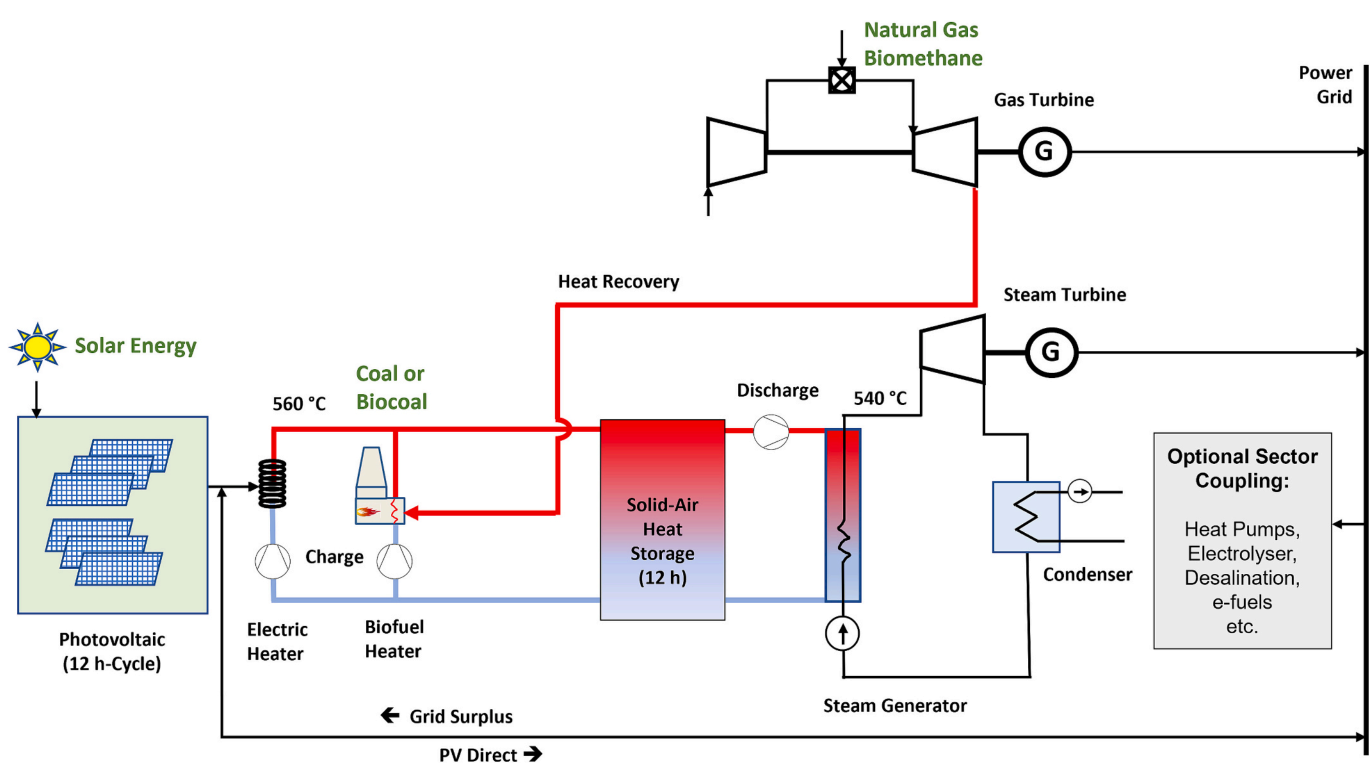

Fig. 2. Technical concept of a TSPP with a solid-air thermal storage [20].

level benefits.

3. TSPP technology and its role in the energy system

To provide a technical reference for the subsequent framework analysis, this section briefly outlines the TSPP concept and its role in electricity systems with high shares of variable renewable energy.

A TSPP consists of a photovoltaic power plant, a gas turbine, and a Carnot battery comprising an electric heater, a high-temperature thermal storage unit and a steam turbine, complemented by an additional co-firing unit (Fig. 2). Depending on the application and temperature requirements, the thermal storage can be based on molten salt or solid-air technology. PV electricity can either be supplied directly to the grid or, together with surplus grid electricity, converted into heat and stored in the thermal storage. This stored energy is subsequently reconverted into electricity through the steam turbine to cover residual load gaps, thereby transforming variable renewable generation into dispatchable power. For longer residual load periods, the co-firing unit ensures firm capacity. Peak power exceeding the capacity of the steam turbine is supplied by the gas turbine, whose waste heat is recovered either into the thermal storage or directly into the steam cycle. The heat-to-power efficiency of the thermal storage discharge cycle is around 40–41%, while the integrated combination of direct photovoltaic supply and thermal storage operation results in an overall PV-to-load efficiency of approximately 63%, with values of up to 70% depending on the share of directly supplied photovoltaic electricity and operating mode. Gas turbine and combined-cycle efficiencies are approximately 30% and 52%, respectively. Previous simulation studies further indicate reduced steam and gas turbine efficiencies under part load operation [20,24]. The gas turbine and co-firing unit can initially operate on fossil fuels and be progressively switched to renewable biofuels as they become available in the market.

In addition, heat can also be extracted at different temperature levels for industrial processes or district heating applications, linking dispatchable, renewable electricity and heat supply within one plant concept.

During periods of high vRE availability the steam cycle can be maintained in warm standby, preserving plant availability and synchronous inertia without continuous fuel consumption. The electric heater and gas turbine further enable grid-supporting services as both components can contribute to frequency regulation due to their rapid response capability. Additionally, the TSPP supports balancing requirements by absorbing surplus electricity and storing it thermally during oversupply periods, while the gas turbine can quickly deliver capacity during supply deficits. As a result, higher shares of variable renewable electricity can be integrated without proportionally increasing the need for additional grid reinforcement, redispatch and dedicated stability assets.

The overall TSPP configuration can be adapted to national and site-specific conditions, including solar irradiation, existing generation assets and the availability of dispatchable renewable resources such as hydro, geothermal or bioenergy.

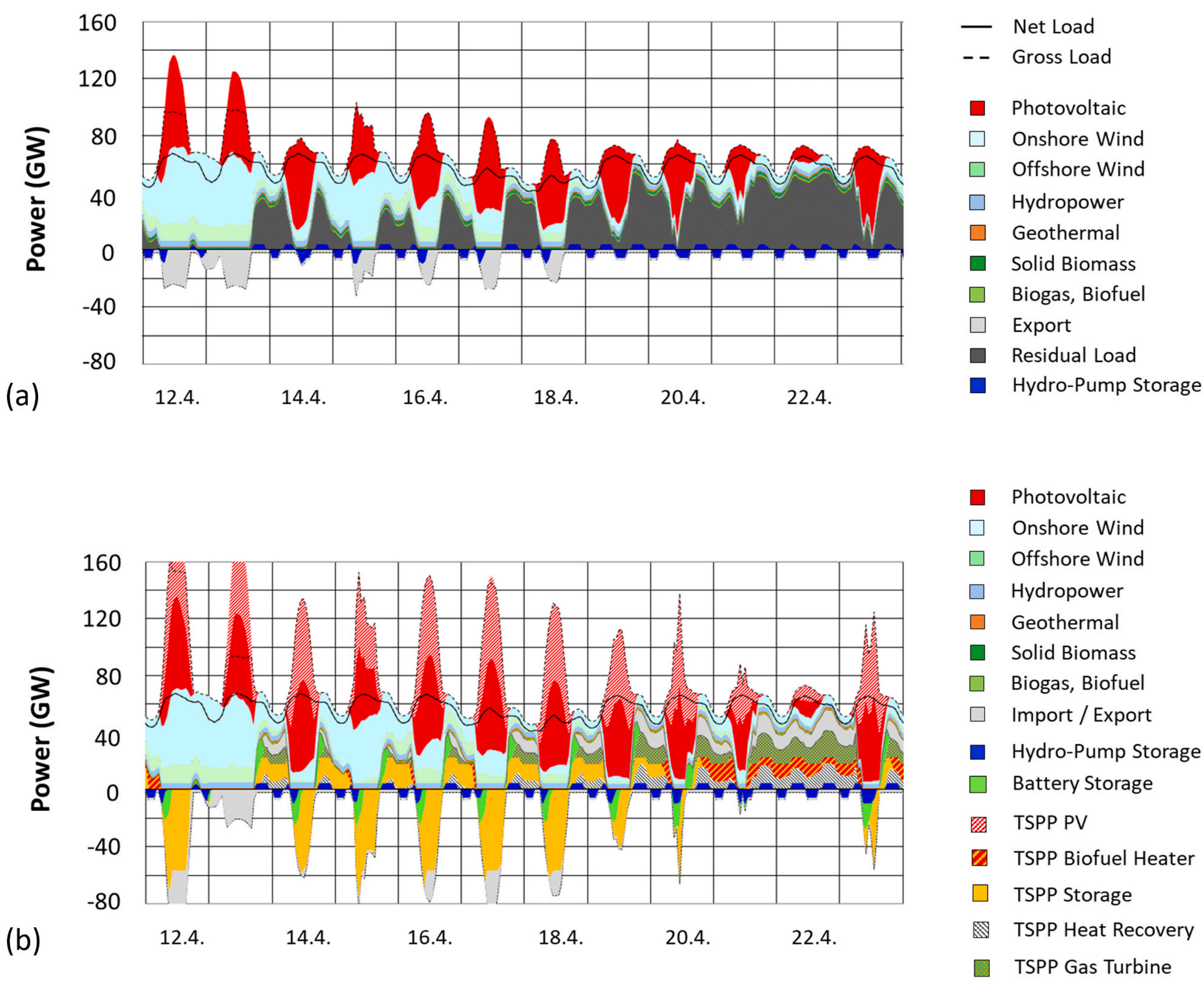

Fig. 3. Hourly dispatch time series of the RES 67% (a) and the TSPP 100% (b) scenarios for a representative twelve-day period.

To examine the challenges of high-vRE energy systems and the potential contribution of TSPP, a scenario targeting carbon neutrality by 2045 in Germany was developed. The base scenario (RES 67%) represents a system state in which variable renewable energy reaches a level at which further expansion would lead to increasing curtailment, while significant residual load remains during periods of low solar and wind availability. In this scenario, the resulting residual load is hypothetically covered by flexible gas-fired power plants and electricity imports, assuming sufficient flexibility and availability. To assess the system-level effects of TSPP in a highly renewable electricity system, a second scenario (TSPP 100%) was constructed by repurposing all remaining thermal power plants in the RES 67% system into TSPP. Detailed assumptions and data are provided in the supplementary material. Fig. 3 illustrates the characteristics of both scenarios using hourly dispatch time series over a representative twelve-day period in April. In the RES 67% scenario, residual load varies from periods of zero demand over multiple days to nightly patterns and multi-day phases with near-full load requirements, which are met by fossil generation and imports. In the TSPP 100% scenario, the same residual load profile is covered by flexible generation from the different TSPP components, complemented by batteries, pumped hydro storage and imports.

As a result, and compared with conventional thermal plants, the integrated thermal storage of TSPP enables greater flexibility in covering rapidly varying residual loads and allows surplus electricity to be absorbed, thereby reducing curtailment and grid load. At scenario level, this allows installed PV capacity and corresponding PV generation to almost doubled relative to the baseline scenario without significantly increasing curtailment (See Table 2). At the same time, imported electricity decreases from 119 TWh/a to 53 TWh/a, indicating a substantially lower dependency on external electricity supply. Approximately half of the electricity supplied by TSPP originates from integrated PV, stored surplus electricity and heat recovery, resulting in lower specific fuel consumption per kilowatt-hour.

The use of multiple primary energy sources - solar energy, surplus grid electricity and fuels - improves not only technical flexibility but also economic resilience, since plant operation can be adjusted according to fuel availability and price developments. In periods of high fuel prices, a larger share of electricity can be supplied through stored renewable electricity and power-to-heat operation, while fuel-based generation remains available for prolonged residual load periods, thereby supporting security of supply. This diversification reduces exposure to volatile fuel markets and contributes to more robust energy supply under uncertain geopolitical conditions, both at system level through reduced import dependency and at plant level through greater operational and economic flexibility in primary energy use. In addition, repurposing existing thermal power plant sites into TSPP preserves technically relevant infrastructure and enables continued economic utilisation under renewable operating conditions.

4. Analysis of framework conditions and roadmap for TSPP

As shown in Section 3, TSPPs exhibit strong technical and system-level potential in electricity systems with high shares of variable renewable energy. However, their deployment is considerably determined by the framework conditions governing technology assessment, remuneration and market integration.

Table 2
Indicators of the RES67% and TSPP 100% scenarios.

Scenario indicators	RES 67%	TSPP 100%
Demand (gross) [TWh/a]	550	550
PV - generation [TWh/a]	99	188
Curtailment [% of gross demand]	0.6%	1.5%
Imported electricity [TWh/a]	119	53
Electricity from fuels [TWh/a]	121	89

Therefore, in this section the framework conditions shaping the transition from technological readiness to market implementation for TSPP and comparable residual-load technologies were analysed. Fig. 4 synthesises the key framework dimensions analysed in this section and illustrates how research and technology development, policy and regulatory design, as well as market and societal conditions jointly influence the deployment of multi-service power plant concepts. The following subsections examine these dimensions in detail, identify the main barriers within each domain, and derive implications for creating an enabling environment that supports system stability, security of supply and high shares of variable renewable energy.

4.1. Research and technology

All key components required for a TSPP plant are commercially available. These include photovoltaic plants, high-temperature thermal storage systems (molten-salt and solid-air), electric heaters, biofuel co-firing units, and heat recovery systems. TSPP rely on technologies that are well established in concentrating solar power and combined-cycle power plants, and several first-of-its-kind projects are currently being planned or constructed internationally [46–48]. Key innovation priorities include enhancing efficiency, reducing operational and equipment costs as well as ensuring an appropriate lifetime. Furthermore, developments in power-to-heat systems focus on increasing energy output and efficiency [49,50] while advanced thermal storage systems that can reach higher temperature levels with improved material properties are being developed to increase power plant efficiency [51,52]. Additionally, research into the improved utilisation of biofuels [53,54], and increased flexibility of power-to-heat units and turbines plays a key role in achieving a more adaptive TSPP technology. Table 3 summarises the research focus areas for each TSPP component, highlighting that current activities primarily address performance optimisation rather than basic technological availability. Dedicated demonstration projects under real-world conditions—particularly in Europe—are still missing. Such projects are essential for validating performance, reducing investment risks and enabling the transition from concept to large-scale deployment.

4.2. Policies and regulations

Public policy shapes the technological landscape of the energy transition through targeted research funding and regulatory incentives. An analysis of German federal project funding in 2023 revealed a substantial imbalance in the allocation of public resources across technologies. Of the total project-funding budget of €1.08 billion, approximately €342 million—around 32%—was directed towards hydrogen technologies. In contrast, storage technologies and thermal power plants received about €34 million and €35 million respectively, each representing roughly 3% of total funding [78]. Although some funding categories, particularly those related to energy use in consumption sectors, do not provide a full technology-specific breakdown, the available data indicate a prioritisation of hydrogen over other technologies that contribute to system adequacy, flexibility and stability. Table 4 provides a structured overview of the funding categories and reported technology allocations.

Regulatory structures reinforce these asymmetries. As an example, the German Combined Heat and Power Act (KWKG) subsidises electricity produced in CHP (Combined Heat and Power) plants to promote efficient, low-carbon heat supply [76]. §6 KWKG clearly specifies the fuels eligible for these subsidies. For example, combined cycle gas turbines, which are included in the TSPP concept, are granted additional payments as long as they use natural gas or renewable fuel. However, electricity as a fuel subsidy is not listed as an eligible energy source. Consequently, TSPP are excluded from receiving equivalent payments, despite their ability to supply efficient, dispatchable and decarbonised electricity and heat in alignment with the objectives of the law.

These funding and regulatory conditions create uneven market

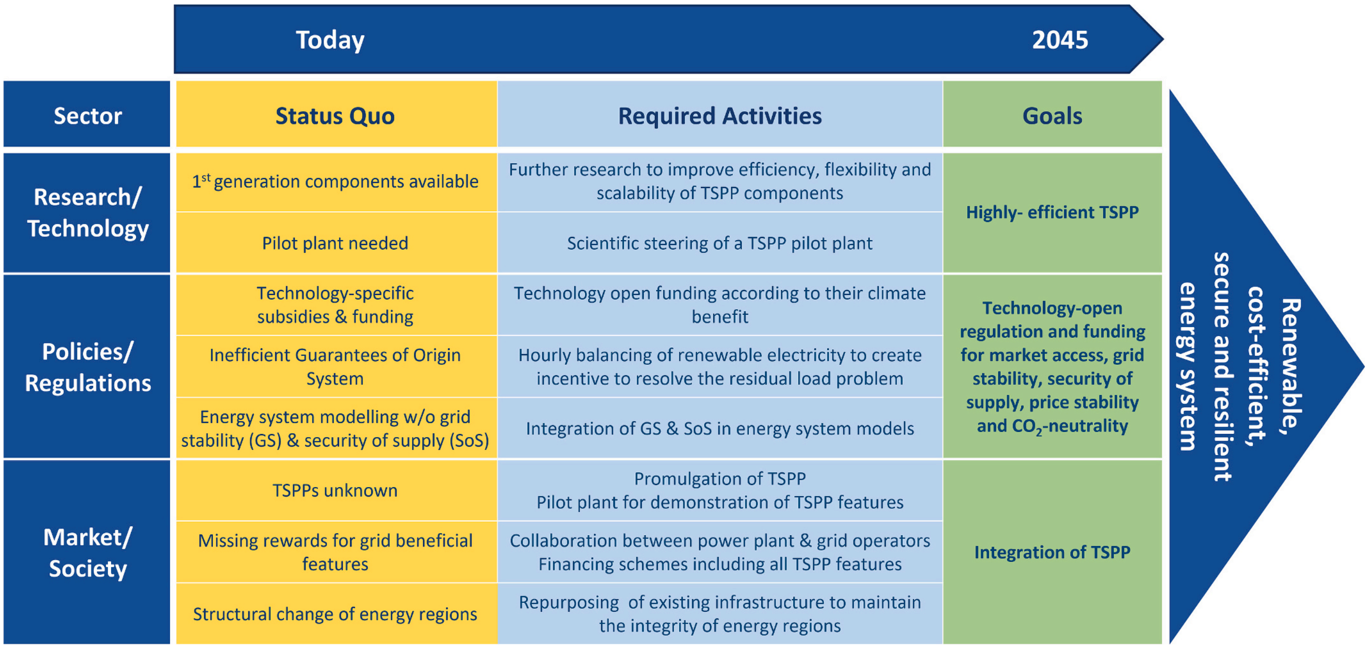

Fig. 4. Framework conditions governing the deployment of TSPP in high-vRE energy systems, structured along the dimensions research and technology, policies and regulations, and market and society.

environments and place TSPP at a disadvantage compared with other emerging technologies. Establishing technology-open policy frameworks that reward contributions to residual load coverage, stability and decarbonisation—rather than technology- or fuels-specific—will create more balanced conditions and enable technologies such as TSPP to compete based on their system-level benefits.

Another factor delaying the transition to true green electricity is the Guarantees of Origin system used for CO_2 emissions balancing. This system allows electricity consumers to declare their purchased electricity as green by purchasing certificates from renewable energy generators. In theory, the system enables green electricity to be traded over distances where a physical exchange of electricity is not feasible and therefore accelerate the integration of new renewable energy installation. In practice, however, the current implementation exhibits structural shortcomings that limit its contribution to the expansion of renewable energy.

Because GOs remain valid for up to one year after electricity generation, a persistent oversupply of low-cost certificates exists during periods of high variable renewable generation. Particularly in summer, large volumes of inexpensive GOs are issued. These certificates can subsequently be used during periods of low renewable availability, such as winter nights, when fossil generation is required to meet demand. As a result, fossil-based grid electricity can be declared virtually renewable at minimal cost at any time. This temporal decoupling eliminates economic incentives to develop and deploy solutions for renewable residual load coverage. Moreover, since a large share of GOs originates from regions with already high renewable penetration, the system provides little stimulus for additional renewable capacity expansion [79]. The low price of GOs weakens incentives for both producers and consumers to address the challenge of supplying electricity on a continuous, fully renewable basis. For example, industrial consumers can achieve emission reduction targets through certificate purchases without reducing actual emissions or investing in zero-emission energy supply or efficiency measures [80]. Consequently, the GO system, in its current form, allows compliance with climate targets while postponing investments in technologies required for firm and dispatchable renewable supply.

Introducing temporal granularity into the GO system—by limiting certificate validity to the hour of renewable electricity generation—would fundamentally change these incentives. Hourly matching would prevent temporal shifting of renewable attributes and create a dynamic certificate market with higher prices during periods of high residual load. Such price signals would better reflect the cost of providing renewable residual load coverage, as also highlighted by EPICO Klimainnovation and the Konrad Adenauer Foundation [81]. Some ambitious industrial players are already moving in this direction. For instance, the NGO EnergyTag unites renowned companies, including energy producers and consumers, and advocates for the international granular balancing of energy certificates [82]. Under such a framework, GO prices would become more volatile and increase precisely when system services are scarce, thereby generating appropriate revenues for technologies such as TSPP that enable renewable residual load coverage.

Energy policy decisions in many countries, including Germany, increasingly rely on long-term energy system scenarios. These scenarios are generated using large-scale optimisation models, as summarised in Table 1 under cost-optimised long-term energy system models and robustness extensions. While such models are indispensable for analysing feasible transition pathways, the underlying assumptions and scope of their modelling frameworks require careful and transparent assessment.

One critical aspect is the large number of input parameters required to represent the energy system at a sufficient level of detail. Energy system models integrate assumptions on future fuel prices, technology cost developments, the availability of system flexibility options, expected developments in neighbouring countries, and assumed net transfer capacities. Table 5 provides an overview of general key input parameters. For example, the German long-term scenarios (Langfristszenarien) of 2022 were based on more than 188 million generation variables [83]. The complexity of these scenarios increased even further in the 2024 modelling cycle leading to a doubled size of the linear programming problem [84].

Additionally, a closely related aspect is the high sensitivity of model results to individual input assumptions [85,86]. Small variations in key parameters can shift entire system configurations in the optimisation output. An example is provided by the German long-term scenarios, which assume hydrogen prices of around 100 €/MWh by 2030, combined with substantial domestic production and imports [25,87]. Under these assumptions, hydrogen-fired gas turbines emerge as the economically sufficient option for residual load coverage within the

Table 3
Availability and research status of key components of Thermal Storage Power Plants.

	Commercially demonstrated	Further research	Research projects
Electric heater	✓	High performance/ large scale electric heater	Molten salt electric heaters - DLRTESIS Test Facility [55], large scale electric heater [56], thermo-economic design of an electric heater [57]
		High temperature heat pump	Multistage turbomachinery optimization for high temperature heat pumps [58], simulation of a safe start-up maneuver for a Brayton heat pump [49], transient analysis and control of a Brayton heat pump [50]
Thermal storage	✓	Molten salt (290–565 °C): Higher temperatures for higher efficiency, higher storage capacities and further industrial applications	Performance evaluation of molten nitrate salt components at 620 °C [59], impact of elevated wall temperatures on nitrate salt stability [60], molten chloride technology for large-scale thermal energy storage at above 700 °C [61]
		Solid air (temperature range up to 1500 °C): Higher temperatures for higher storage capacities and further industrial applications	Experimental discharge analysis of a high-temperature thermal energy storage system [62], investigation of the dynamic behavior of Brayton batteries [63], high temperature sensible thermal energy storage [64], macro-encapsulated metallic phase change material over 1000 °C for high-temperature thermal storage [65]
Gas-& steam turbine	✓	Higher flexibility, H_2 compatible (GT)	Enhanced fuel flexibility [66], GT36 first stage development enabling load and fuel flexibility [67], impact of gas turbine flexibility improvements [68], fatigue lifetime assessment on a high-pressure heater in supercritical coalfired power plants during transient processes of operational flexibility regulation [69] Improving the load flexibility of coal-fired power plants by the integration of a thermal energy storage [70]
PV	✓	Energy and material efficiency, organic PV	Semitransparent organic photovoltaics [71], 20.2% efficiency organic photovoltaics [72]
Biofuel	✓	Biogas, biomass available. Research on improved flexibility and improved conversion technologies	Emerging technologies for biogas production [73], pilot-scale in-situ biomethanation of sewage sludge [74], hydrothermal conversion of biomass to fuels, chemicals and materials [54] Catalytic hydrothermal carbonization of pomelo peel [53] Business and market analysis of hydrothermal carbonization process [75]
1st TSPP	×	Pilot project for performance validation	In Europe, no pilot project exists. In China, 2 pilot projects of integrating Molten Salt Storage coal power plant (at Longshan & Suzhou) realised [76,77]

Table 4
Funding under the German government's 7th Energy Research Programme [78].

2023 [Mio. €]	Total project funding	Thereof H_2	Thereof storage	Thereof thermal PP	Other
Strategic funding formats	220	193	2	0	26
Energy transition in the consumer sectors	178	7	15	0	156
Energy generation	242			35	207
System integration	220	143	17	0	60
Cross-system research topics	164				164
Nuclear safety research	51				51
Sum	**1076**	**343**	**34**	**35**	**664**

optimisation framework. As a consequence, additional dispatchable solutions are not required in the model outcome, while alternative multi-service technologies such as TSPP are generally not represented as endogenous options. Conversely, assuming high availability of flexibility options—combined with a two- to threefold expansion of cross-border net transfer capacities—allows large amounts of variable renewable generation to be shifted temporally or geographically. Under such conditions, cost-optimised models frequently do not select storage technologies endogenously. For example, the German long-term scenarios assume large flexible electricity demands by 2045, including 61 GW of electrolyser, 93 GW of heat pumps and 76 GW in transport applications, which can shift demand under model-defined conditions [84]. Because these flexibility options are already embedded in the system, batteries are not selected endogenously and only appear when exogenously predefined [25]. A similar effect arises from the assumed increase of cross-border transfer capacities to around 80–93 GW [84], further reducing the endogenous need for storage technologies. Under these assumptions, load shifting or grid expansion appears more cost-effective within the optimisation than the deployment of storage technologies.

Together, these two characteristics— the extensive set of input assumptions and the marked sensitivity of resulting scenarios—underline the importance of a transparent and critical interpretation of long-term modelling results and their underlying input parameter set. This is particularly relevant when such scenarios inform strategic policy

Table 5
Overview of input parameters for energy system modelling (own data, [66]).

Hourly generation time series	• PV • CSP • Wind • Hydro • Geothermal • Tidal, Wave
Hourly load times series	• Electrical load • If sector coupling: electrical load of heat, mobility & hydrogen sector
Fuel and CO_2 cost	• Natural gas • Oil • Coal • Biofuels • Hydrogen and derivatives
Technology data	• Cost CAPEX (component) BOP (Balance of Plant) Grid connection Installation cost OPEX fix and var (incl. reinvestments as i.e. stack exchange for electrolysers) Project management • Efficiencies • Lifetime • Financing Costs • Flexibility data i.e. full flexibility, must run capacities, start-up times and costs • Current generation capacity • Power plant availability • Environmental parameters i.e. GHG- emissions, land use, fine particulate matter • Available potential (i.e. for renewable installations, biofuel use, cavern storage…)
Grid data	• Current grid status, expected grid extension.
Political influences	• Technology support • Decarbonisation goals • Retirement plans

decisions, as both the complexity of the models and the sensitivity of their outputs imply that results may change substantially under alternative but equally plausible assumptions.

Secondly, security of supply is divided into "resource adequacy" and "risk preparedness" based on European electricity market regulation [88–90]. The concept of "resource adequacy" is used to monitor the adequacy of the electricity supply via the mechanisms of the electricity market. It is founded upon optimised energy models calculating probabilistic indicators of the reliability of hourly demand coverage under a defined set of assumptions. Conversely, "risk preparedness" denotes the array of risk management strategies to guarantee security of supply in extraordinary and unforeseen circumstances, such as extreme weather conditions or political tensions. "Risk preparedness" is defined as a genuinely governmental task. This division in energy system modelling gives rise to a systemic blind spot. The likely increase in costs and responsibilities associated with risk preparedness is regarded as a public externality [88], while market mechanisms for "resources adequacy" and planning models are optimised for an idealised, risk-free system. As an illustration, the monitoring of security of supply ("resource adequacy") calculates a secure, market-based power supply for the subsequent years [88]. Concurrently, the cost of German grid reserve power plants and their operation escalated from €228 million in 2015 to €1 billion in 2022 and 2024 [91]. Furthermore, system analysis conducted by transmission system operators for the subsequent two years anticipates an augmentation in redispatch requirements, encompassing the demand for all reserve power plants and redispatch needs from neighbouring countries [92]. In conclusion, it is evident that this practice creates a fallacious representation of system costs and the needed capacities of controllable power plants. Moreover, it disregards the inherent resilience value of certain technologies and synergies that have the capacity to mitigate risks to a secure energy supply [93,94].

Thirdly, these models generally do not consider grid stability [12,16,17,84] and, as Ahmed et al. [12] state, there is an urgent need for research to define the amount of synchronous generation capacity required for stable grid operation. Illustratively, ENTSO-E subjected its energy scenarios based on cost-optimised energy system models to a frequency stability analysis. This analysis aims to verify that the European power system will not become unstable or collapse during major disturbances (e.g. system splits), and to determine the risk of blackouts. As a result, numerous blackout cases were identified, and in a simplified example, ENTSO-E calculated that 455 GW of additional kinetic energy would be required to solve all "global severe splits" in the National Trends 2030 scenario [15]. The additional kinetic energy can be provided by e.g. synchronous condensers or technologies with synchronous rotating masses such as TSPP.

Taken together, these limitations suggest that energy system models map the cost-optimised load coverage of complex energy systems under specific assumptions, while disregarding other significant elements that will increase in complexity and cost during the energy transition. Consequently, the results of energy system optimisations may be overly optimistic with respect to curtailment, local residual load coverage, security of supply, grid stability and system costs. However, it is precisely these issues that can be addressed by TSPP. If these energy system forecasts are utilised without adequately accounting for their inherent limitations, the result is an unduly negative assessment of multi-service technologies. Consequently, integrating all aspects of the energy system, regularly reviewing input assumptions, and integrating the TSPP technology option into the energy models are important steps towards achieving more holistic, realistic, and resilient energy system simulations.

4.3. Market and society

Awareness of Thermal Storage Power Plants in the energy market remains limited and requires targeted outreach to power plant operators, grid companies and investors through industry associations and professional networks. Demonstrating the technical and economic capabilities of TSPP under real market conditions is therefore essential. Pilot projects play a central role in validating their ability to simultaneously provide electricity generation, heat supply and grid-stabilizing services, and in translating their multi-service potential into bankable investment cases.

Current market structures, however, create significant barriers to the deployment of TSPP. Since the unbundling of electricity generation and grid operation in Germany in 2005 [95], power plant operators have been unable to capture the full value of grid services that technologies such as TSPP inherently provide. By compensating for local imbalances in supply and demand, TSPP can reduce network congestion, limit the need for transmission expansion and decrease redispatch volumes. In addition, their rotating turbine masses provide synchronous inertia, a service that is becoming increasingly critical as conventional thermal power plants are decommissioned [96]. Despite these benefits, existing remuneration schemes do not compensate power plant operators for providing synchronous inertia or for reducing grid congestion. While grid operators benefit from lower redispatch costs and enhanced system stability, these advantages are not reflected in the revenue streams of generation assets. This misalignment constitutes a market failure in which essential system services remain economically unvalued. Addressing this gap requires new forms of coordination between grid operators and power plant operators, enabling shared benefits from reduced redispatch and avoided grid expansion. Furthermore, the development of dedicated remuneration mechanisms for synchronous inertia would establish appropriate market signals and improve the investment case for technologies such as TSPP that contribute to system stability by design.

In parallel, suitable financing models are needed to reflect the multiple revenue streams of TSPP. Long-term power purchase agreements can provide investment security and reduce exposure to short-term price volatility. In addition, lowering implementation barriers through accessible and transparent planning tools is essential.

Beyond market considerations, the conversion of existing fossil power plant sites into TSPP offers important societal benefits, particularly in regions affected by the phase-out of coal-fired generation [97]. Repurposing existing infrastructure helps preserve skilled jobs and local value creation. This increases the social acceptance of TSPP technology and saves investments for reshaping the qualification fields in the regional education system. Moreover, the reuse of established sites significantly mitigates two major bottlenecks of new energy projects: grid connection and permitting - therefore reducing investment costs and shortening project development timelines. In this way, TSPP can contribute not only to system stability and decarbonisation but also to a socially balanced energy transition.

5. Conclusions

This short communication set out to examine why multi-service power plant concepts such as Thermal Storage Power Plants (TSPP), despite demonstrated technical feasibility and system-level benefits, remain largely absent from real-world deployment in high-vRE electricity systems. By combining an illustrative energy-system scenario with a structured framework analysis, the study explicitly addressed the gap between technological readiness and market implementation.

The analysis showed that TSPP provide a broad portfolio of system services whose benefits accrue to different stakeholders (Fig. 5). Policymakers benefit from higher achievable shares of variable renewable energy, reduced curtailment, support for structural transition in former coal regions and lower electricity and fuel import dependency. Power plant operators benefit from dispatchable renewable electricity, operational flexibility and fuel cost resilience, while grid operators benefit from reduced redispatch, preserved synchronous inertia and lower grid expansion needs. However, because these benefits are distributed across institutional boundaries, the full system value of TSPP remains unrecognised, creating a structural barrier to their deployment.

A central contribution of this work is the identification of four interlinked framework barriers that systematically disadvantage multi-service technologies: (i) technology-specific funding and support schemes, (ii) the annual balancing of Guarantees of Origin, which weakens incentives for renewable residual load coverage, (iii) energy system modelling practices that insufficiently represent grid stability, and security of supply, and (iv) market structures shaped by unbundling and fragmented responsibilities. In contrast to much of the existing literature, which focuses primarily on technical performance or cost-optimised system modelling, this study examined the institutional and regulatory structures that constrain the uptake of integrated solutions, even when their system benefits are well established.

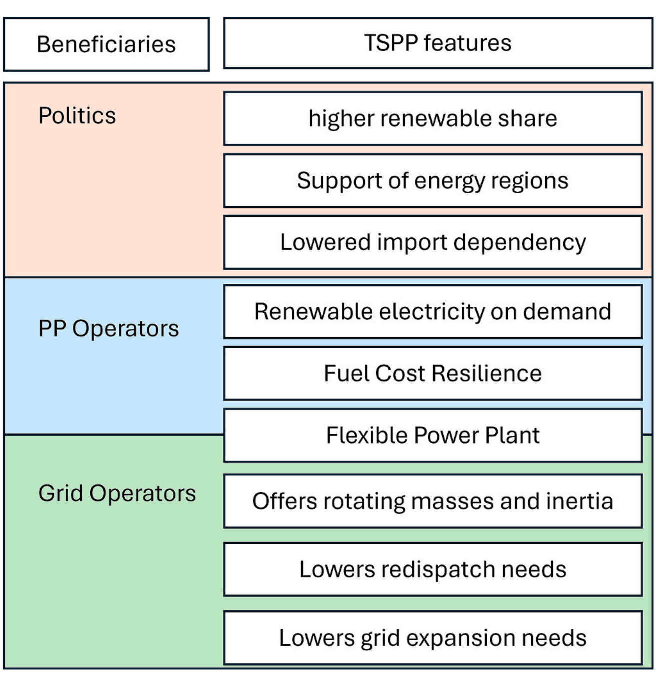

Fig. 5. TSPP features and its beneficiaries.

The findings imply that advancing high shares of variable renewable energy requires a shift towards technology-neutral, service-oriented framework conditions. Policies and market mechanisms must consistently value residual load coverage, grid stabilizing features and security of supply alongside decarbonisation objectives. Achieving this requires a combination of appropriate regulatory signals—such as robust CO_2 balance constraints and stronger sector integration—and analytical tools, including holistic energy system models that jointly represent load coverage, stability and security of supply. To enable early deployment, targeted financial instruments, improved valuation of system services and transparent planning tools are essential to translate the technical potential of TSPP and comparable multi-service technologies into market implementation.

This study focused primarily on the German context and, to a lesser extent, the European context, which limits direct transferability to other regions. While key barriers and recommendations were identified, the complexity of regulatory frameworks implies that the analysis cannot be exhaustive. Future research should prioritise studies assessing the effects of holistic modelling approaches, sector coupling, and regulatory adaptations in order to provide a more robust basis for decision-making. In parallel, the implementation of a pilot TSPP with scientific monitoring is essential to empirically validate the technology's multi-service benefits. In addition, further work is required to assess conversion efficiencies under different operating of combined electricity and heat supply conditions and for varying temperature levels relevant to district heating and industrial process heat. Economic research should further examine revenue stacking across electricity, heat and ancillary service markets, including day-ahead and intraday trading, balancing services and potential capacity remuneration mechanisms, in order to assess economically robust operating strategies for multi-service power plants.

Overall, this work contributed a framework-oriented perspective to the existing research by showing that the deployment of multi-service technologies depends not only on technical performance, but equally on the institutional conditions under which technologies are assessed, rewarded and deployed. Moving beyond the mere expansion of variable renewable generation, the next phase of the energy transition requires a rethinking of market design, regulatory frameworks and modelling practices. A holistic, service-oriented approach can unlock the full potential of multi-service technologies such as TSPP and support the development of renewable, cost-effective, secure and resilient energy system.

CRediT authorship contribution statement

Judith Jäger: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Philipp Trompetter:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Gerrit Koll:** Writing – review & editing, Validation, Methodology, Conceptualization. **Maria Isabel Roldan Serrano:** Writing – review & editing, Project administration, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the authors used ChatGPT and Gemini in order to improve the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to have influenced the work reported in this paper.

Acknowledgements

This work was carried out within the internally funded DLR project Coal Phase-out Atlas – Decarbonisation of the Global Coal Power Plant Fleet (Globaler Kohleatlas) (Reference ID: 4cea82c0-894e-4b55-8ae6-51009a3d4d3c). No external grant funding was received for this study. The authors gratefully acknowledge André Thess for scientific support and guidance in several TSPP-related activities. The authors further thank the Institute of Low-Carbon Industrial Processes (DLR-DI) for project financing and Maria Isabel Roldan Serrano for scientific guidance and valuable advice.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2026.122442.

Data availability

Data will be made available on request.

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