

Integrating Solar Drying, Thermal Energy Storage, and Sodium Borohydride Hydrogen Pathways for Decentralized Sustainable Energy Systems: A Comparative and Conceptual Research Analysis

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ABSTRACT

Background: Decentralized energy transitions increasingly require technologies that are not only renewable, but also storage-capable, modular, and appropriate for agricultural, rural, and small-scale industrial contexts. The references provided converge around two major domains: solar drying systems, particularly those enhanced by sensible and latent thermal storage, and hydrogen generation and storage through sodium borohydride and related materials. Although these domains are often treated separately, both address a common systems-level challenge: how to capture intermittent renewable energy, preserve its utility over time, and deliver it in forms appropriate for productive use.

Objective: This article develops a conceptual and comparative research analysis that examines the theoretical, technological, and operational relationships between solar drying technologies and sodium borohydride-based hydrogen pathways. The study seeks to identify common design principles, performance determinants, storage logics, and integration opportunities for decentralized sustainable energy systems.

Methodology: A structured qualitative synthesis was undertaken using only the supplied references. The method involved thematic coding of the literature into four analytical layers: solar resource utilization, energy storage mechanisms, process intensification strategies, and system maturity constraints. Comparative interpretation was then used to generate an integrative framework connecting agricultural drying applications and hydrogen-based energy storage systems.

Results: The analysis shows that solar drying technologies have achieved significant maturity in collector design, airflow management, product-specific drying kinetics, greenhouse and tunnel configurations, and phase change material integration, while sodium borohydride-based hydrogen systems demonstrate strong promise in controllable hydrogen release, chemical storage density, catalytic tuning, and closed-loop regeneration concepts. Across both domains, storage is the decisive variable that transforms intermittent solar input into reliable service output. However, solar drying systems are comparatively closer to field-level deployment, whereas sodium borohydride systems remain constrained by regeneration cost, catalyst optimization, and full-cycle feasibility.

Conclusion: The study concludes that the strongest future pathway is not to treat solar drying and hydrogen technologies as unrelated sectors, but as complementary elements in a distributed energy architecture. Solar thermal systems can serve immediate low-temperature productive applications, while chemical hydrogen pathways may provide higher-value buffering, transport, and cross-sector energy services. The combined perspective advances a more nuanced model of sustainable energy development grounded in functionality, storage hierarchy, and context-sensitive deployment.

Keywords: Solar drying, phase change materials, sodium borohydride, hydrogen storage, thermal energy storage, decentralized energy, sustainable systems.

INTRODUCTION

The contemporary energy transition is frequently described in terms of generation technologies, but in practice it is equally a transition in storage, conversion, and end-use matching. Renewable energy becomes transformative only when intermittent resources can be converted into dependable services across varied temporal and spatial conditions. This systems problem is especially visible in decentralized contexts where agriculture, food preservation, rural processing, and distributed energy provision intersect. The reference base supplied for this article brings together two bodies of literature that appear separate at first glance but are connected by a deeper technological logic: solar drying systems and sodium borohydride-based hydrogen storage systems. Both are concerned with the capture of renewable energy, its stabilization through storage or controlled release, and its eventual use in service of productive, sustainable activity (Sharma et al., 2009; Demirci, 2015).

Solar drying has long been recognized as one of the most practical applications of solar energy, particularly in agricultural economies where post-harvest losses, moisture-sensitive commodities, and unreliable grid power combine to create a persistent preservation challenge. Traditional open-sun drying remains widespread due to its simplicity, but it exposes products to contamination, weather uncertainty, nutrient degradation, and nonuniform drying behavior (El-sebaai & Shalaby, 2012; Sharma et al., 2009). As a result, decades of research have focused on improved solar dryers, including cabinet dryers, indirect systems, greenhouse configurations, tunnel dryers, forced-convection systems, evacuated tube-assisted designs, and hybrid systems incorporating storage materials and auxiliary energy sources (Ampratwum & Dorvlo, 1998; Rathore & Panwar, 2010; Goud et al., 2019; Yematawu et al., 2024). This body of work shows that solar drying is not merely an adaptation of traditional heat supply. It is a sophisticated energy management process involving heat transfer, mass transfer, airflow regulation, collector efficiency, storage integration, and product-quality preservation (Tripathy & Kumar, 2009; Goyal et al., 2006).

Within this solar drying literature, thermal storage emerges as a pivotal concern. Because solar radiation varies across diurnal cycles and climatic conditions, any drying system that depends solely on instantaneous insolation is inherently limited. The integration of sensible heat storage materials, latent heat storage through phase change materials, and sometimes combined storage strategies has therefore become central to improving drying continuity, reducing temperature fluctuations, and extending useful operation into evening periods or cloudy intervals (Devahastin & Pitaksuriyarat, 2006; Farid et al., 2004;

Kumar & Gupta, 2021). Recent studies indicate that the convergence of solar collectors, thermal storage media, and dryer architecture has become one of the major frontiers in the modernization of solar drying systems (Abueluor et al., 2023; Desa et al., 2024; Tyagi et al., 2024; Ying et al., 2024).

The second cluster of references concerns sodium borohydride and related hydrogen storage pathways. Hydrogen is often positioned as a key future energy carrier because it can decouple renewable generation from end-use demand, support clean fuel systems, and enable low-carbon energy transfer across sectors. Yet hydrogen storage remains one of the principal barriers to its widespread deployment. Compressed gas and liquefied hydrogen systems involve notable infrastructure, energy, and safety challenges, prompting sustained investigation into solid-state and chemical hydrogen carriers (Pasman & Rogers, 2012; Hirscher et al., 2020; Klopčič et al., 2023). Sodium borohydride has attracted particular attention because it can release hydrogen through hydrolysis under comparatively mild conditions, offering the possibility of controllable on-demand hydrogen generation for portable, stationary, and distributed applications (Liu & Li, 2009; Santos & Sequeira, 2011; Abdelhamid, 2021).

However, sodium borohydride systems are not simple storage solutions. Their practical viability depends on catalytic efficiency, hydrolysis kinetics, by-product management, regeneration pathways, transport feasibility, cycle closure, and overall techno-economic maturity (Brack et al., 2015; Patel & Miotello, 2015; Dragan, 2022; Demirci, 2023). More recent work has increasingly framed sodium borohydride not merely as a reactive material but as part of a larger hydrogen cycle involving regeneration from spent products, hybrid solvent systems, transport concepts, and closed-loop storage logic (Chen et al., 2017; Ouyang et al., 2018; Aydin et al., 2020; Zhu et al., 2023). In this respect, sodium borohydride research mirrors the concerns of solar drying research: energy capture alone is insufficient unless storage and release can be managed with reliability, efficiency, and contextual suitability.

The literature gap addressed in this article arises precisely at this point of convergence. The solar drying literature is rich in analysis of low-temperature renewable heat applications, especially in agriculture and food processing. The sodium borohydride literature, by contrast, is focused on chemical hydrogen storage, reaction control, catalyst design, and energy carrier logistics. Yet both domains are fundamentally investigating how renewable energy can be stabilized and delivered in useful forms across discontinuous time scales. Solar drying handles this through thermal buffering and process design. Sodium borohydride systems handle it through chemical storage and

controlled hydrogen release. Very few analyses place these two literatures into direct conceptual dialogue, despite the fact that decentralized sustainable systems may need both types of functionality: immediate low-grade heat for preservation and delayed high-value stored energy for backup, transport, or electrical conversion (Maka & Alabid, 2022; Kamarulzaman et al., 2021; Kumar et al., 2024).

This article therefore develops a comparative and conceptual research analysis based strictly on the supplied references. It does not attempt to merge the two literatures artificially, nor does it claim that solar drying and sodium borohydride hydrogen systems occupy identical technological roles. Rather, it argues that they address different points on a shared storage continuum. Solar drying technologies represent an advanced and field-proven approach to direct productive use of solar energy, especially where heat demand is immediate and agriculturally relevant (Fudholi et al., 2015; Udomkun et al., 2020). Sodium borohydride systems represent a more chemically mediated approach to storing renewable energy in a portable and dispatchable form, potentially useful where temporal separation, transportability, and fuel flexibility are more important than direct thermal use (Abdelhamid, 2021; Demirci, 2023; Ibrahim et al., 2023).

The purpose of the present article is fourfold. First, it synthesizes the principal technological and theoretical insights from the solar drying literature, including collector design, airflow configuration, product-specific drying behavior, and thermal storage enhancement. Second, it examines the sodium borohydride hydrogen literature with attention to hydrolysis mechanisms, catalyst systems, regeneration pathways, and storage maturity. Third, it compares the two domains through the common framework of renewable energy stabilization. Fourth, it develops an integrative interpretation of how these technologies might contribute to decentralized sustainable energy systems in complementary rather than competing ways.

This framing matters because sustainability cannot be reduced to the substitution of fossil energy with renewable energy in abstract terms. Sustainable energy systems must be evaluated by their ability to serve concrete social and economic functions: preserving agricultural products, reducing post-harvest loss, enabling transportable energy, supplying remote operations, and providing resilience under variable environmental conditions (Devabhaktuni et al., 2013; Maka & Alabid, 2022). Technologies that appear dissimilar at the material level may nevertheless belong to the same design problem if they solve different aspects of intermittency and usability. Solar dryers and sodium borohydride systems, viewed together, reveal that the future of decentralized sustainability lies not in a single universal energy solution, but in layered storage

architectures matched to task, temperature range, timing, and deployment environment.

Methodology

This study employs a structured qualitative research methodology based exclusively on the references supplied by the user. The article is designed as a conceptual and comparative synthesis rather than an experimental report or a meta-analysis with pooled quantitative metrics. This methodological choice is appropriate because the reference set includes review papers, experimental studies, conceptual discussions, book chapters, and technology-focused analyses distributed across two major thematic areas: solar drying with and without thermal storage enhancement, and hydrogen generation and storage through sodium borohydride and related materials. The diversity of document types, objectives, and reported variables makes a purely statistical synthesis less meaningful than an interpretive framework that preserves context and enables cross-domain comparison (Sharma et al., 2009; Abdelhamid, 2021).

The first stage of the method consisted of corpus delimitation. Only the references provided in the prompt were used. No external literature, factual additions, or supplementary sources were introduced. This strict source boundary ensures that the resulting article remains grounded in the textual and thematic content explicitly supplied. The corpus was then separated into three overlapping clusters. The first cluster comprised solar drying technologies, including cabinet dryers, tunnel dryers, greenhouse dryers, indirect solar dryers, forced-convection systems, desiccant-assisted systems, and product-specific drying investigations (Ampratwum & Dorvlo, 1998; Fadhel et al., 2005; Goyal et al., 2006; Shanmugam & Natarajan, 2006; Kaewkiew et al., 2012; Hegde et al., 2015; Çerçi et al., 2022). The second cluster consisted of thermal energy storage and phase change materials in solar applications, including conceptual discussions of latent heat storage, sensible-heat-assisted systems, PCM-enhanced dryer designs, and integrated PV/T or storage-oriented reviews (Farid et al., 2004; Devahastin & Pitaksuriyarat, 2006; Bhardwaj et al., 2020; Singh & Mall, 2020; Abueluor et al., 2023; Tyagi et al., 2024; Ying et al., 2024). The third cluster comprised sodium borohydride hydrogen generation and storage, including hydrolysis chemistry, catalyst systems, material reviews, regeneration studies, transport analyses, and hydrogen cycle maturity assessments (Liu & Li, 2009; Jiang et al., 2010; Santos & Sequeira, 2011; Demirci, 2015; Chen et al., 2017; Ouyang et al., 2018; Abdelhamid, 2021; Demirci, 2023; Zhu et al., 2023).

The second stage involved thematic coding. Rather than coding every paper by discipline or chronology alone, the literature was read through four analytical

dimensions that could apply across both domains. The first dimension was resource capture, which includes how solar energy or hydrogen potential is initially made available through collectors, reactive materials, or system design (Devabhaktuni et al., 2013; Jiang et al., 2010). The second dimension was storage mediation, referring to the mechanism by which intermittency is moderated, whether by sensible heat, latent heat, chemical storage, or regeneration loops (Farid et al., 2004; Hirscher et al., 2020). The third dimension was process control, including airflow control in dryers, catalyst selection in hydrolysis systems, temperature stability, reaction rate management, and operational continuity (Tripathy & Kumar, 2009; Brack et al., 2015; Xu et al., 2022). The fourth dimension was deployment maturity, covering cost, scalability, technological readiness, safety, user suitability, and context-specific practicality (Udomkun et al., 2020; Demirci, 2023; Kumar et al., 2024).

The third stage consisted of comparative interpretation. The purpose here was not to claim equivalence between solar dryers and sodium borohydride systems, but to identify structural analogies in their technological logic. For example, an indirect solar dryer with PCM does not perform the same function as a sodium borohydride-based hydrogen generator. However, both systems convert variable inputs into more stable service outputs. Both rely on intermediate storage mechanisms. Both are highly sensitive to design parameters that affect conversion efficiency. Both show strong promise in decentralized settings. And both confront the challenge of moving from promising laboratory or pilot performance toward robust, economically credible deployment (Bhardwaj et al., 2020; Abdelhamid, 2021; Kherrafi et al., 2024; Demirci, 2023).

The fourth stage was integrative model development. Based on the coded themes and comparative findings, a conceptual framework was developed that places solar drying and sodium borohydride hydrogen systems along a continuum of renewable energy stabilization. At one end of this continuum are direct-use solar systems where the value of energy depends on immediate conversion into low-temperature useful heat, as in drying agricultural products (El-sebaili & Shalaby, 2012; Kamarulzaman et al., 2021). At the other end are indirect-use chemical systems where energy is stored in reactive media and released later in a different form, as in on-demand hydrogen generation from sodium borohydride (Liu & Li, 2009; Dragan, 2022). Between these ends lies a broad range of storage-intensified, hybrid, and context-specific renewable pathways.

This methodology has several strengths. It enables rigorous source discipline, preserves cross-disciplinary nuance, and allows theoretical integration of literatures that are rarely interpreted together. It is especially useful when the research objective is not to produce a universal

metric, but to generate a robust conceptual understanding of how different technologies solve related sustainability problems. At the same time, this approach has limitations. Because the study does not introduce new experiments or perform a quantitative meta-analysis, its findings are interpretive rather than predictive. It depends on the internal richness of the selected references, and its conclusions remain contingent on the scope and representativeness of the provided literature. In addition, the source set contains more studies on technological characteristics than on lifecycle economics, user behavior, or policy implementation, which means that the analysis is strongest on engineering logic and weaker on adoption sociology or market forecasting (Maka & Alabid, 2022; Kumar et al., 2024).

Even with these limitations, the methodology is appropriate to the task. The article aims to produce an original, publication-style argument derived strictly from the references supplied, not to introduce external evidence. The originality therefore lies in the comparative structure, the integrative reading of thermal and chemical storage pathways, and the reframing of solar drying and sodium borohydride hydrogen systems as complementary elements in decentralized sustainable energy design.

Results

The analysis of the supplied literature produces several interrelated findings. The first and most immediate result is that solar drying has developed into a technically diverse and application-sensitive field in which the primary engineering challenge is no longer the basic feasibility of solar-driven drying, but the optimization of reliability, product quality, and thermal continuity. Early evaluations of cabinet and air-heating dryer systems established that useful drying performance could be achieved through relatively simple solar collector configurations, but also showed that airflow patterns, collector temperature, and chamber conditions strongly influence practical outcomes (Ampratwum & Dorvlo, 1998). Subsequent work expanded this insight by examining product-specific kinetics, collector types, indirect heating methods, greenhouse enclosures, and tunnel architectures. The literature on mango slices, grapes, banana, garlic, mushroom slices, and chilli indicates that drying performance cannot be generalized abstractly. It is highly dependent on product geometry, moisture diffusivity, layer thickness, ambient conditions, and desired quality parameters such as color retention or uniformity (Goyal et al., 2006; Fadhel et al., 2005; Hegde et al., 2015; Kaewkiew et al., 2012; Malakar et al., 2021; Çerçi et al., 2022).

A second result is that the strongest recent advances in solar drying are associated with the incorporation of

storage and hybridization mechanisms. Reviews consistently show that conventional solar dryers can suffer from temperature instability and performance decline during low-radiation periods, which directly affects drying duration and quality (Sharma et al., 2009; El-sebaili & Shalaby, 2012). The integration of phase change materials, sensible heat storage, rock beds, desiccants, photovoltaic-powered fans, and evacuated tube collectors has increasingly been used to address this challenge (Shanmugam & Natarajan, 2006; Goud et al., 2019; Bhardwaj et al., 2020; Yematawu et al., 2024). The literature indicates that storage changes the function of the solar dryer from a passive daytime device into a partially buffered thermal process system. This is not a minor modification. It redefines the operational profile of the technology by extending usable drying periods, smoothing thermal peaks and troughs, and improving process control (Devahastin & Pitaksuriyarat, 2006; Abueluor et al., 2023).

A third result is that phase change materials occupy a particularly important role in the contemporary evolution of solar drying. The broad literature on phase change storage emphasizes their ability to absorb and release latent heat near desired operating temperatures, making them attractive for low- to moderate-temperature solar applications (Farid et al., 2004; Kumar & Gupta, 2021). In dryer-specific studies, PCM integration is associated with more stable drying chamber temperatures, reduced dependence on instantaneous radiation, and improved evening or off-sun performance (Singh & Mall, 2020; Bhardwaj et al., 2020). The more recent reviews further indicate that the integration of PCM is moving beyond isolated prototypes toward a systematic design topic involving encapsulation, melting temperature selection, thermal conductivity enhancement, and integration with solar air collectors or PV/T systems (Abueluor et al., 2023; Tyagi et al., 2024; Ying et al., 2024). The evidence therefore suggests that storage is no longer peripheral to solar drying research; it is the central pathway through which dryer performance is being modernized.

A fourth result concerns the maturity gradient within solar drying technologies themselves. Not all designs occupy the same position in terms of complexity, field adaptability, and likely dissemination. Greenhouse and tunnel dryers offer large-scale agricultural relevance and have been demonstrated for commodities such as chilli and grapes, especially in contexts where land and solar exposure are available (Kaewkiew et al., 2012; Rathore & Panwar, 2010; Hamdi et al., 2018). Indirect dryers and forced-convection systems allow better process control and hygiene, but may require more mechanical support and system integration (Goud et al., 2019; Shanmugam & Natarajan, 2006). Evacuated-tube-assisted and reflector-enhanced systems show higher sophistication and performance potential, though their cost and maintenance requirements may affect

adoption in low-resource settings (Malakar et al., 2021; Yematawu et al., 2024). Reviews from Malaysia, Asia, and Africa reinforce the point that technology suitability depends not only on thermal performance, but on local manufacturing capacity, user practices, commodity type, and economic conditions (Fudholi et al., 2015; Udomkun et al., 2020).

The fifth result is that the sodium borohydride literature presents a technologically rich but less deployment-mature landscape. The references collectively confirm that sodium borohydride is one of the most extensively studied chemical hydrogen carriers because it can generate hydrogen through hydrolysis under mild conditions and with potentially high controllability (Liu & Li, 2009; Santos & Sequeira, 2011; Abdelhamid, 2021). The hydrolysis process is attractive because hydrogen can be produced on demand rather than stored entirely as compressed gas, which may reduce some infrastructure pressures associated with conventional hydrogen handling (Jiang et al., 2010; Dragan, 2022). However, the literature also makes clear that hydrogen yield, reaction rate, and practical system viability depend strongly on catalyst selection, material design, water balance, by-product behavior, and reactor conditions (Brack et al., 2015; Patel & Miotello, 2015; Xu et al., 2022; Xu et al., 2024).

A sixth result concerns the centrality of catalysts in sodium borohydride systems. Across the relevant references, catalysts emerge as the equivalent of process intensification tools in solar dryers. Just as airflow regulation and thermal storage determine dryer effectiveness, catalytic systems determine whether sodium borohydride hydrolysis is practical, efficient, and scalable. The literature on cobalt-based and related catalysts shows continued efforts to enhance hydrogen generation kinetics while reducing reliance on costly noble metals (Patel & Miotello, 2015; Xu et al., 2024). Reviews of heterogeneous and homogeneous catalyst systems similarly indicate that catalytic design is not a secondary optimization variable, but the heart of operational performance (Brack et al., 2015; Xu et al., 2022). This result suggests that any realistic appraisal of sodium borohydride must be made at the system level, not at the material formula level alone.

A seventh result is that the greatest unresolved issue in sodium borohydride technology is not hydrogen release itself, but cycle closure. Hydrogen generation by hydrolysis has been well established conceptually and experimentally, but the spent reaction products must be regenerated if the system is to function as a sustainable storage loop rather than a one-directional chemical consumable (Demirci, 2015; Chen et al., 2017; Ouyang et al., 2018). Studies on regeneration via mechanochemical methods, coupled methanol systems, and closed-loop borohydride cycles show that this challenge is receiving increasing attention (Aydin et al.,

2020; Huang et al. not included, so omit; Zhu et al., 2023). The current literature indicates progress, but also underscores that regeneration remains energy-intensive and crucial to overall feasibility. Demirci (2023) explicitly frames the technological maturity question in terms of this broader systems reality. Thus, while sodium borohydride is promising as a hydrogen carrier, its viability depends on whether the full material-energy cycle can compete technically and economically with other storage options.

An eighth result is that sodium borohydride is increasingly being situated within broader hydrogen storage debates rather than treated as an isolated specialty material. Reviews of metal hydrides, chemical hydrogen carriers, and emerging hydrogen storage technologies place sodium borohydride alongside a broader set of physical and chemical storage pathways, each with distinct trade-offs involving density, safety, portability, reversibility, and infrastructure requirements (Hirscher et al., 2020; Klopčič et al., 2023; Kumar et al., 2024). In this broader context, sodium borohydride's appeal lies less in universal superiority and more in application-specific strengths such as controllable hydrogen generation, transport possibilities, and suitability for distributed systems where compressed gas logistics are undesirable (Ibrahim et al., 2023; Liu et al., 2024). The literature therefore supports a differentiated view: sodium borohydride is unlikely to displace all other hydrogen storage methods, but may occupy valuable niches where chemical storage advantages outweigh regeneration burdens.

A ninth result emerges from comparing the solar drying and sodium borohydride literatures directly. The core commonality between them is not temperature range, chemistry, or sectoral use. It is the conversion of intermittent renewable opportunity into stable functional output. In solar dryers, the unstable input is solar radiation, and the stable output sought is reliable low-temperature drying heat over extended hours (Tripathy & Kumar, 2009; Kamarulzaman et al., 2021). In sodium borohydride systems, the unstable input is broader renewable energy availability or hydrogen production opportunity, and the stable output sought is dispatchable hydrogen released when needed (Abdelhamid, 2021; Demirci, 2023). In both cases, storage is the mediating principle that transforms resource abundance into usable service continuity.

A tenth result is that the two domains differ sharply in proximity to field deployment. Solar drying systems, even advanced storage-enhanced variants, are already closely tied to concrete use cases such as fruit, vegetable, spice, and mushroom drying (Goyal et al., 2006; Hegde et al., 2015; Çerçi et al., 2022). Their benefits are legible at the user level: reduced spoilage, improved hygiene, better product quality, and lower

dependence on fossil-fuel drying or open-sun methods (El-sebaili & Shalaby, 2012; Udomkun et al., 2020). Sodium borohydride systems, by contrast, are still negotiating the transition from laboratory viability and niche prototypes to broader adoption. The complexity of catalyst systems, regeneration pathways, and hydrogen cycle economics means that commercial maturity is more conditional (Demirci, 2023; Zhu et al., 2023). This result does not diminish the value of sodium borohydride research. Rather, it situates it within a longer innovation horizon than most solar drying technologies.

An eleventh result is that decentralized sustainability favors layered energy architectures rather than single-technology solutions. The literature on solar energy trends and sustainable development emphasizes the need to match renewable technologies to end-use context rather than seek a universal device (Devabhaktuni et al., 2013; Maka & Alabid, 2022). Within such a framework, solar drying technologies appear especially suited to direct productive uses in agriculture and food systems, while sodium borohydride-based hydrogen pathways may serve as complementary storage options for portable power, fuel cells, or backup applications where energy must be dispatched in a different time or location (Santos & Sequeira, 2011; Ibrahim et al., 2023). The evidence therefore supports integration at the systems level, not convergence at the device level.

Finally, the twelfth result is conceptual. The supplied references collectively indicate that sustainable energy technology should be understood less by energy source alone and more by storage hierarchy. Direct solar utilization, thermally buffered solar utilization, chemically stored energy, and regenerable hydrogen cycles represent different positions along a hierarchy of conversion complexity and temporal flexibility. Solar dryers occupy the lower-complexity, immediate-use end of this hierarchy, especially when enhanced by sensible or latent heat storage. Sodium borohydride systems occupy a higher-complexity, delayed-use end of the hierarchy, where the goal is not immediate heat application but transportable and controllable hydrogen service (Farid et al., 2004; Demirci, 2015; Tyagi et al., 2024; Kumar et al., 2024). This hierarchy provides a useful explanatory model for understanding why both technology families matter, even though they solve different practical problems.

Discussion

The findings of this study suggest that the most productive way to interpret the supplied literature is not to ask whether solar drying systems or sodium borohydride hydrogen systems are better technologies in any generalized sense. That question is too coarse and assumes a false uniformity of purpose. A more

analytically meaningful question is how each technology family addresses the fundamental challenge of renewable energy usability under intermittent conditions. Once framed in this way, the significance of both literatures becomes clearer. They are part of a broader inquiry into how renewable energy can be transformed from an episodic environmental resource into a reliable, socially useful, and economically meaningful service.

Solar drying represents a particularly instructive case because it demonstrates that renewable energy can be highly effective when matched to the right end use. One of the recurring lessons from the solar drying literature is that low-temperature agricultural processes are inherently compatible with solar thermal input, provided that system design is attentive to product characteristics and environmental variability (Sharma et al., 2009; El-sebaai & Shalaby, 2012). This compatibility matters. Many energy transition narratives focus disproportionately on electricity or transport fuels, but a significant share of real-world energy demand, especially in agrarian and rural economies, involves thermal tasks such as drying, heating, and preservation. Solar drying therefore offers an example of what might be called direct renewable appropriateness: the energy source and the end-use temperature range are well aligned.

However, the literature also shows that appropriateness alone does not guarantee reliability. Solar radiation varies. Agricultural products differ in moisture behavior. Drying is not simply heating; it is a coupled heat-and-mass-transfer process in which inadequate temperature control can reduce quality, prolong drying, or produce uneven outcomes (Tripathy & Kumar, 2009; Goyal et al., 2006). This is why storage becomes central. The incorporation of PCM, sensible heat storage, rock beds, and other buffering strategies is theoretically important because it transforms solar drying from a strictly weather-following process into a semi-managed process. In effect, storage decouples the act of energy capture from the moment of energy use, even if only over relatively short time scales of hours rather than days or months (Devahastin & Pitaksuriyarat, 2006; Bhardwaj et al., 2020; Abueluor et al., 2023).

This decoupling is the conceptual bridge to sodium borohydride systems. In chemical hydrogen storage, the time separation is more radical. Here, the ambition is not merely to extend thermal service into the evening, but to store energy in chemical form for later conversion into hydrogen when required. The references suggest that sodium borohydride is compelling precisely because it offers controlled, on-demand hydrogen generation under comparatively mild conditions, which is attractive for distributed and potentially mobile applications (Liu & Li, 2009; Abdelhamid, 2021). Yet the sodium borohydride literature also reminds us that every

increase in temporal flexibility tends to increase system complexity. The move from direct solar use to chemically stored hydrogen involves new burdens: catalyst optimization, by-product management, regeneration energy, full-cycle economics, and safety governance (Patel & Miotello, 2015; Demirci, 2023; Kumar et al., 2024).

A major theoretical implication of the comparison is that storage hierarchy may be a more useful organizing concept than energy hierarchy. Technologies are often compared as though solar thermal, hydrogen, and chemical storage belonged to the same evaluative frame. In practice, what differentiates them is not only source or carrier, but the degree and type of storage mediation. A solar dryer without storage is a direct-use system. A solar dryer with PCM is a short-horizon buffered system. A sodium borohydride hydrogen system is a chemically mediated delayed-use system. Each step up this hierarchy increases flexibility, but also tends to increase cost, material intensity, process complexity, and dependency on advanced supporting components (Farid et al., 2004; Dragan, 2022; Tyagi et al., 2024). This suggests that the design of sustainable energy systems should begin not from abstract preferences for particular technologies, but from an assessment of how much storage mediation the target application actually requires.

This perspective also helps explain why solar drying technologies appear closer to broad social impact than sodium borohydride systems. The former solve a clear and immediate need in many regions: reducing moisture content in agricultural products while preserving quality and lowering dependence on open-sun drying or conventional fuels (Udomkun et al., 2020; Kamarulzaman et al., 2021). Their performance can be judged directly by users in terms of faster drying, cleaner products, reduced losses, and potentially higher market value. In contrast, sodium borohydride systems address a more abstract but still important need: the storage and controlled delivery of hydrogen in contexts where other storage methods are difficult or undesirable. Their utility is potentially large, but more mediated by technical infrastructure and economic conditions. The literature on technological maturity underscores this distinction clearly, especially in Demirci's analysis of the distance between scientific promise and practical readiness (Demirci, 2023).

Another important discussion point concerns the role of integration. In the solar drying literature, integration refers to combining collectors with fans, storage media, reflectors, desiccants, or greenhouse structures in order to improve performance (Goud et al., 2019; Yematawu et al., 2024). In the sodium borohydride literature, integration concerns catalysts, regeneration pathways, solvent systems, hydrogen-use technologies, and transport frameworks (Chen et al., 2017; Aydin et al.,

2020; Ibrahim et al., 2023). In both domains, the era of stand-alone devices is giving way to integrated systems thinking. This shift is highly significant. It suggests that the future competitiveness of sustainable technologies will depend less on the excellence of isolated components and more on the coherence of multi-component design.

There is also a subtle but important sustainability lesson in the contrast between the two fields. Solar drying research is strongly embedded in the logic of productive sufficiency. It seeks to improve real processes such as food preservation using relatively direct and context-sensitive means. Hydrogen storage research, especially in sodium borohydride systems, is more strongly embedded in the logic of flexibility and portability. It seeks to make energy available beyond the moment and location of generation. Neither logic is superior in absolute terms. Rather, they correspond to different sustainability functions. Productive sufficiency is about serving local needs effectively with minimal conversion layers. Flexibility is about enabling broader temporal and spatial redistribution of energy services. Sustainable development requires both, but not always in equal measure (Maka & Alabid, 2022; Devabhaktuni et al., 2013).

Counter-arguments must also be addressed. One might argue that comparing solar drying and sodium borohydride systems is methodologically awkward because they serve different markets and operate on different scientific principles. This objection is valid if the goal is one-to-one technological comparison. It is less persuasive if the goal is systems-level interpretation. The comparison undertaken here does not rest on physical similarity, but on functional analogy: both domains are concerned with stabilizing renewable energy for useful output. Another counter-argument is that sodium borohydride may never become a broadly competitive storage pathway because of regeneration burdens and materials cost. The supplied references certainly justify caution on this point (Demirci, 2023; Zhu et al., 2023). Yet even if sodium borohydride remains niche, niche technologies can still be strategically important, especially in distributed, portable, or safety-sensitive applications where conventional hydrogen storage is impractical (Ibrahim et al., 2023). Conversely, one might overstate the maturity of solar drying by assuming that field-level feasibility automatically translates into adoption. The literature on regional innovation landscapes and implementation contexts suggests otherwise; social acceptance, affordability, maintenance, and local manufacturing remain decisive (Fudholi et al., 2015; Udomkun et al., 2020).

A further insight emerging from the discussion is that materials research and systems research must remain connected. In solar drying, it is tempting to focus on

collector efficiency or PCM properties in isolation. In sodium borohydride systems, it is tempting to focus on catalytic performance or hydrogen release rates. But the supplied references consistently indicate that material excellence alone does not determine deployment success. For solar dryers, the decisive outcomes include drying continuity, user operability, and product quality (Malakar et al., 2021; Kherrafi et al., 2024). For sodium borohydride, they include regeneration feasibility, system integration, safety, and economics (Abdelhamid, 2021; Demirci, 2023). Sustainable energy research therefore requires a balance between deep materials innovation and practical systems evaluation.

The study also points toward a future in which cross-sector renewable architectures become more important than single-use technologies. Imagine a rural or peri-urban agro-processing environment. Solar thermal systems could support daytime drying and preservation. PCM-based storage could stabilize thermal operation through variable sunlight. Excess renewable electricity or centralized renewable energy elsewhere might be converted into hydrogen carriers for backup power, mobility support, or dispatchable fuel-cell applications. In such a setting, the question would not be whether solar drying competes with sodium borohydride hydrogen storage, but how different storage modes can be layered according to task and timescale. The literature reviewed here supports precisely this layered logic, even though the underlying studies do not explicitly formulate it in these terms.

Several limitations shape this interpretation. First, because the article relies strictly on the supplied sources, it does not include adjacent literatures on techno-economic assessment, lifecycle emissions, rural adoption behavior, or policy frameworks beyond what is embedded in the given references. Second, the solar drying references are more application-oriented and experimentally grounded than the sodium borohydride references, which may bias the comparison toward practical immediacy in the former and conceptual maturity assessment in the latter. Third, the analysis is interpretive and conceptual rather than quantitative. It does not rank technologies by cost, efficiency, or carbon intensity, because the source set does not support a standardized comparison across all those variables. These limitations do not invalidate the findings, but they define their scope.

Future research should proceed in at least four directions. The first is comparative techno-economic modeling of layered renewable systems that combine direct-use thermal technologies with chemical storage pathways. The second is lifecycle-oriented analysis of sodium borohydride regeneration under realistic renewable energy supply assumptions. The third is field-based social and institutional research on solar dryer adoption, maintenance, and local manufacturing

ecosystems. The fourth is application mapping: determining which decentralized contexts genuinely require the higher flexibility of chemical hydrogen storage and which are better served by direct or thermally buffered solar systems. The literature synthesized here strongly indicates that the most important advances will come from context-matching rather than technological maximalism.

Conclusion

This article has developed a comparative and conceptual research analysis linking two bodies of literature that are rarely interpreted together: solar drying technologies and sodium borohydride-based hydrogen storage systems. Based strictly on the supplied references, the analysis demonstrates that both domains confront the same foundational challenge of sustainable energy engineering: how to transform intermittent renewable resources into reliable, usable, and context-appropriate services. Their solutions differ in mechanism, scale, and maturity, but they belong to a common systems logic centered on storage mediation.

The solar drying literature shows a mature and expanding field characterized by strong progress in collector design, airflow control, product-specific optimization, greenhouse and tunnel systems, and especially thermal storage integration through sensible and latent heat strategies. Its chief strength lies in high functional alignment with agricultural preservation needs, particularly in decentralized or resource-constrained settings. Storage-enhanced solar drying is revealed as a practical way of improving continuity, product quality, and operational reliability without departing from the direct-use logic of solar thermal energy.

The sodium borohydride literature reveals a more chemically complex but strategically important pathway for hydrogen storage and generation. Its key advantages include on-demand hydrogen release, controllability, portability potential, and relevance to distributed energy applications where conventional storage routes may be less suitable. At the same time, the literature makes clear that full-cycle feasibility depends on catalysts, regeneration pathways, systems integration, and technological maturity. The greatest challenge is not simply hydrogen release, but economically and energetically credible cycle closure.

The central conclusion of the study is that these two technology families should be understood as occupying different positions on a renewable storage hierarchy. Solar dryers represent direct and short-horizon buffered use of solar energy for productive thermal applications. Sodium borohydride systems represent delayed and chemically mediated use of stored renewable potential in the form of hydrogen. The future of decentralized

sustainability is therefore unlikely to depend on choosing between them. Rather, it will depend on building layered energy architectures in which direct solar use, thermal buffering, and chemical storage are deployed according to the needs of specific tasks, timescales, and local conditions.

Sustainable energy development will be strongest where technological complexity is justified by functional need, and where storage strategies are matched precisely to the service being delivered. The references synthesized in this article collectively support such a view. They show that the path forward is not a single universal technology, but a coordinated portfolio in which low-temperature productive uses and higher-flexibility energy carriers coexist within an integrated systems framework.

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