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INTEGRATION OF THERMAL ENERGY STORAGE, ELECTRICAL CONTROL SYSTEMS, AND ENERGY PERFORMANCE IN SOLAR-POWERED HEATING SYSTEMS: A SYSTEMATIC REVIEW

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Abstract: Although solar heating systems seem to be of increasing significance for building decarbonization, their efficiency can not only be influenced by the efficiency of the individual components, but also by a coordinated design and operation of the thermal energy storage and electrical control. While studies range from experimental, simulation-based to case study type, the evidence on this integration is still dispersed across technologies, climate and system scales. This review builds on the existing research and summarizes the knowledge on the interaction between storage, control and energy performance in solar powered heating concentrating on integration architecture, reported results and methodological limitations. The evidence base indicates that there is significant variation in system configurations, in approaches to assessment, and geographic and climatic representation is uneven, and that, generally, simulation-based assessments are prevalent. The synthesis suggests that the introduction of storage doesn't necessarily result in better performance. Most consistent benefits have been reported when the storage is combined with appropriate control strategies to regulate charging and discharging and auxiliary heat supply as per the availability of the sun and the demand. In contrast, the addition of storage is correlated with marginal or inconsistent gains with no control logic adaptation. The results presented imply that the control is an important part of the value of storage realization and that performance may be related to the co-design of the system as a whole, and not necessarily to the individual components. The review also identifies the importance of geographically more extensive empirical research, clear reporting and/or comparable performance indicators to enhance the ability to make inferences across studies and guide robust system design and deployment.

Keywords: solar thermal systems; thermal energy storage; control strategies; building energy performance; systematic review

1 Introduction

Solar heating systems are now shifting from niche application to an integral part of decarbonization strategies for buildings all around the world and are being driven by the sun. In temperate and cold climate zones, space heating and domestic hot water preparation are the largest energy end uses in the buildings and the direct use of fossil fuels for space heating and DHW is one of the most ubiquitous sources of urban and peri-urban emissions (Nazari *et al*., 2023). To address this, various alternative technologies have been encouraged by the policy makers and practitioners such as solar thermal collector, solar assisted heat pump and PV heating (Badiei *et al*., 2020). The heating demand is greatest during winter time, early morning and evening, while solar irradiance is greatest during the day and in summer (Stutz *et al*., 2017).

Thermal energy storage has thus been enjoying a special status in the research and practice. The use of the sensible storage in the water tanks is the basic solution, as it is cheap, chemically stable and compatible with the traditional hydronic circuits (Herrando *et al*., 2023). The use of phase change materials has been studied extensively in the past for the storage of high energy density in space-constrained retrofits, as they offer high energy density (per unit volume) and near-isothermal discharge (Hassan *et al*., 2021).

The second, and frequently overlooked, leg in solar heating integration is electrical control systems. Controllers decide the time for harvesting the solar energy, its route, storage charging and discharging, and when to run auxiliary heaters (Herrando *et al*., 2023). Simple thermostat and differential controllers have been replaced by schemes that predict differential signals, occupancy, and weather conditions and that learn (Afram & Janabi-Sharifi, 2013; Pataro *et al*., 2025). As such, the use of the control layer can no longer be seen simply as an operational add-on, but can even become a design variable that determines the energy performance that can be achieved by the entire system.

The 3rd axis of integration is Energy performance assessment. Physical behaviours can be converted into quantities for comparison between different designs and to convey to decision makers using metrics like solar fraction, coefficient of performance, primary energy savings and lifecycle emissions (Shirazi *et al*., 2015). But such metrics are subject to the definitions of the boundaries, the selection of the reference system and the time resolution of the data of the underlying simulation or measurement (Omoyele *et al*., 2024). What looks like a good system based on one set of assumptions may be the same as one of its competitors based on another set of assumptions.

There is a large literature that has discussed each of these aspects individually. Thermal storage materials reviews list up the phase change temperature, the way of encapsulating them and the number of cycles they can undergo without degradation (Hassan *et al*., 2021). Comparisons of survey on control strategies are conducted for the building heating applications between the rule based, optimal and learning based methods (Maddalena *et al*., 2019). Techno-economic assessment uses payback period and levelized cost of solar heating configuration to report in a specific location (Saini *et al*., 2026). What is still lacking is a synthesis which considers storage, control and performance as a system and queries what mixes of design decisions are consistently linked to better results.

This fragmentation places a number of research gaps. First, there seems to be no common taxonomy of integration architectures of solar heating systems, which hinders comparison of studies and makes it difficult to grasp the way in which the storage and control are interacting. Second, the evidence about which of the two features (storage capacity or sophistication of control) is more influential on performance seems to not have been systematically considered and in individual studies, both features change simultaneously without distinguishing their impact (Saloux & Candanedo, 2021).

It is these gaps that provide the motivation for this review. This paper reviews the idea that the performance of solar-powered heating systems may not rely so much on the merits of the thermal storage or electrical control as on an intentional co-design of the two, and that control logic could be a key way of unlocking the value of thermal storage. If this claim is true, there are immediate implications for the design of systems, the reporting of research results and the design of policy incentives. Considering how to test this claim can involve pulling together evidence from materials science, control engineering and building energy performance and evaluating evidence, not just for the headline results, but study design.

This review has four-fold contribution. In this review, a functional taxonomy is built to organize the literature in terms of the coupling of the storage, control, and performance assessment components, instead of according to the type of material or the type of controller. It then compares the evidence relating to integration design elements consistently found to have a positive relationship with efficiency, reliability, and solar fraction and considers the importance of storage capacity versus sophistication of control. This synthesis is accompanied by a critical evaluation of methodological strength based on the validation of the models, the reporting of parameters and the reproducibility.

2 Methodology

2.1 Review Protocol

This systematic review was performed and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page *et al*., 2021), which guided the protocol and the screening process, as well as the reporting of results. The protocol was defined prior to performing the search and included the research question, search strings, eligibility criteria, data extraction fields, and synthesis approach.

6 bibliographic databases and search engines were searched. Scopus was chosen first because, in addition to the extensive number of journals covered in engineering and energy, it has very specific query syntax for its fields, which could enable very specific and reproducible retrieval. Secondly, Web of Science was selected because it indexes high impact peer-reviewed journals, which could be used as a supplement to the more comprehensive data bases in order to get a quality-oriented view. This was followed by ScienceDirect as it supports 2,650+ full text journals (Cellura *et al*., 2023; Østergaard *et al*., 2022), many of which are applied energy and thermal engineering.

Four concept blocks were used in conjunction with Boolean operators to create the search strings. Within each block these were combined with OR and between blocks they were combined with AND. The string used for Scopus and ScienceDirect was field restricted, that is, TITLE-ABS-KEY((“solar heating” OR “solar thermal” OR “solar water heating”) AND (“thermal energy storage” OR “phase change material” OR PCM) AND (“control strategy” OR “model predictive control” OR “energy management”) AND (“energy performance” OR “energy efficiency” OR “solar fraction”)).

2.2 Analytical framework and thematization of the categories:

In order to synthesise the 126 studies included in the review, we categorised each study with regard to a set of analytical dimensions that were chosen based on the review question, and not on bibliographic data. The first one is the main research objective: studies that quantify and optimize energy performance; and studies that design and evaluate integration architectures and operational control strategies; and studies that focus on thermal energy

storage materials and configuration design. The residual class is for studies where the main contribution does not fall into the above categories but where the study is nevertheless relevant to the integration question such as studies in policy analysis or life cycle assessment or development of methodologies.

2.3 Inclusion and exclusion Criteria

The studies had to include at least two of the three key components of thermal energy storage, electrical control systems and energy performance and investigate solar heating systems, such as solar water heaters, solar space heating systems and solar combisystems. Studies had to report or analyse the combination or interaction between these aspects instead of just mention them separately. Eligible study types included experimental studies, simulation and modeling, and case studies as well as review articles that contained new data or synthesis pertinent to the integration question.

Studies were not included if they only dealt with one aspect such as only thermal storage materials, only control algorithms, or only performance metrics, but did not include integration of at least one other core aspect. Studies where the PV system could not be used for heating or heating studies without PV systems were excluded. Studies that discussed integration but not in detail or with any results and opinion pieces, editorials, conference abstracts without full papers and non-English publications were excluded.

2.4 Study Selection Process

The selection process used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 flow (Page *et al*., 2021) and the records were managed using a reference manager which was set to detect duplicates. There are 1,313 hits in the initial search on 6 sources. Of the original 752 records, 561 were removed as duplicates and two for other reasons, leaving 750 for title and abstract screening. These records were independently screened by two reviewers with a third resolving any conflicts; 359 of these records were excluded at this stage, leaving 391 reports sought for retrieval. The other 126 studies were selected to be reviewed.

The quality appraisal was adapted to the characteristics of the study and was performed in parallel to the full text assessment. In experimental studies, we evaluated the completeness of the description of the test rig, instrumentation, measurement uncertainty and operating conditions. In simulation and modelling studies, we evaluated the availability of measurements for model validation, the use of validation measures and tolerances, the inclusion of important parameters and boundary conditions and whether the demand profile was based on measured data or idealized data. We evaluated transparency of search strategy and consistency of synthesis for reviews.

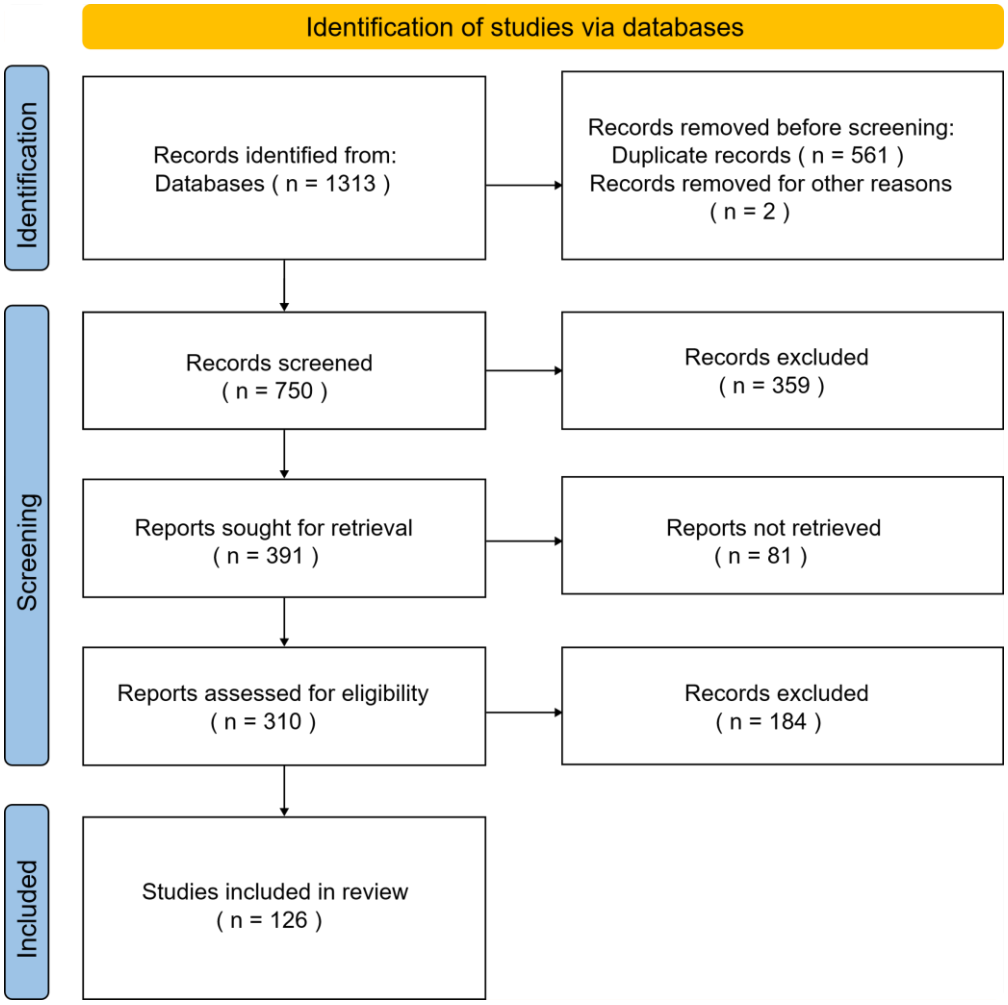


Figure 1. PRISMA 2020 flow diagram of the study identification, screening, eligibility assessment, and inclusion process.

There are two problems with the selection process that need to be recognized. The focus on English-language publications and on records retrievable in full text might not have captured relevant work from research communities in non-English-speaking countries, especially in areas where solar heating has been widely implemented. Second, the focus on keywords may not have captured research where the concepts of storage and control were referred to by other terms, although Google Scholar was used as a supplement to search for these other terms, adding another layer of selection bias due to Google Scholar's opaque ranking. The independent dual screening and design-specific quality appraisal minimise, but will not remove, the risk that the evidence base that was included overrepresents the simulation-based research of a few research groups that are well indexed.

3 Results

3.1 Research Trends

The temporal distribution of the 126 studies included reveals a research domain that has been well established long before the time frame of most bibliometric windows, and is now in a stage of consolidation with a few surges of interest. There is a significant body of pre-2016 evidence (42 studies) that forms the basis of the evidence. The high proportion of early research could be due to the foundation of the basic physics and operation of solar heating systems, such as the design of sensible storage, latent storage systems (Sârbu & Sebarchievici, 2018), the logic of differential controllers, the solar fraction concept, which are still the basis of the current research.

The trend since 2015 is not monotonic. Publication counts rose from 6 in 2016 and 5 in 2017 to 12 in 2018 and 12 in 2019, then peaked at 17 in 2020, before declining to 10 in 2021 and 3 in 2022. Another, smaller wave came in the next two years, 8 in 2023 and 3 in 2024 and the latest years show 7 in 2025 and 7 in 2026. The 2020 high may correspond to an increase in the attention given to the decarbonisation of buildings, and to the electrification of heat, while the subsequent decrease could be due to publication time-lag in the measurement of recent research activities rather than to a decrease in research efforts themselves.

For the synthesis below, there are two aspects of this distribution that have analytical significance. The first, is a long tail of pre-2016 publications that are more oriented towards storage materials and rule-based control, while more recent publications start to include predictive and learning-based approaches, and to evaluate whole-system performance. Secondly, the fluctuations in the annual counts, sometimes one year high, the next low, suggest that it is not prudent to take any single year as a typical year of showing a trend. Although the field seems to move in fits and starts related to outside technology and policy changes, rather than a gradual accretion of knowledge, and this may be the context in which the thematic evidence in the sections that follow should be understood.

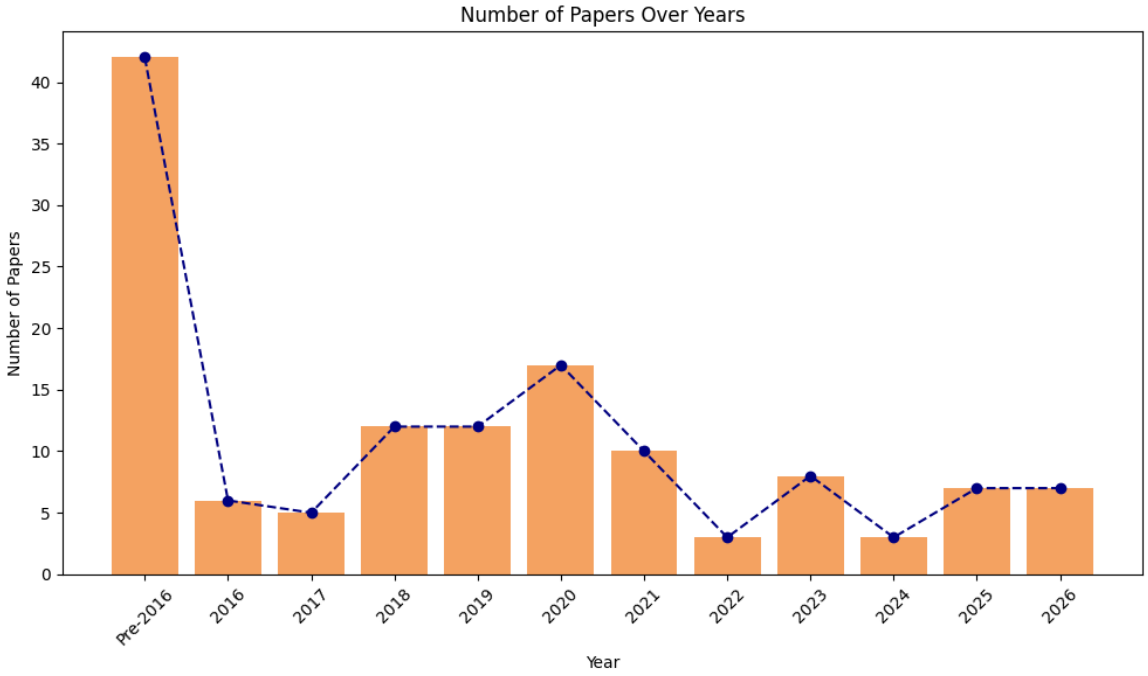


Figure 2. Temporal distribution of publications on the integration of thermal energy storage, electrical control systems, and energy performance in solar-powered heating systems.

3.2 Overview of Included Studies

The key features of the studies included are shown in Table 1. The extracted information from the study comprised of the study identification, study design, type of heating provided, TES system type, system integration configuration, and performance parameters (if available).

Table 1. Characteristics of Included Studies

STUDY ID	STUDY DESIGN	HEATING APPLICATION	THERMAL ENERGY STORAGE TYPE	SYSTEM INTEGRATION CONFIGURATION	PERFORMANCE METRICS
(Abid *et al.*, 2018)	Experimental study analyzing a solar thermal water heating system from first- and second-law thermodynamic perspectives under various scenarios and water consumption patterns	Space and water heating in buildings		Solar collector circuit with secondary circuit, heat exchanger, and pumps	Energy and exergy efficiencies, exergetic product/fuel basis, relative irreversibility (solar collector 85.73%, heat exchanger 2.45%), overall system exergy efficiency 20.28%
(Guo *et al.*, 2025)	Simulation-based feasibility study of an improved solar thermal and coal-fired power generation coupling framework, using steady-state and	Solar thermal integration with coal-fired power generation for peak load capacity improvement and	Three-tank molten salt thermal energy storage system	Parabolic trough collector field and three-tank molten salt thermal energy storage system connected in series and then in parallel with the outlet of the reheater	Energy utilization efficiency of 88.82%; daily reduction in coal consumption by 36.49 tonnes; peak-shaving performance; carbon emission reduction

	numerical models, with a neural network predictive model trained on actual solar radiation data to simulate peak-shaving performance under varying thermal energy storage hours.	carbon emission reduction			
(Pascual *et al.*, 2021)	An energy-management strategy for a residential microgrid, evaluated through simulation using one year of real data and experimentally validated in a laboratory microgrid at the Renewable Energy Laboratory at UPNA	Electric water heater / hot water tank	Hot water tank	Residential microgrid comprising photovoltaic (PV) panels, a small wind turbine, and solar thermal collectors, with a battery and a controllable electric water heater, connected to the grid	Grid power profile; battery size (smaller battery than previous works); overall system cost
(Zheng *et al.*, 2023)	Simulation study comparing solar heating systems with PCM floor and conventional radiant floor using TRNSYS	Space heating of a residential building	Phase change material (PCM) floor	Air source heat pump assisted solar heating system combined with PCM floor (solar collector, air source heat pump, heat storage tank, circulating pump)	

3.3 Performance Assessment and Optimization

The evaluation of the energy performance of solar-powered heating systems is not a measurement per se, but a modelling decision, which can affect which systems are considered better. Although the indicators to describe performance vary across the studies included in this review, and they are a limited set of recurring indicators: solar fraction, coefficient of performance (COP), seasonal performance factor (SPF), exergy efficiency, primary energy savings and life-cycle cost.

In the corpus, it seems that there are two general approaches to optimization. The first one is parametric sizing where collector area, storage volume and components size are varied to optimize a selected target (Ebaid *et al.*, 2024). The second is operational optimization where it is the control trajectory that is adjusted and not the physical plant. The main optimization studies are grouped by objective, method and reported results in Table 2.

Table 2. Performance assessment and optimization studies: objectives, methods and reported outcomes

STUDY ID	OPTIMIZATION OBJECTIVE	METHOD / TOOL	KEY DESIGN OR CONTROL VARIABLES	REPORTED PERFORMANCE OUTCOME
(Abid *et al.*, 2018)	Component-level diagnosis of irreversibility	Experimental energy and exergy analysis, exergetic product/fuel basis	Mass flow rates in collector and secondary circuit	Overall exergy efficiency 20.28%; collector irreversibility 85.73%, heat exchanger 2.45%
(Wei & Calautit, 2023)	Balance comfort and cost under variable occupancy	Price-responsive model predictive control (MPC), validated numerically and experimentally	Set-points, storage charging, tariff periods	63% of heating energy from solar; more than half of electricity cost saved
(Liu *et al.*, 2019)	Relate thermal energy storage (TES) size, solar multiple, and dispatch to usage efficiency	General analytical model	TES size (hours), solar multiple, dispatch fraction	Usage ability depends only on TES size below 6 h; on both size and dispatch above 6 h

The second strand, and more recent, deals with operational optimization. An integrated solar and air-source heat pump system with cascade storage tanks seems to have maintained the heat storage tank at a lower temperature during the day, and this could have benefited the energy consumption and efficiency of the collector and heat pump, and reduced the annual energy consumption by up to 26% compared to the thermostatic control (Wang *et al*., 2020). Predictive schemes can take this a step further and predict disturbances before they occur (Wei & Calautit, 2023).

A third category of studies is a fidelity and robustness assessment of the assessment apparatus itself, and this category of studies may be analytically important to the extent that it seems to limit confidence in the results of the previous studies. Synthetic TRNSYS output was used to train deep learning models and indicated that for predicting the temperature sequences, the recurrent models might be more effective than the feedforward models and the LSTM models might be more accurate than the deep feedforward networks (Afridi *et al*., 2021). Such models, however, will inherit whatever simplifications are included in the underlying physical model from the use of synthetic training data.

3.4 System Integration and Operational Control Strategies

The studies included under the system integration and operational control umbrella seem to converge to a structural lesson: the way thermal storage is charged and discharged (when, how quickly, at what temperature) may be more important than its actual material presence (Crespo *et al*., 2023). Integrations in the corpus span from series and parallel combinations of collectors, stores and heat pumps, to combinations of multiple sources, including combinations of thermal and electrical storage, PV generation and grid exchange, coordinated by a supervisory controller (Brandi *et al*., 2022; Zhang *et al*., 2022).

Table 3. System Integration and Operational Control Strategies in Thermal Energy Storage Systems

STUDY ID	CONTROL OBJECTIVE	CONTROLLED COMPONENTS	SIMULATION / EXPERIMENTAL PLATFORM
(Shabgard *et al*., 2018)	Minimisation of phase-change material mass and reduction of output-temperature fluctuations	Evacuated tube collectors, latent heat thermal energy storage unit, heat exchangers, absorption chiller/heat pump	Thermal network model
(Chen *et al*., 2015)			Experimental setup
(Khanmirza *et al*., 2017)	Building-temperature control with simultaneous energy-use reduction in hybrid heating systems	Hybrid heating system with gas and solar heat sources	
(Serale *et al*., 2018)	Improvement in the operational performance of multi-source thermal energy generation systems to maximise the exploitation of on-site renewable resources; anticipation of future disturbances and optimisation of the utilisation of more efficient energy sources	Latent heat thermal energy storage unit coupled with a solar thermal collector and a backup electric heater	

The base level controller for every advanced scheme listed in this cluster consists of both the rule-based and thermostatic controllers and several studies have indicated that even simple improvements of the rule base can be used to obtain disproportionate returns. This is exemplified in the case of the parallel solar and air-source heat pump system with cascade tanks, where the implementation of the reference temperature curves based on seasons and different demands instead of thermostatic activation seems to have reduced the daytime tank temperatures, increased the collector and air source heat pump efficiencies and decreased the annual energy consumption by up to 26% (Wang *et al*., 2020). The electrical aspect of integration brings with it a second set of parallel choices.

So far, predictive and learning-based control can well be the methodological horizon of the cluster and the reported potential seems to be always greater than the rule-based refinement. A predictive control of the pump speed between short and long term storage in a district heating system of the Drake Landing Solar Community resulted in 47 % electricity savings for pump operation (Saloux & Candanedo, 2021), while a techno-economic comparison between two heat pump reference-temperature control mechanisms in a district heating system in Madrid led to a deviation of 10 % in total electricity consumption and up to 99 % in solar fraction (Abokersh *et al*., 2021).

Integration goes beyond the single building and addresses communities, districts and multi-energy systems. Based on an energy system Modelica simulation model, a building Modelica simulation model was co-simulated with an EnergyPlus building model to enable control strategies for a low-temperature district heating network of 10 homes powered by ground-source heat pumps, photovoltaics, and electric and thermal storage, with the clear aim

of reducing consumption on the grid and maximizing the self-consumption of photovoltaics (Cucca & Ianakiev, 2020).

There are two cross-cutting patterns that seem to be apparent from this body of evidence and may warrant emphasis. First, there may be a greater difference in performance between different levels of control sophistication than between different storage sizes: studies have added storage to the same control logic, and the results have been based on marginal increases, while studies that have adapted control logic around the same storage have reported savings exceeding 80% in purchased grid electricity for the electric storage water heater (Clift & Suehrcke, 2021).

3.5 Design of Thermal Energy Storage Material and Configuration

The physical boundary conditions in which the control strategy has to operate are defined by the design of the storage unit itself, namely its material, geometry and internal arrangement. Within the selected studies, there are three design families which seem to reoccur: sensible water storage, latent storage (using phase change materials (PCMs) in encapsulated, slab, shell and tube, and/or packed bed designs) and hybrid (which is a combination of latent and sensible and/or thermochemical in a one system design). Table 4 shows an overview of the material and configuration selected by the studies whose storage designs could be summarized, and it indicates that paraffin wax is the most common material used in the experimental literature, while salt hydrates, sugar alcohols and fatty acids are used in addition for higher melting points or for long term supercooled storage (Sadeghi, 2022; Sadeghi *et al*., 2022).

Table 4. Thermal energy storage material and configuration design in the included studies

STUDY ID	PHASE CHANGE MATERIAL	THERMAL STORAGE UNIT GEOMETRY	PCM CONFIGURATION / ARRANGEMENT
(Asral *et al*., 2025)	Paraffin wax	Stratified water storage tank	Encapsulated PCM spheres mounted on the heat exchanger inside the tank
(Huang *et al*., 2021)	Paraffin wax	Alternative heat storage tanks on a test bench	Controllable heater emulating solar input at 85 °C
(Shahsavar & Mojaver, 2026)	PCM unit combined with thermochemical storage	Hybrid dual thermal energy storage	PCM and thermochemical units coupled to a photovoltaic-thermal (PVT) collector and heat pump

Material selection evidence is generally consistent in overall structure, but is weak when compared. Due to its attractive properties, such as chemical stability and a melting range that is appropriate for domestic water heating, paraffin wax is one of the most extensively studied PCMs. Several experimental systems have been based on paraffin wax: a water–PCM tank filled with paraffin embedded in cylindrical aluminum containers resulted in hot water up to 9.5 °C warmer than the conventional hot water store and maintained 28.5 °C above ambient temperature in collector testing (Damene *et al*., 2026); a tank containing fifty copper tubes each filled with about 100 g of paraffin wax enabled the heat transfer rate and the effectiveness of the system to be quantified under domestic draw profiles (Kanimozhi & Bapu, 2012).

The corpus includes various enhancement strategies that make up for the low thermal conductivity of pure organic PCMs (Hayat *et al*., 2023), and whose reported improvements can be directly compared. Dispersion of TiO_2 nanoparticles in the stearic acid media at different concentrations (0.05–0.3 wt%) was effective in reducing the complete melting and solidification times progressively from the initial values, with the highest concentration dispersed in stearic acid showing 43.72% reduction in the complete melting and solidification times (Harikrishnan *et al*., 2013), and a numerical investigation of RT50 slabs added with Al_2O_3 nanoparticles together with a flat-plate collector have been carried out using meteorological data from Marrakesh (Elbahjaoui & Qarnia, 2018). The further extension is configuration-level innovations.

The most unique design branch in this subsection is hybrid/long term storage configurations. A dual-tank latent storage system was designed and tested specifically to illustrate the energy-efficiency advantage of dividing latent capacity between two units, which were connected in a solar heat-pump heating system (Qu *et al*., 2015), while a hybrid dual storage composed of a PCM latent storage unit, a thermochemical latent storage unit and PVT collectors demonstrated that the energy-efficiency advantage of using direct PVT assistance was limited compared to the combined store (Shahsavar & Mojaver, 2026).

4 Discussion

Altogether, the evidence presented in this review suggests a simple but consequential conclusion: The overall performance of solar-powered heating systems seems to be more driven by the conscious co-design of thermal storage and electrical control than by any of these individual technologies themselves; and control logic might be

a key component in the process of generating value from thermal storage. This trend is found to be consistent in both the experimental and simulation traditions and case studies.

The second pattern that can be discerned in studies relates to the extent to which the thermal and electrical aspects are emphasized. Where controllers coordinate the operation of heat pumps, charging of storage, dispatch of batteries and tariff signals at the same time, the largest improvements in self-sufficiency and cost are reported, where about 80% of self-consumption and self-sufficiency are reached – neither domain is able to reach these levels on its own (Langer & Völling, 2020). This finding may be theoretically significant as it could conversely be seen as a coupling mechanism between two energy carriers instead of simply an operational add-on to a thermal system in the control layer.

Evidence-based contradictions are helpful and not just a nuisance. The reported solar fractions of supposedly similar systems vary between 39% and 99% (Abokersh *et al*., 2021; Antoniadis & Martinopoulos, 2018) while the reported seasonality of the performance factors range between 2.42 and 4.6 (Huang *et al*., 2020; Trinkl *et al*., 2009). Some of this dispersion is due to the true differences in climate, load profile, and size of the systems, while a significant amount of this dispersion is due to the different ways in which the boundaries are defined, different reference systems used, and the temporal resolution of the data used. (Mahdavi *et al*., 2021; Omrany *et al*., 2020). The dispersion could thus not be interpreted as a lack of a strong field signal but rather as evidence that the signal is masked by the heterogeneous way in which the field is assessed.

This interpretation is further developed in the methodological appraisal. Evidence suggests that simulation dominates and lots of simulation studies use models that have not been validated, idealized demand profile and incomplete reporting of parameters (Fraga *et al*., 2017) The most innovative integration architectures (such as the combination of thermal storage and battery dispatch and predictive control) are often the least tested in experiments, and this may have direct implications on the level of confidence in the headline savings figures as noted in Section 3.4.

The theoretical implications of these findings have to do with the conceptualization of integration. The functional taxonomy we created is based on the combination of storage, control, and performance assessment (not on material class or controller type), and the synthesis indicates that the organizing principle might be more explanatory—studies group based on integration profile in ways that may predict the outcome reported better than their material or algorithmic choice does. This indicates that integration architecture should be considered as the first level of design and storage material and controller algorithm as second level design variables to be constrained by the integration architecture.

Practical implications are clear and precise. The evidence shows that, for designers, it is better to invest in the control layer instead of providing more storage if there is a limited budget and it suggests that there are hydraulic details that are easy to overlook: a four-pipe combistore connection increased seasonal performance 9% compared to a three-pipe connection, while an external heat exchanger for domestic hot water preparation added a further 2% (Poppi & Bales, 2014). The policy message is that storage capacity incentives are likely to result in less energy savings than incentives that require or reward coordinated storage capacity control, commissioning, and monitoring.

A few caveats of this review need to be noted and will directly affect the interpretation of the conclusions. The limitation of the English-language publications, and to only those for which the full text could be retrieved (due to either being paywalled or incomplete bibliographic records), may have cut out relevant work from non-Anglophone research communities, especially in areas where solar heating has been deployed in a large scale.

These limitations indicate a research agenda that is a logical extension of gaps identified in this research. Validated whole-system studies, measuring thermal and electrical performance together for real occupancy and real weather are needed as the electrical coordination layer is currently supported mainly by simulation (Haller *et al*., 2014). Future research should focus on establishing the integration studies in standardized reporting templates that include boundary conditions, reference system, temporal resolution and component-level loss distributions, to ensure that results are comparable across climates and scales.

5 Conclusion

This study aimed to identify whether the thermal storage or the logical control dominates the performance of solar-powered heating systems, and to develop a workable taxonomy to classify the scattered pieces of evidence based upon integration architectural form, rather than class of material or type of controller. The synthesis indicates that integration can be a conditional benefit: storage added to purpose-built control systems results in higher solar utilization and reduced auxiliary energy use, while storage added to existing control systems provides marginal benefits. The sophistication of control seems to cut performance apart more than the amount of storage and the biggest gains may be in the region where both thermal and electrical domains are controlled simultaneously.

The implications for theory and practice may emerge from these results. They claim that the control layer is not an add-on for operation, but an “add-on” for “energy carriers”, and that the sizing of capacities does not necessarily have to be optimized, independent from the control logic for which it is designed. The evidence suggests that

control-layer investment should be prioritized by designers, and storage capacity alone by policymakers be wary of providing incentives for.
Future research might focus on filling the gaps mentioned in the discussion: simultaneous thermal and electrical performance studies with validation; standardized reporting of boundary conditions and component level losses; coverage of less studied climates; and factorial designs separating capacity and control. This work would enable the field to transition from individual demonstrations to collective knowledge of the same nature.

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