

Research Papers

Bridging stakeholder perspectives through deliberation: A participatory approach to weighting decision criteria for seasonal thermal energy storage

Richard Lüchinger^{a,*}, Martina Haase^b, Manuel Baumann^b, Heimo Walter^c, Jörg Worlitschek^a

^a Competence Centre Thermal Energy Storage, Lucerne University of Applied Sciences & Arts, Switzerland

^b Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology, Germany

^c Institute for Energy Systems and Thermodynamics, TU, Wien, Austria

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ABSTRACT

Seasonal Thermal Energy Storage (STES) is central to the heat transition, but decision-makers must master a heterogeneous, highly context-dependent technology landscape. This study combines Constructive Technology Assessment (CTA) with elements of Multi-Criteria Decision Analysis (MCDA) to identify and weight 13 decision criteria for Seasonal Thermal Energy Storage. It examines how deliberative processes shift the perspectives of Selectors and Enactors. It is based on 19 expert interviews, two stakeholder workshops ($n = 25$ participants), and a pre/post survey. The results show that economic criteria dominate across all roles. Selectors systematically weight social aspects such as acceptance, space requirements, and visibility more heavily, while enactors place greater emphasis on technical criteria. It is also apparent that deliberation leads to noticeable shifts in weighting. The study thus makes three contributions: First, it demonstrates MCDA as a CTA platform for reflection and negotiation of conflicting goals. Second, it is the first MCDA application for STES selection with role-specific stakeholder weights. Third, it shows that the involvement of non-technical actors establishes MCDA as an instrument of participatory technology design and that technological assessments remain context- and perspective-dependent.

1. Introduction

Decarbonizing the building sector demands a substantial effort, but it is indispensable to achieving the energy transition [1–4]. The thermal supply of the building sector makes up nearly half of the world's total energy use. In Europe and North America, thermal energy supply accounts for around 40% of total energy consumption and a third of CO₂ emissions [5]. Switching to renewable energy is crucial, but solar and wind are weather-dependent, making energy balancing critical to stability [6–9].

The lack of storage prevents the effective use of renewable thermal energy and reinforces fossil fuel dependence [10]. Seasonal thermal energy storage (STES) addresses this disparity, allowing the reliance on fossil fuels to be broken. STES systems enable long-term storage, allowing thermal energy from periods of high production to be utilized during phases of lower production or increased demand [11]. This addresses the problem of seasonal fluctuations in renewable energy sources [12–14], reduces dependence on fossil fuels, and increases the overall efficiency of the heat supply [15–17].

Despite its key role, STES technology remains underutilized in many countries and faces an uncertain future [18]. Reasons for this include high initial investments [19], challenges in system integration [10], social barriers [20], inadequate legal frameworks, a lack of experience, and low public awareness [21]. In addition, STES are a highly heterogeneous group of technical solutions that vary widely in design, space, and integration requirements, which complicates decision-making and hinders broader adoption. With no one-size-fits-all solution and new concepts emerging all the time [22], decision-makers are faced with a growing number of alternatives. The appraisal of STES technologies necessitates considering complex interactions among technical, economic, ecological, social, and regulatory factors. Technological decisions can create path dependencies and lock-ins that can lead to conflicts over the means, speed, and direction of change [23].

Constructive Technology Assessment (CTA) supports the development of emerging technologies, such as STES, by promoting dialogue, reflection, and anticipation of societal impacts. However, it lacks standardized methods for incorporating the views of different stakeholders in making decisions [24–26]. Multi-Criteria Decision Analysis (MCDA) complements this by structuring complex decisions and evaluating

* Corresponding author.

E-mail address: Richard.luechinger@hslu.ch (R. Lüchinger).

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Abbreviations

CTA	Constructive Technology Assessment
GWP	Global warming potential
KPI	key performance indicator
LCOS	Levelized cost of storage
HELDA	Helmholtz MCDA Tool
MCDA	Multi-Criteria Decision Analysis
STES	Seasonal thermal energy storage
T1	Point in time: first individual survey
T2	Point in time: deck of cards for homogeneous groups
T3	Point in time: presentations in plenary
T4	Point in time: deck of cards, heterogeneous groups
T5	Point in time: second individual survey
TES	Thermal energy storage

alternatives transparently [27–29]. Combined with participatory workshops, MCDA can act as a ‘bridging event’ in the sense of CTA, promoting mutual understanding and informed joint decisions.

In addition to structured decision-making, the interaction between stakeholders plays a central role. Bridging events in the sense of CTA create spaces for reflection in which new information is absorbed, assumptions are questioned, and perspectives are broadened [30]. This learning process can result in changes to weightings. This leads to the hypothesis that the MCDA workshop, as an interactive participation format, encourages stakeholders to adjust their original weightings by learning from new perspectives and reflecting on their assumptions. This demonstrates that decision-making processes are dynamic and evolve through dialogue. These dynamics require approaches that not only involve stakeholders but also facilitate the structured comparison of technological alternatives based on weighted decision criteria.

Literature shows that MCDA is used to evaluate thermal energy storage (TES) in different contexts, for example, for material selection [31,32], for improving TES systems, and for integrating TES into district heating systems [33]. In a further MCDA study, the suitability and sustainability of Aquifer Thermal Energy Storage are evaluated worldwide, and region-specific potentials are identified [34]. To our knowledge, there is a lack of studies that systematically examine STES decision-making processes or combine MCDA with stakeholder analysis in the CTA context of STES. While there are technical and economic analyses of STES, it remains unclear how stakeholders evaluate the technology and adapt their evaluations through reflection and learning. This work fills this gap by integrating Enactors and Selectors in a CTA-informed, deliberative process to identify and weight decision criteria for STES.

Against this backdrop, the central question concerns the selection of decision criteria for assessing STES in heating networks, how different stakeholder roles (Enactors and Selectors, see Section 2.3) weight these criteria, and how these weightings change through deliberative interaction. To address this question, the present study develops a MCDA-supported CTA framework. This enables systematic identification, structuring, and weighting of decision criteria for STES in a deliberative stakeholder process. The study operates within a generic application framework restricted to the STES context. Common STES technology types serve as contextual anchors, while the analysis remains criteria-centered, deliberately avoiding detailed technological evaluation. The application framework is based on heating networks with reference to a Swiss use case; the process logic is transferable, while the criteria and weights determined are context specific. A performance matrix, criteria aggregation, technology rankings, and sensitivity analyses are not part of this study.

Methodologically, expert interviews, workshops as CTA bridging events, and pre-post surveys are combined. In this way, criteria, and weights are collected and shifts in perspectives are made visible. MCDA

acts as a platform for reflection and negotiation, making differences between stakeholder roles (Enactors vs. Selectors) transparent and promoting social learning. The contribution of this work is threefold: (i) Methodologically, it shows how MCDA structures reflexivity and negotiation in the frame of CTA. (ii) Empirically, to our knowledge, it is the first role-dependent stakeholder process for selecting and weighting decision criteria for STES assessment. (iii) Normatively, it shows how to strengthen the democratization of technical decisions by specifically involving non-technical actors and highlights the context- and perspective-dependence of CTA-based decision processes.

The paper is structured as follows: Section 2 introduces the theoretical framework and methodology, including the identification and selection of decision criteria; Section 3 presents results on criteria weights and perspective shifts; Section 4 discusses the interpretation of the results, including implications and limitations of the criteria selection and weighting process; and Section 5 concludes.

2. Theoretical framework and methodology

Selecting a suitable STES alternative is challenging due to the variety of options available and the complexity of the decision-making process. To address this, we have adopted a methodological approach that combines the theoretical framework of CTA with MCDA. This chapter summarizes the fundamentals of STES and the evaluation criteria relevant to our study. It also explains how CTA can be used as a framework for deliberative negotiation, reflexivity and social learning. Finally, it describes the MCDA approach to identifying and weighting criteria.

2.1. Background on STES

TES facilitates the thermal storage of excess energy for later use in heating applications [35]. Depending on how long the heat is stored, the literature distinguishes between short-term and long-term storage, with the latter also being referred to as STES. STES stores excess heat during months of high energy supply to provide heat during periods of high demand [11]. While short-term storage systems primarily help to balance peak loads and increase the efficiency of energy systems, STES provides a sustainable heat supply and enables the use of renewable but weather-dependent energy sources. As a result, STES can provide a large share of the annual heat demand, typically between 50 and 70%, while short-term storage normally contributes only 10 to 20% [11,36].

There are three basic principles for storing heat: sensible, latent, and thermochemical storage. Sensible TES utilizes the temperature change, i.e., the heating and cooling of a storage medium, to store and release energy [37]. Latent heat storage systems use the phase change process of materials to store latent heat, i.e., phase change materials absorb or release heat during melting and solidification without changing their temperature [11]. Thermochemical heat storage systems are based on reversible chemical reactions that can be reversed when needed [38]. Of the three, only sensible STES solutions are commercially available and field-tested; latent and thermochemical STES technologies are at the laboratory or concept stage [22]. However, STES technologies also continue to face challenges, such as scaling and integration issues. Market penetration, regulatory integration, and economic establishment are not yet complete. In the following, this study considers STES as a black box that can encompass various technological realizations (for illustrative overviews of common STES concepts, see e.g. [17], among others. During the workshops, different STES technologies served as contextual reference points, while the analysis remains independent of technology-specific evaluation.

2.2. Parameters and criteria for selecting STES technologies

The STES technology best suited for a system depends on various factors, including geological and hydrological conditions, available space, legal requirements, cooling demand, and costs. References

[13,17] illustrate the diversity of STES systems and provide a decision-support flowchart to reduce the complexity of choosing a suitable technology. Reference [22] emphasizes this complexity by stating that there is no one-size-fits-all STES solution. The differences between STES technologies are discussed in detail in the scientific literature [10,13,17,39–42].

A substantial body of literature systematically investigates the characteristics and parameters of TES and STES systems. In [43], the authors made a first attempt to collect, structure, and classify key performance indicators (KPIs) for heat storage systems. They identified a total of 22 KPIs for TES in building applications and 12 for solar thermal power plants, with technical, economic, and ecological aspects being weighted differently depending on the type of storage. The SWS Heating project created a long list of 30 technical, seven socio-economic, and five environmental performance indicators for TES, from which 12 KPIs were selected, considering the perspectives of various stakeholders [44]. In [45], the authors also developed a long list of 36 literature-based performance indicators, from which seven technical, four socio-economic, and two ecological KPIs for TES in building applications were defined. The work in [46] analyzes 16 KPIs for various storage technologies at the building level and develops a simplified selection to facilitate comparison. The indicators encompass both technical and economic aspects and were utilized to evaluate heterogeneous technologies. The study highlights the need for standardized evaluation procedures to enable monitoring and technology comparisons. The work in [47] focuses on energy density as a key indicator of TES, but also lists further technical, economic, and ecological parameters. Later in this study, this body of literature will serve as a starting point for identifying decision criteria for STES technologies.

2.3. Constructive technology assessment as a theoretical framework

CTA was developed in the 1980s as a branch of technology assessment [48]. The latter aims to support technological change by anticipating the impacts of technologies, thereby reducing the costs of learning by trial and error [49]. CTA goes a step further and involves a broader range of stakeholders, including society, who have an interest in the development, adoption, and use of new technologies [50]. CTA is based on socio-technical systems theory, in which technology is viewed as one part of a highly interconnected network of heterogeneous elements, such as organizations, scientific elements, and laws [51]. To understand how technological development takes place in a socio-technical system, the dynamics of the different actors need to be considered, as technological development is at its core a process that depends on the decisions of the actors involved [26,52]. CTA sees technological developments as malleable, socially embedded processes in which stakeholders contribute and continuously adapt their visions and expectations [25,48].

However, it is challenging to predict the technical, social, economic, and commercial impact of a technology, especially in the case of emerging technologies like STES. This means that decisions are made in a context of uncertainty and based on a system of hardly reliable convictions, visions, and expectations [26,53]. Nevertheless, decisions must be made in the early stages of development, while technologies are still malleable, to facilitate sustainable development pathways over the long term [54]. CTA addresses this dilemma by promoting negotiation processes between actors and thus steering technological developments in a socially desirable direction through soft intervention [48].

In a nutshell, the elements of the CTA approach can be outlined as follows [24,25,30,48,55]: CTA is based on the premise of integrating the anticipation of technological impacts on society at an early stage of technological development. CTA calls for the involvement of various stakeholders, including not only technological actors but also social groups and policymakers, as part of the design process for new technologies, to align progress with societal needs and values. Since technological change is an ongoing process, CTA advocates continuous

learning about how technology interacts with design choices, user expectations, and political, cultural, and environmental factors. It also encourages stakeholders to think critically about their role in the co-evolution of technology and society, as well as its broader implications. CTA extends the decision-making process not only to a wider group of stakeholders but also to broader substantive criteria for technological development.

CTA assumes that there is an asymmetry between actors in a technology development process. This asymmetry is related to power and knowledge, as well as timing [55]. Actors involved in technology development have more knowledge, have invested, and have more opportunities to shape the technology at an early stage. Other actors, such as society affected by technological development, must, to some extent, await the consequences of the new technology, often without specific knowledge and with little influence on its design. On the other hand, technology developers may not be well-versed in the outside world. However, this can be a major obstacle, as the adoption and diffusion of technology depend on outsiders with different interests and expectations [56]. In CTA, there is a segmentation of these two groups of actors (i.e., stakeholder roles) who have different perspectives [50]:

- Enactors are technology developers and promoters who work to achieve their goals and visions. They implement (i.e., enact) technological developments and identify with them. They tend to emphasize positive aspects of technologies and rally behind a particular technology.
- On the other hand, Selectors weigh various options and make their decisions (i.e., selecting) based on a formal or informal cost-risk-benefit analysis. Selectors are potential users, social groups, and government agencies that take a more distanced perspective of technologies than Enactors.

These different mindsets and asymmetries between stakeholders can lead to conflicts. According to reference [26], an emphasis on the positive aspects of a technology (on the part of Enactors) can go hand in hand with a tendency to dismiss other opinions as irrational and misguided, or as advocating a personal agenda. This can be frustrating for both sides when they either must convince the public or have their needs ignored. This is where CTA steps in, organizing bridging events between stakeholders, where Enactors and Selectors can interact to a certain extent [50]. The Enactors learn about the perspectives and selection cycles of the Selectors. Conversely, the Selectors can learn from the Enactors about the insider knowledge of technology. Both groups are allowed to explore the reality of the other and to reflect on the extended dynamic [57]. The added value of bridging events is that it is not only about discussing a specific topic, but also about actively engaging with different perspectives. In this way, a basis for further and more productive interactions can be created, and asymmetries in promotion and control can be reduced [50]. Bridging events are protected spaces, akin to a microcosm, where actors can reflect on alternatives and adjust their strategies and eventual interactions in the real world without immediate repercussions. From the CTA's point of view, it is crucial to create such confrontations and exchanges early and more regularly, for example, through interactive workshops [26].

Bridging events promote reflexivity and social learning processes among stakeholders, two central mechanisms in CTA [48]. During the technological development process, the actors involved gain new insights, whereby existing assumptions are questioned and possibly modified. In this process, reflexivity is necessary on the one hand to encourage actors to reflect on the co-production of technology and its impacts. On the other hand, it is necessary to recognize the different roles of actors in technological development and the necessity of the presence of all types of actors. This is particularly important in the case of emerging technologies, where the roles are often not yet clearly defined and are constantly evolving and taking shape [26,58]. The reflexivity of stakeholders should lead to opportunities for improving

the co-production process. CTA promotes this by encouraging actors to question the presence of subjective assumptions and to recognize the co-creation of technology and society. Social learning, on the other hand, helps to explore new aspects of the evolving technology. According to reference [48], learning must take place broadly and deeply: broad learning serves to explore new connections between a range of aspects, such as user requirements, needs, and issues of political and social acceptance. In-depth learning, on the other hand, enables one to examine their work concerning specific goals and to understand values in detail.

The participation of stakeholders in the evaluation of technology does not necessarily guarantee learning and reflexivity [59,60]. People resist changes in their worldviews unless they are challenged by new information and alternative perspectives [61]. In this context, learning should not be understood as a mere transfer of knowledge, but as a constructive process of knowledge reconstruction. According to this perspective, individuals are active experimenters who formulate hypotheses about their world, test them, and revise them if necessary [59]. Awareness and targeted reflection on these implicit and explicit worldviews are crucial [62,63]. The use of structured decision-making approaches can help stakeholders learn about the options and trade-offs, as well as their values and interests, and those of the other participants [64].

As a theoretical framework, CTA enables the understanding of technological developments in STES as socially embedded processes. However, CTA does not provide a standardized method for systematically capturing and evaluating the diverging preferences of STES stakeholders. At this point, structured decision-support approaches such as MCDA can complement the CTA approach by combining reflection and learning processes with a participatory evaluation of STES. Recent work has emphasized that MCDA can also be applied as a criteria-centred structuring and learning framework, supporting preference articulation and deliberation without requiring aggregation or ranking of alternatives [65]. In this sense, MCDA complements CTA by providing a structured setting for articulating and comparing stakeholder perspectives, while its methodological implementation within the CTA framework is introduced in Section 2.4.

2.4. Methodological implementation of the MCDA-supported CTA

MCDA provides the methodological basis for this study. The overall

process follows a sequential logic, combining decision problem structuring and stakeholder integration through participatory workshops and individual surveys, as illustrated in Fig. 1. Section 2.4.1 outlines the general principles of MCDA. Section 2.4.2 explains how MCDA is implemented in this study as a criteria-centred and deliberative approach within CTA. Sections 2.4.3 and 2.4.4 describe the use case, the expert interviews, and the identification of decision criteria. Section 2.4.5 presents the design and sequence of the MCDA workshops, and Section 2.4.6 describes the individual pre- and post-surveys.

2.4.1. Theoretical background on MCDA

MCDA has supported decision-making for decades [66], helping to organize information, assess alternatives, and explore needs [67]. MCDA systematically helps structure decision problems, identify preferences, and recommend decisions [66,68]. The approach represents decisions and preferences through equations, inputs, and coefficients, making them observable and reproducible [69]. As decisions become more complex, MCDA enables decision-makers to assess them from multiple angles, weigh trade-offs, and evaluate options against various criteria. MCDA offers transparency, focus, and an iterative process that supports decision-making while incorporating social, political, and environmental factors, balancing multiple objectives and conflicts, and integrating stakeholders into the decision-making process [27,70–73]. MCDA methods widely and successfully solve large-scale socio-technical decision problems in the energy and sustainability field [66,68,74–77] with several reviews covering this topic [69,78–82]. Their effectiveness lies in their ability to address complex energy management challenges and support structured, transparent, and reliable technology decision-making [27,78,83]. In addition, MCDA can highlight commonalities and potential conflicts among stakeholders, fostering a deeper understanding of differing values [84].

Literature offers various schemes and frameworks describing the MCDA process [79]. Reference [69] states that MCDA enables integrated assessments by considering individual indicators, their interrelations, and their varying importance. The process consists of two overlapping phases: (1) the construction phase, which defines goals, scope, and alternatives, selects criteria, and creates a stakeholder interface; and (2) the exploitation phase, which measures criteria performance, aggregates MCDA criteria, and compares results. Based on this, [69] presents a simplified MCDA approach for energy storage systems in grid applications. Due to the thematic proximity, we use this approach as a starting

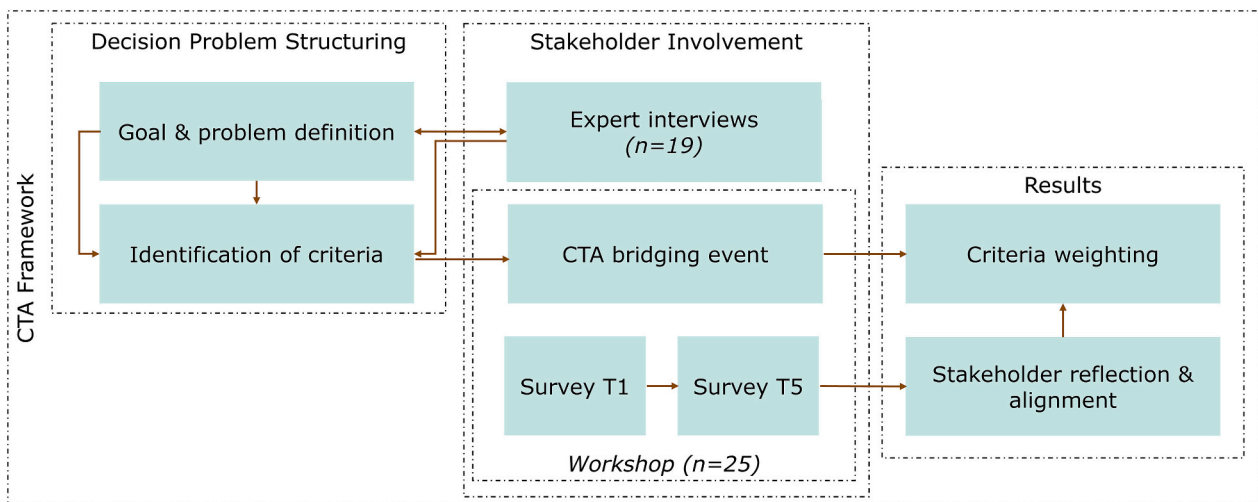


Fig. 1. The methodological approach of this study within the framework of the CTA is based on MCDA as its core. Starting from the definition of goal and problem, the criteria are determined and continuously refined through 19 expert interviews. The centerpiece is the CTA bridging event (workshop with $n = 25$ participants), where the criteria are discussed and weighted jointly. In parallel, two short surveys (T1 pre-event, T5 post-event) capture individual weights; T5 is informed by the workshop. The process culminates in criterion weightings and in the reflection and alignment of stakeholder perspectives. The arrows represent information flows between the steps and illustrate how results from earlier phases influence subsequent steps.

point and extend it as described below.

In this context, MCDA is not limited to the aggregation and evaluation of alternatives, but also supports the structuring of decision-making problems, the selection of criteria, and the elicitation of preferences. Previous work shows that the suitability of MCDA approaches depends strongly on the decision context, including the cognitive demands placed on participants and the way preferences are articulated and weighted, particularly in participatory and group-based settings [78,85,86]. Against this background, simple and transparent weighting methods are often used in energy-related MCDA applications, as they facilitate preference expression and discussion of trade-offs without requiring far-reaching formal assumptions [65,69].

2.4.2. Methodological implementation

In this study, MCDA is not applied as a decision or ranking model for evaluating technological alternatives. Instead, elements of MCDA are used in a criteria-centred and deliberative structuring approach to elicit and compare decision criteria and their relative importance. This methodology is based on [69] and was further developed through stakeholder integration processes described in the EU project StoRIES (see [87,88]), for example to determine stakeholder preferences in interviews and during workshops using individual surveys and group work.

The analysis in this study focuses on how stakeholder preferences are articulated and evolve through structured exchange, rather than on the aggregation of criterion performance or the ranking of alternatives. This positioning is consistent with the CTA framework, which emphasizes early reflexive processes and social learning. Accordingly, no sensitivity or robustness analysis is included, as the study deliberately does not produce aggregated rankings or decision outputs.

The MCDA process follows a sequential logic, as illustrated in Fig. 1. It starts with goal and problem definition and criteria identification informed by expert interviews. The core of the process consists of stakeholder workshops serving as CTA bridging events, beginning with an individual pre-survey at the start of the workshop (T1), followed by role-specific group work (T2), plenary exchange across stakeholder roles (T3), and joint weighting in mixed groups using the deck-of-cards method (T4). An individual post-survey (T5) captures reflections and revised weightings after the deliberative process. The timing of T1 to T5 corresponds to the workshop phases shown in Fig. 2. This design allows changes in expressed preferences to be identified and interpreted in relation to the structured exchange during the workshops.

Within this approach, the analysis is based on a fixed set of jointly developed decision criteria and on procedures for individual and collective weight elicitation applied consistently across all phases. The resulting weights are interpreted as relative priorities within this criteria set. They are not treated as parameters of a value or utility function, and no normalization of criteria performance or mathematical aggregation across criteria is performed. To support a shared understanding during the workshops, a use case is defined and four common types of STES

(aquifer-, borehole-, pit-, and tank-TES) are used as contextual anchors. Accordingly, the following analysis remains independent of technology-specific performance assessment, aggregation, or ranking.

2.4.3. Use case

The use case provides a common reference context that makes the criteria-weighting process understandable and comparable. It describes a planned CO₂-neutral district heating network for a municipal utility in Switzerland, designed to supply around 700 residential units with approximately 4 GWh of heat per year, combining heat pumps, biogas boilers, and photovoltaics. To ensure energy security and to reduce winter electricity demand, a seasonal storage unit is foreseen.

For orientation, the setup draws on a reference system [89] with an indicative storage capacity of about 1.4 GWh. At the beginning of the workshops, four common types of STES (aquifer-, borehole-, pit-, and tank thermal energy storage) were explicitly introduced by the facilitators and provided in the workshop handout as illustrative reference points. These technologies served to establish a shared understanding of the STES solution space and to support discussion. However, STES was treated as a black box throughout the analysis. No technology-specific performance assessment was conducted. The use case served solely to anchor deliberation and to provide a common reference context for the identification and weighting of decision criteria.

2.4.4. Expert interviews and identification of criteria

As a starting point, we identified a set of potentially relevant actors. We then refined this set through an iterative, snowball-like process as part of the expert interviews, in which interviewees were asked to suggest additional relevant actors, whose inclusion was subsequently assessed. Based on recommendations and references made during the interviews, we identified additional stakeholders whose relevance we continuously assessed and adjusted as the process evolved. Building on this foundation, we further developed the stakeholder classification and adapted it to the specific context of this research. The resulting stakeholder group identified through this mapping is provided in Appendix A.2, including assignments to the two CTA stakeholder roles (Enactors and Selectors). The expert interviews were also used to purposefully select workshop participants along these two CTA roles. However, this assignment was not always clear-cut, as overlaps between the groups were possible, double roles were common, and the STES ecosystem is evolving.

The expert interviews conducted as part of this study served to structure the problem and objectives by defining use cases, validating relevant stakeholders, and identifying decision criteria. To ensure continuous validation of assumptions and intermediate results, expert perspectives were integrated iteratively into the analysis process. The interviews followed a semi-structured format, allowing for a focused yet open discussion. All interviews were recorded and evaluated retrospectively, without a systematic content analysis. In total, 19 expert interviews were conducted, with an average duration of 56 min. The

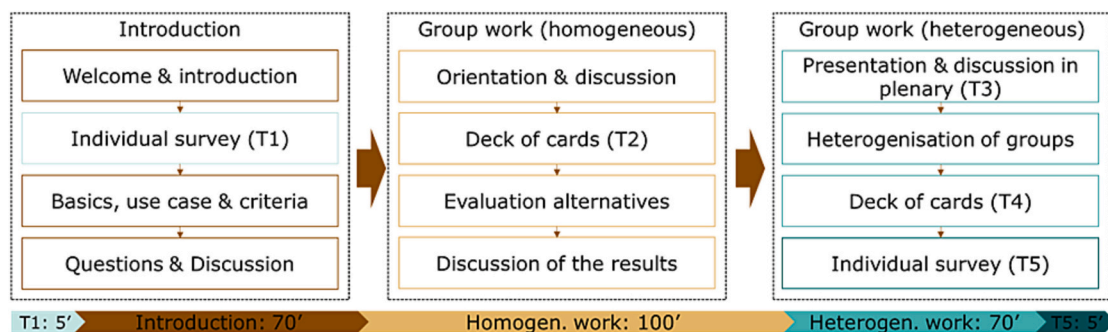


Fig. 2. Sequence and structure of the MCDA workshops in three blocks. Relevant points in time (T1 to T5) are marked to establish an explicit reference in the further course. Additionally, a timeline in minutes and colour coding are provided to classify the duration of each section.

interviewed experts represented engineering and planning offices with a focus on thermal networks and/or STES, utilities as active or potential STES end users, researchers in the field of STES or related topics, and authorities involved in STES regulation. The experts interviewed were not invited to participate in the workshops; instead, workshop participants were selected separately based on the identified stakeholder roles. This approach allowed for a broader range of perspectives to be captured across the different stages of the process.

The decision criteria are determined in two steps: first, a long list is created, which is then condensed into a short list. The longlist of potentially relevant criteria for selecting an STES alternative is based on the available literature [10,11,13,17,43,45,90–93]. The subsequent consolidation is conducted in an iterative process, with experts being interviewed until a shortlist of 13 decision criteria remains. We grouped the resulting shortlists into five categories based on themes: economic, social, ecological, technological, and spatial. In doing so, we are considering the spatial impact of STES technologies, which varies greatly across different types, but was frequently highlighted as a relevant factor in the interviews. Some criteria span more than one thematic dimension (e.g. spatial and social); in the main text, they are grouped by their dominant dimension, with overlaps documented in Appendix A.4.

2.4.5. Stakeholder workshops

The stakeholder workshops represent the central element of stakeholder interaction in this work. The aim is to integrate diverse backgrounds and perspectives into the decision-making process, enabling transparent and structured decision-making, and laying the groundwork for a consensus-based approach.

The workshops took place in two rounds with different groups of participants. The representation of stakeholders, the distribution of participants across the two workshops, and the composition of the groups are presented in the Appendix A.1. Participants were selected under two premises: on the one hand, the broadest possible spectrum of stakeholders should be represented, given the nature of the CTA; on the other hand, participants require a certain amount of knowledge about the technologies or the demands of technology. However, this means that some relevant stakeholder groups are only considered to a limited extent due to the low prevalence of STES technologies and the associated lack of knowledge about the technology. This is supported by a representative survey, in which 65% of the Swiss population reported never having heard of STES [94]. Nevertheless, to incorporate the societal perspective, political representatives and government agencies with the relevant knowledge take on this role.

A total of 25 selected participants took part in the two workshops, 15 of whom were Selectors and 10 Enactors. The Selector group primarily consists of individuals in leading positions within utilities, as shown in Table 1. As end-users of STES technologies, utilities are one of the most critical stakeholder groups. Four other Selectors represent the societal perspective in political or administrative functions, such as energy officers, spatial planners, or elected officials. Among the Enactors, half are engineering experts who plan and implement STES projects in leading positions. The group is complemented by two STES technology manufacturers and three researchers with a focus on STES. The asymmetric composition of workshop participants (Selectors: Enactors with a ratio of 3:2) reflects their different institutional roles in STES decision-making

Table 1

Distribution of participants across workshops by stakeholder groups and CTA role.

Stakeholder group	Selector	Enactor
Utilities	10	–
Admin/politics	4	–
Research	1	3
Engineers	–	5
Manufacturers	–	2
Total	15	10

processes and is considered in the interpretation of role-specific patterns. Due to last-minute cancellations, Enactors are slightly underrepresented in the final sample. Criteria weights are elicited at the group level, such that differences in the number of participants across roles do not directly translate into structural asymmetries at the group level. The workshop sample of 25 participants is not intended to support statistically representative or generalizable claims, but is designed as an exploratory sample capturing role-specific perspectives under deliberative conditions.

Each workshop is divided into three blocks and lasts a total of four hours (see Fig. 2). The first block, “Introduction”, ensures that all participants understand the basics of the workshops, particularly the use case, relevant criteria, basics of MCDA, and the weighting method to be used in the group work, and can discuss and ask questions about them. Participants receive the workshop documents in advance for self-study as needed. Immediately after the welcome, an individual survey (T1) is conducted, which is described in more detail in Section 2.4.6.

In the second block, “Group work (Homogeneous)”, the stakeholders first work in homogeneous groups, separated according to whether they belong to Selectors or Enactors, on the weighting of the decision criteria. To do this, they use the deck-of-cards method (T2), an established procedure for weighting decision criteria according to [95]. First, groups rank the criteria cards according to their subjective importance on a linear scale and insert blank cards in between to express the strength of preference differences. Then, they determine the number of times the most crucial criterion is more important than the least important, which serves as the basis for calculating the weights. As an extension of the deck-of-cards method, groups can add new criteria to the thirteen predefined criteria [96]. Any additional criteria are documented and discussed but are not analysed beyond weighting within the scope of this paper. Group moderators transfer the results from the deck-of-cards exercise into the software HELDA (Helmholtz MCDA Tool; [97]). HELDA implements the formal deck-of-cards procedure described in [98] and translates the qualitative preference ordering into numerical criteria weights. The software supports systematic documentation and visualization of the weightings during group deliberation. The evolving weight profiles can be displayed live during the workshops, which facilitates reflection and structured discussion among participants. Each group also appoints a note-taker to take minutes for additional documentation as a basis for the group presentation.

In block 3, “Group work (heterogeneous)”, the exchange and comparison of perspectives are promoted beyond homogeneous stakeholder groups. To this end, the groups present their results from block 2 in short pitch presentations in plenary (T3), whereby different perspectives are made visible and brought into a dialogue. The audio of the presentations is recorded for documentation purposes. After that, the groups are mixed to create heterogeneous constellations. The Mixed Groups then reevaluate the criteria using the deck-of-cards method (T4). The workshops end with another individual survey (T5). The aim of block 3 is to bring together different evaluation logics, enabling a comparison of viewpoints and building bridges between stakeholder groups to reflect on differences and identify overlaps. Additionally, the individual survey conducted after the group work reveals whether and how individual preferences change compared to T1.

Systematic reviews document a wide variety of subjective weighting methods (e.g., [99]). This study focuses on preference articulation and change in a deliberative workshop setting and applies the deck-of-cards method. Its physical and tangible character makes changes in prioritisation directly visible, as participants can move criteria relative to one another, which lowers cognitive barriers and supports intuitive engagement across different backgrounds. This makes it well suited for deliberative MCDA embedded in participatory formats focused on learning and interaction, as also discussed in [100].

2.4.6. Individual surveys

The individual survey captures the perspectives of stakeholders at

two points in time, during the two workshops, and enables a quantitative analysis of potential changes. To do this, the participants answer a short online survey at the beginning (T1) and at the end (T5) of the workshops.

The core of the survey is the weighting of the most important aspects for personal decision-making when choosing an STES alternative in a hypothetical project. Participants distribute 100 points across six overarching aspects: political, economic, social, technological, environmental, and legal aspects. We use a 100-point allocation because it is a simple and widely applied elicitation technique for capturing relative priorities in exploratory settings, independent of any specific MCDA aggregation model. It is frequently used in energy and sustainability research to reveal preference structures in a transparent and intuitive way [78]. The same question is asked again at T5 to identify potential shifts in priorities over the course of the workshop. By comparing the answers, any shifts in priorities between T1 and T5 can be identified. Additionally, the T1 survey includes a question asking respondents to rate their knowledge and expertise about STES on a Likert scale. This question aims to explore asymmetries in stakeholder knowledge.

It is worth noting that the six aspects used in the individual surveys represent the well-known PESTEL framework and do not directly reflect the decision criteria applied in the subsequent group weighting exercise. For the individual surveys we chose this generic framework to capture stakeholders priorities, even if they are not (yet) familiar with the specifics of the use case.

3. Results

This section presents the results of the two stakeholder workshops, structured by the individual surveys, the group work on criteria weighting, and qualitative observations from the group work.

3.1. Individual participant survey

The survey provides information on the participants' self-assessment of their knowledge of STES at the beginning of the workshops (T1), as

shown in Fig. 3. Among the responses from Enactors, the category 'high' ($n = 6$) dominates, followed by 'very high' and 'medium' (both $n = 2$), which reflects their direct involvement in the development and implementation of STES projects. Most Selectors rate their knowledge as medium ($n = 9$), followed by high ($n = 3$), low ($n = 1$), and very high ($n = 1$). Given the unequal group sizes (Selectors $n = 15$; Enactors $n = 10$), Fig. 3 is interpreted descriptively rather than statistically. The results are consistent with the CTA theory discussed in Section 2.3, which describes the asymmetrical distribution of knowledge between the two groups.

The following evaluation illustrates the impact of the workshops on the participants' perspectives, based on individual survey data collected at T1 and T5 (see Fig. 2). The change in the perceived relevance of the evaluated aspects is shown in Fig. 4 for the two roles: Enactors (left) and Selectors (right). The values represent the average (mean) rating of each aspect within the respective group, indicating which categories the participants consider most relevant for their decision-making when selecting a STES technology.

A significant adjustment of the original average evaluation by the Enactors can be observed, particularly regarding the increased importance of economic aspects (from 23.5 to 48.1 points). The legal aspects also gain slightly in importance from the Enactors' perspective during the workshops. By contrast, there was a noticeable decline in the importance attached to ecological aspects (from 19 to 3.75 points) and a slightly smaller but significant decline in the importance attached to technological aspects. Political and social aspects were also slightly downgraded on average.

By contrast, the weightings of the Selectors remained more stable throughout the workshops. Here, too, economic aspects gained in relevance (from 34.6 to 39.1 points). At the same time, ecological aspects were devalued, albeit not as much as for the Enactors (13.2 to 8.2 points). Technological aspects showed a slight increase, while social, legal, and political aspects remained largely unchanged. A complete overview of the distributions can be found in the Appendix.

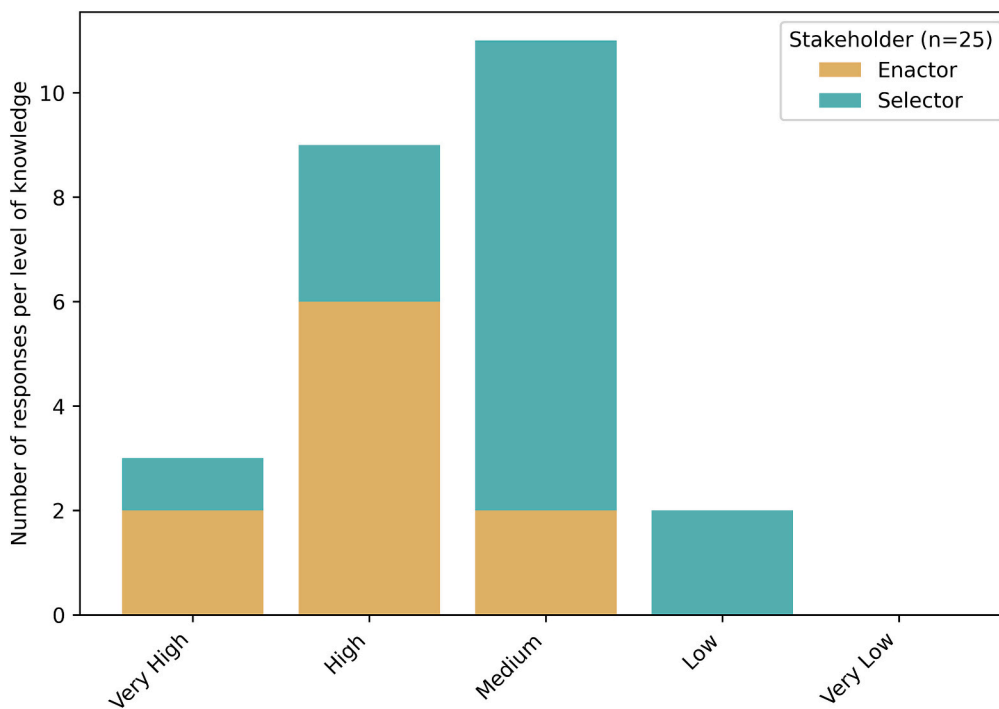


Fig. 3. Self-assessed level of STES-related knowledge among the 25 participants in the MCDA workshops, differentiated by Selectors and Enactors. The descriptive frequency distribution indicates role-related differences in self-assessed knowledge levels, reflecting the asymmetric knowledge positions of the two stakeholder roles as expected in CTA-oriented settings.

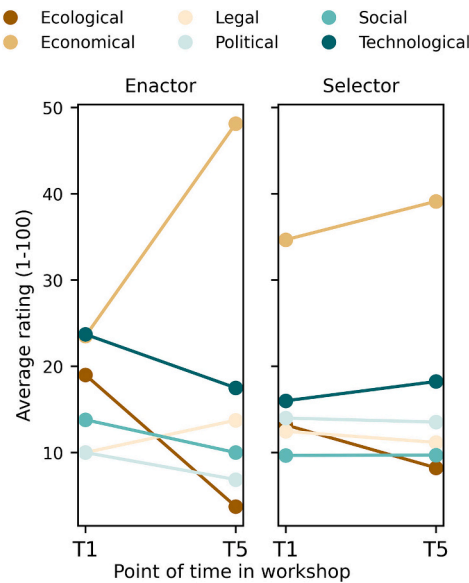


Fig. 4. Change in the average individual perceived relevance (100 = highest) of the decision aspects for STES technologies between T1 and T5, separated into Enactors and Selectors. The values represent the mean of individual ratings within each group and illustrate how the perceived importance of each category changed from the participants' perspective during the workshops.

3.2. Analysis of criteria weighting

This section is dedicated to the weighting of the decision criteria by the various stakeholder group constellations from both workshops. In addition, it shows to what extent the workshops as a bridging event influenced the weighting during the process. The following data and evaluations are based on the deck-of-cards method, whereby the weighting of the Homogeneous Groups is carried out at T2 and for the Mixed Stakeholder Groups at T4 (see Fig. 5). Each point in Fig. 5 represents one group-level weighting; group numbers and composition are shown in Appendix A.1.

Overall, the Selectors demonstrate a high level of agreement in their weighting, particularly regarding social acceptance, land requirements, visibility, and the dual use of the area, which underscores the importance of social factors. The main differences lie in lifespan and winter electricity reduction potential, although these differences are not particularly pronounced. The high weighting of technological maturity as the third most important criterion is striking, indicating a preference

for established solutions. However, there are also differences in weighting: while one group of Selectors rates both lifespan and Levelized Cost of Storage (LCOS) as equivalent, the other group rates lifespan significantly lower. There are also differences in social acceptance and investment costs. However, these differences are not fundamental contradictions, but nuances that individual backgrounds or experiences with STES technologies may shape.

For Enactors, economic considerations are also important, primarily driven by the high relevance attributed to LCOS. However, unlike Selectors, technical criteria and social acceptance receive comparatively higher weighting. In contrast to the Selectors, technical aspects such as winter electricity reduction potential and modularity are given higher weighting. Visibility, on the other hand, plays a subordinate role for this group, suggesting that aesthetic factors are less relevant in this context. Compared to the Selectors, the Enactors show greater variability in their weighting, which implies less agreement on the relevance of individual criteria. There are significant differences, particularly in terms of technological maturity, investment costs, and modularity. While some Enactors attach great importance to established technologies, others are more open to innovation. For some Enactors, investment costs are central, for others, they are of secondary importance. However, there is explicit agreement regarding social acceptance, global warming potential (GWP), and land requirement.

After the discussion, the Mixed Groups show a convergence, particularly in the economic aspects. Investment costs gain in importance, and the Enactors give visibility significantly more weight than before. This shift indicates that aesthetic aspects were given more consideration as a result of the exchange. Compared to Enactors, technical criteria such as winter electricity reduction potential and thermal output are becoming less important, reflecting a growing emphasis on economic and social factors. The average spread is highest among the Enactors (0.029), while the Selectors show the greatest agreement (0.017). The Mixed Group lies in between with 0.020, indicating a partial harmonization of perspectives, especially in economic and societal criteria. Nevertheless, different perspectives on technical aspects remain.

Fig. 6 shows that there are major differences in the evaluation of the criteria between the Selectors and Enactors. In addition, it can be observed that the break in discussion time (T3) and the mixing of the groups strongly influence the weighting of the criteria. While LCOS and GWP remain consistently in first and thirteenth place, the groups weigh other criteria, such as visibility and winter electricity demand, quite differently. Compared to the Homogeneous Groups, the Mixed Group shows an increase in the importance of investment costs and a slight decrease in the importance of technical criteria. Societal criteria remain essential for all groups. Overall, the heterogeneous groups are moving slightly closer to the weighting and decision-making logic of the

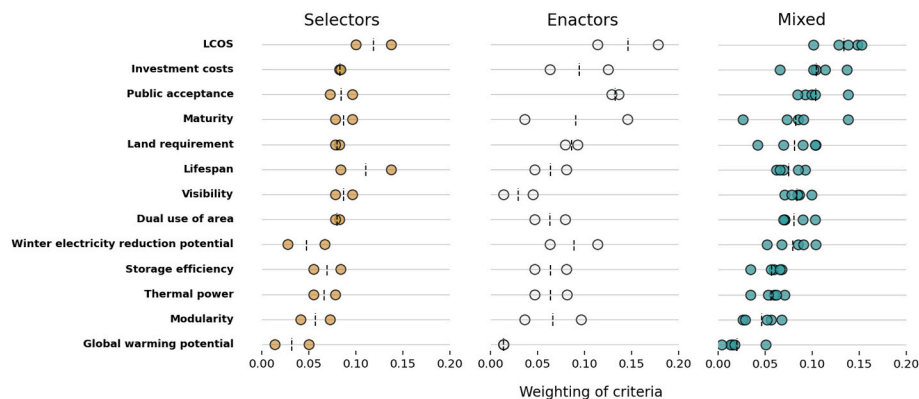


Fig. 5. Weighting of the decision criteria for Selectors, Enactors, and the Mixed Group, shown as group-level outcomes. Each point represents the criteria weights derived by one group using the deck-of-cards method; dashed lines indicate the mean within each role. The x-axis shows relative criteria weights (summing to one within each group), not rankings or performance scores. The figure illustrates the dispersion of priorities within roles and the partial alignment emerging in the mixed-group setting after deliberation.

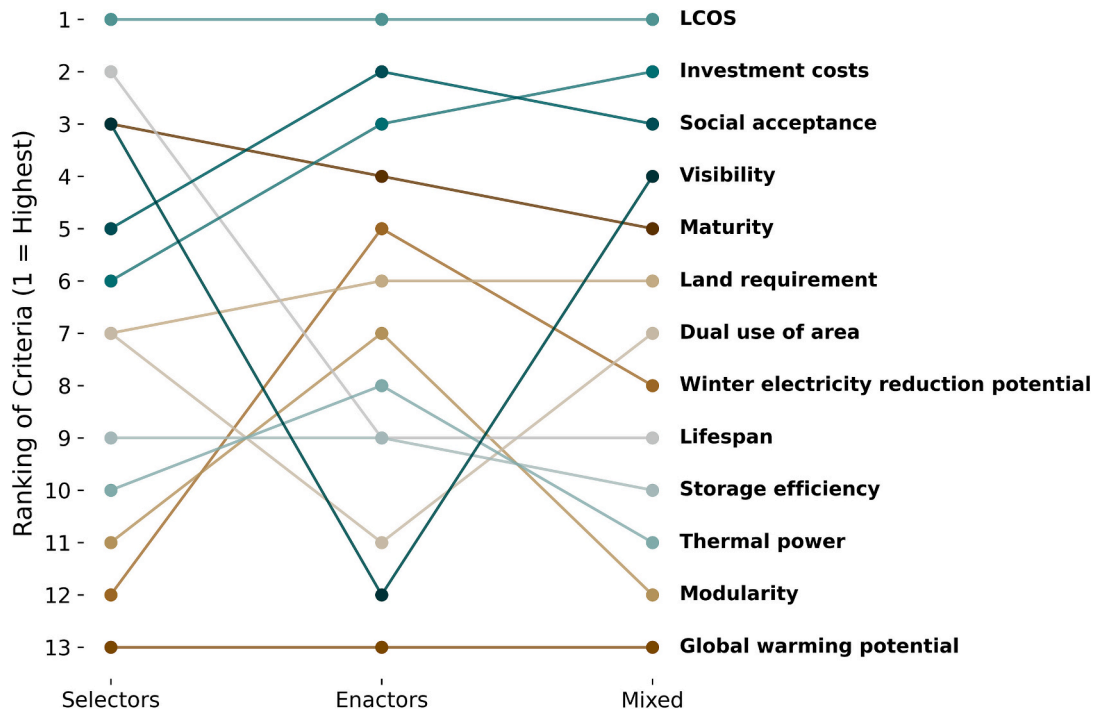


Fig. 6. Ranking of decision criteria by stakeholder group (1 = highest priority), derived from the group-level weightings at T2 (Selectors, Enactors) and T4 (Mixed Groups). Lines indicate changes in relative priority across groups following deliberation. While LCOS remains the top-ranked criterion throughout, investment costs gain importance in the Mixed Groups, whereas several technical criteria decline in relative priority.

Selectors, which suggests a learning and reflection process through the workshops.

3.3. Qualitative results of the workshops

This section presents the qualitative results of the group presentations and the subsequent discussion (T3), as well as the additional criteria that the groups included in the extended deck-of-cards method.

In the group presentations and subsequent discussion, all groups emphasized the importance of non-technical criteria. One group of Enactors described land requirements and social acceptance as “knock-out criteria” that must be met for any project to go ahead. They went on to explain that visibility played a subordinate role for them, as relevance depended heavily on social acceptance. The group argued that once a highly visible project is accepted, visibility per se no longer plays a role. In the following Mixed Group (T4), however, visibility was considered important, along with acceptance, indicating a shift in thinking in this regard.

The relevance of the investment cost criterion was put forward for discussion by one group, with the argument that it is closely related to the LCOS. The group argued that with good LCOS, investment costs become irrelevant in the decision-making process. However, it was noted in the plenary session that the initial investment costs are also important in the realization process of an STES, independently of the LCOS, and are relevant to the financing and the political process. In the Mixed Groups, the investment costs were weighted according to the LCOS, except for one group.

During the discussions, it was noted that reducing GWP is one of the original drivers for low-carbon technologies such as STES. The GWP criterion was only of minor relevance when choosing between the alternatives, as all the options considered contribute to decarbonization in principle. The participants emphasized that GWP would become significantly more critical if fossil technologies were also included in the comparison. The low weighting is therefore due to the scope of technical alternatives.

The level of technological maturity was another point of discussion

in the plenary session. One group of Enactors emphasized that the level of maturity must be assessed within the local context, as knowledge and development levels in other countries cannot always be directly transferred to the local market. Others argued that, for the discussed STES concepts used as reference points during the workshop, maturity was perceived as sufficiently high and therefore not decisive for differentiation. However, it was agreed that the criterion should be given much more weight for technologies with a low level of maturity, to the point of being a clear disqualifier.

Another point of criticism raised by workshop participants concerned the scope of the selected storage concepts and their use cases. The discussion focused on individual storage concepts rather than their combinations. In practice, however, viable systems may consist of hybrid configurations that combine different storage concepts. The exclusion of such combinations was therefore perceived as a limitation, as hybrid configurations are even more context-dependent and would have substantially increased the complexity of the deliberative process.

The participants also discussed the overlap between individual criteria. Specifically, visibility and social acceptance, as well as investment costs and LCOS, were discussed. Some participants perceived these pairs of criteria as closely related, which could potentially lead to double counting. However, after discussions in the group and the plenary, all groups decided to retain the criteria. They explained that the criteria represent different dimensions within the overarching evaluation context, with investment costs primarily reflecting upfront feasibility and decision thresholds, while LCOS captures life cycle efficiency and long-term cost performance.

The groups had the opportunity to contribute their new criteria using the extended deck-of-cards method. In doing so, each Homogeneous Group added one criterion related to the technical risk, feasibility, or approvability to the predefined criteria deck, in a specific form. The different criteria are: approvability, entrepreneurial risk, technical implementation risk, and regulatory and legal approvability. In this context, the criterion was given a medium to a critical level. Participants emphasized that risk and feasibility become particularly critical under conditions of higher technical uncertainty and regulatory complexity, in

some cases functioning as exclusion criteria.

Another criterion added by a mixed group was the full costs, including heat supply. They argued that the costs of the overall system must be right in the first instance and that not only the costs of the storage tank should be considered in isolation. The group weighted this criterion higher than the LCOS.

Overall, the Mixed Groups in T4 added fewer new criteria than the Homogeneous Groups in T3. This suggests that the participants achieve a greater degree of agreement with the given criteria through the exchange and discussion in the plenary session.

4. Discussion

4.1. Interpretation and contextualization of results

This study is unique in the scientific literature as it provides the first systematic weighting of decision criteria for STES, as well as combining MCDA and CTA to capture stakeholder perspectives. Conflicts and commonalities between stakeholder roles are identified at an early technology stage. The study further traces changes in stakeholders' perspectives during the conducted participatory workshops. The results reveal pronounced role-specific differences in criteria weighting and indicate that the structured workshop dialogue supports reflection and, in some cases, partial alignment of perspectives.

In addition it is shown, that economic criteria, particularly LCOS, receive the highest weights across Enactors, Selectors, and Mixed Groups, indicating their central importance in the selection of STES technologies. As an indicator, LCOS enables a cross-technology assessment of life cycle costs and provides a tangible basis for comparison. Given the high upfront investments and long payback periods typical for STES projects, economic efficiency represents a key prerequisite for implementation, which is consistent with findings from the broader literature on renewable energy technologies [101–103]. While direct one-to-one comparisons with existing studies are limited, parallels can be drawn with MCDA studies in related technological fields, such as battery storage and other renewable energy technologies. For example, [104] also find that economic criteria, particularly life cycle costs, receive the highest weighting by Selectors, while social criteria are considered less relevant and environmental criteria more important than in the present study.

The different weighting of social criteria compared to reference [69] can be explained by technology-specific characteristics. In contrast to battery storage, STES technologies typically require more space and have a stronger visual impact, which makes local acceptance a critical factor for implementation. A similar pattern is reported for wind energy projects, where social criteria receive high priority due to visibility and land-use impacts, as illustrated by the Nimby phenomenon [105]. These findings suggest that energy infrastructure projects with large spatial footprints tend to elevate the relevance of social criteria in decision-making. For STES planning and implementation, this implies that technical feasibility alone is insufficient and that potential conflicts related to acceptance, visibility, and land use need to be addressed at an early stage.

The different weighting of environmental criteria compared to previous studies may be because the environmental impact of e.g. battery storage and wind farms is a more controversial topic within public and scientific circles: Battery storage technology is criticized for the potential risk of critical resource material mining, while wind farms are often discussed for their impact on animals such as birds and cows. Environmental conflicts related to STES technologies appear to be less well known, which could be due to the low level of awareness of STES. This could also explain why GWP is given the lowest importance by all groups, since there are no priming effects. Priming effects, known from [106], can influence the evaluation of stakeholders. These can arise when decision criteria are particularly emphasized in the discussion, which may cause these criteria to be unconsciously weighted more

heavily. Another possible explanation is that embodied GWP often carries little weight in the decision-making process for infrastructure projects, as shown in [107], who found that professionals rarely consider embodied GWP during early planning phases.

The fact that technical criteria tend to be given medium importance in both reference studies highlights that functional features, while relevant, often take a back seat to economic and social considerations. This suggests that while technical performance is a prerequisite for the development and diffusion of STES, it is not the sole focus. This is consistent with our findings, where technical criteria received only moderate average weights across both stakeholder roles.

Furthermore, the study in [104] indicates a low level of consensus among stakeholders. The authors point out that an MCDA based solely on an online survey carries the risk of unreflected weightings, as there is no guidance or discussion. Additionally, it remains unclear whether all survey participants understood the given criteria and whether they were perceived in the same manner by all. In this sense, this paper follows the suggestion of reference [104]: “A comparison of a survey and workshop format to gather weights for the same MCDA project would be highly interesting for future research.” The results of this study highlight the added value of participatory formats for consensus building and integrating diverse perspectives, particularly through a structured and reflective discussion process.

Beyond differences in the weighting of individual criteria, the deliberative process itself constitutes a central result of this study. The combination of participatory exchange and repeated formal weighting allows changes in expressed preferences to be systematically traced over the course of the workshops. These changes follow the sequential structure of the workshop phases, from initial individual weighting (T1), through role-specific and intergroup deliberation (T2–T4), to final individual reflection (T5), and suggest that priorities evolve under conditions of structured exchange and joint reflection.

In this sense, the results can be interpreted as reflective learning and reflexive processes discussed in the CTA literature on participatory decision-making. Here, learning is primarily understood as a process of perspective articulation (reflexive) and reconsideration triggered by structured exchange (reflective), rather than as a change in expertise. These patterns are consistent with several mechanisms embedded in the workshop design. Repeated individual and collective weighting supports the gradual articulation and calibration of preferences across phases. The confrontation of different stakeholder roles, particularly during plenary discussion (T3), makes divergent assessment logics visible and may prompt participants to reconsider implicit assumptions. In the mixed-group setting, the deck-of-cards method (T4) facilitates the negotiation of relative priorities by explicitly relating criteria to one another. Across the sequence of individual reflection and intra- and intergroup exchange, a gradual bridging of role-based perspectives becomes visible. This bridging should be understood as partial and issue-specific within the defined criteria set, rather than as a convergence of overall positions.

The weightings determined in this study are to be understood as relational prioritizations within a defined set of criteria. Their comparability refers to differences between stakeholder roles and to changes in weighting profiles over the course of the deliberative process, but not to comparisons between technologies, projects, or contexts. The weights therefore reflect relative importance rather than cardinal utility or aggregation parameters. Accordingly, the analysis makes visible how preferences develop and change through exchange and reflection. In doing so, it makes the differing assessment logics of Enactors and Selectors explicit and open to mutual reflection.

4.2. Methodological reflection

The methodological approach adopted in this study builds on MCDA as a criteria-centred and deliberative framework, which comes with specific strengths and limitations relevant for the interpretation of the

results (see Table 2). Within the MCDA literature, different methodological families assign distinct roles to weighting, aggregation, and normalization, ranging from utility-based ranking models to outranking and rule-based approaches (see, e.g., [102,103]). Building on this perspective, recent work has emphasized that MCDA can be applied as a criteria-centred structuring and learning framework in early-stage sustainability and energy contexts, without requiring aggregation or rankings [65]. This perspective complements earlier contributions that position MCDA beyond purely optimization-oriented decision models [86]. In this view, weights express relative priorities rather than trade-offs in a value function, a distinction emphasized in [109], while weighting under deliberative conditions is shaped by cognitive and social factors that highlight the role of reflection and exchange alongside formal elicitation procedures [110].

Within this methodological framing, one of the key strengths is the combination of structured decision analysis, through MCDA, with the participatory and reflective approach, inspired by CTA as a framework for stakeholder integration. This not only enables the structuring of the decision-making process, but also the early visualization of different perspectives and potentially conflicting goals. In line with CTA, the methodology promotes reflection and learning processes as a basis for aligning and further developing the perspectives of Selectors and Enactors. It also allows for the visualization of different weightings of Selectors, Enactors, and Mixed Groups.

At the same time, this approach has some challenges. Due to the low level of public awareness of STES and its low prevalence, the composition of the workshop participants was limited to professionals in the field. The population was represented by political representatives. This may lead to potential distortions by expert or institutional perspectives. The low prevalence also affects the practical experience of the experts with STES. In this context, it is also worth noting that all participants were from Switzerland, which introduces a national bias to the results.

The workshop sample of 25 participants provides targeted insights into role-specific perspectives but does not aim at statistical representativeness. As in other deliberative settings, group dynamics may allow dominant individual opinions to influence deliberations; however, the group-based elicitation of criteria weights mitigates the impact of such individual-level asymmetries on the resulting weight profiles. In addition, potential priming effects cannot be fully excluded, as the predefined criteria set and the structured workshop format may influence how participants frame and articulate their preferences; the sequential design helps to reduce, but not eliminate, such effects.

From a formal MCDA perspective, partial overlaps between individual criteria cannot be fully excluded [111]. However, this study deliberately refrains from aggregating criteria or deriving composite

Table 2
Methodological strengths and challenges of the combined MCDA and CTA approach in the decision-making processes of STES technologies.

Strengths of the methodology	Challenges of the methodology
<ul style="list-style-type: none"> - Combination of structured MCDA and participatory-reflective approach from CTA - Stakeholder involvement at several levels (interview, workshop and individual surveys) - Differentiable weighting of Selectors and Enactors - Recording of learning and reflection processes - Participatory weighting procedure (deck-of-cards) - Deck-of-cards facilitates negotiation through visibility - High level of interaction and engagement observed 	<ul style="list-style-type: none"> - Limited representativeness of the stakeholders - The number of participants is limited due to the small number of STES experts. - Selective participation: Potential bias due to expert or institutional perspectives. - Small sample (n = 25) - Group dynamics: dominant opinions in groups could influence the weighting - Possible priming effects - Restriction to the Swiss context

scores or rankings. Instead, criteria are understood as representations of distinct decision logics that are relevant at different stages of early-phase STES planning. As discussed by participants during the workshops (Section 3.3), potential overlaps are therefore treated as an explicit element of the deliberative process rather than as unintended double counting.

Criteria weighting is not method-neutral; the applied elicitation methods are consistent with criteria-centred, deliberative MCDA approaches, such as outranking-oriented logics (e.g. ELECTRE or PROMETHEE), in which weights express relative priorities rather than parameters of additive utility functions [66,112]. Such approaches may be considered in follow-up studies. In the context of this study, criteria weights depend on the range of consequences implicitly considered by participants. This range is deliberately bounded by treating STES as a technology class, with common STES types serving as contextual anchors to support a shared understanding, without evaluating or comparing specific technologies.

During the workshops, a high level of interaction and discussion was observed across all phases, particularly during the collective weighting exercises. From the perspective of the moderators, participants actively engaged during the group weighting tasks and the structured exchange, and the workshop format supported sustained discussion across different stakeholder roles. Following the workshops, informal feedback was predominantly positive and indicated that the process was perceived as constructive. Participants' perceptions were not systematically assessed; the observations reported here are based on facilitators' perspectives and informal feedback.

Based on the methodological reflections above, several implications for the design of participatory stakeholder workshops can be derived. A clear differentiation of stakeholder roles and a sequential combination of individual and collective deliberation support the articulation and reconsideration of preferences over time. Focusing on criteria rather than early technology ranking proved useful under conditions of uncertainty, while combining individual and collective weighting helped balance individual perspectives with the negotiation of trade-offs. These implications are context-dependent but may inform the design of similar early-stage, deliberative settings.

4.3. Outlook and future research needs

The integration of the individual survey into the workshops provided valuable insights, especially about changing perspectives. Future studies could deepen this approach by further investigating the extent to which actual reflection processes or social learning take place in such formats, for example, through short interviews or additional surveys during the workshop, but also over a more extended period.

It would also be interesting to apply the methodology in other contexts or countries. This would allow for better consideration of different cultural, political, or technological conditions and a comparison of the significance of the results. A broader application would also help better assess the transferability and robustness of the findings.

Building on the results presented here, future studies can use the weights determined as a basis for evaluating specific STES technologies, integrating data into a performance matrix, and performing sensitivity analyses or rankings. This work thus lays the foundation for further empirical and model-based investigations.

5. Conclusion

This study presents a novel combination of CTA and MCDA to support participatory structuring of decision criteria and stakeholder preferences in the context of STES. This structured, participatory framework facilitates reflection on conflicting goals, negotiation between perspectives, and decision structuring. Particular attention was given to visualizing and comparing the perspectives and weightings of stakeholders who select and implement STES technologies in a participatory

workshop. The results indicate that the assessment of STES technologies varies depending on Selectors and Enactors and proves the systematization of stakeholders within CTA. Economic criteria, particularly LCOS, are considered central in all roles. However, social aspects such as social acceptance, space requirements, and visibility are weighted higher by the Selectors.

In contrast, Enactors focus more on technical characteristics, such as modularity and thermal performance, alongside economic criteria. These differences reflect the distinct perspectives, responsibilities, and experiences associated with the respective roles. This confirms that the weighting of decision criteria is context-dependent and systematically influenced by stakeholder roles. To our knowledge, this role-specific structuring of criteria preferences has not previously been demonstrated for STES technologies.

At the same time, the study demonstrates that these perspectives can be partially reconciled through dialogue, reflection, and joint learning within the framework of a structured exchange, such as the stakeholder workshops. Rather than serving solely as an analytical tool, the workshops functioned as a deliberative intervention in the sense of CTA, enabling participants to articulate and reconsider their priorities and to learn from each other. This effect is made visible through the before-and-after design, which revealed shifts in weighting and perception triggered by the workshop process.

A key contribution of the study is to demonstrate that structured exchange can bring different stakeholder perspectives closer together in early-stage STES decision-making. The stakeholder workshops, as a bridging event in the sense of CTA, promoted dialogue between actors and supported joint learning across differing points of view. This has clear practical implications for STES planning, as role-specific assessment logics and potential conflicts can be made explicit and addressed early in the decision process. In this context, the deck-of-cards method proved effective by making priorities visible and facilitating discussion. While specific weighting outcomes are always context-dependent, the underlying process design can be applied in other institutional and technological settings. In particular, the approach is suited to early-stage planning contexts with institutional uncertainty and heterogeneous stakeholder roles, such as technology development processes, project implementation phases, or strategic planning for future energy infrastructure.

The study makes stakeholder-specific weightings transparent and illustrates how participatory processes can support more inclusive and reflective approaches to technological decision-making in the context of STES. By involving both technical and non-technical stakeholders under the heuristic of CTA, it highlights the importance of evaluations that account for context and perspective, instead of assuming universal ranking systems for technologies. Rather than identifying optimal

solutions, the contribution of this study lies in demonstrating how an MCDA-supported CTA approach can support preference articulation and learning under specific institutional conditions.

CRedit authorship contribution statement

Richard Lüchinger: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martina Haase:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Manuel Baumann:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Heimo Walter:** Writing – review & editing, Validation, Supervision, Conceptualization. **Jörg Worlitschek:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Richard Lüchinger reports financial support was provided by Swiss National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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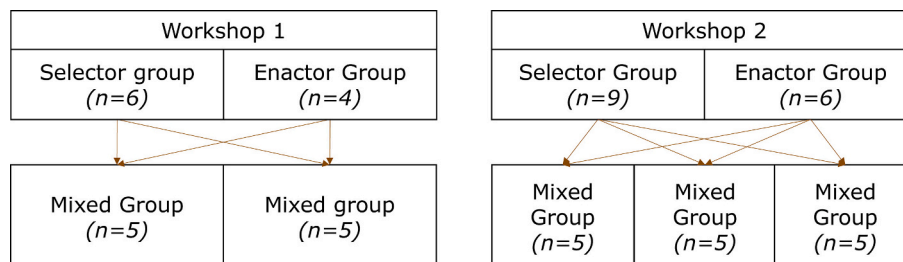
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Appendix

A.1. Assignment of participants to the two workshops according to stakeholder role and subsequent redistribution into mixed groups

Numbers indicate participants per workshop and per group (total $n = 25$; Selectors $n = 15$; Enactors $n = 10$). Mixed groups are formed by redistributing the same participants; no additional participants are involved.



A.2. STES stakeholders, grouped into the stakeholder roles Selectors and Enactors

This appendix documents stakeholder groups identified as relevant in the CTA-based stakeholder mapping, including actors who were not invited to or did not participate in the workshops, in order to make the scope and boundaries of participation transparent.

Stakeholder group	Role	Represented at workshops	Description
Administration (federal, cantonal, municipal)	Selectors	Yes	Government bodies at various levels responsible for creating and enforcing regulations related to energy storage and usage
Architect	Selectors	No	Professionals involved in designing buildings
Association	Selectors	No	Organizations that represent the interests of different stakeholders
Energy consultant	Selectors	Yes	Experts who evaluate energy needs, model energy systems, and provide recommendations for implementing energy solutions.
Energy system engineering and planning office	Selectors	Yes	Firms that provide broad engineering and planning services for various types of energy systems or technology e.g. thermal grids, PV, etc.
Energy system installer	Selectors	No	Companies that install other energy systems or technology
Energy system producer/ manufacture	Selectors	No	Companies that produce of other types of energy systems
Energy system researcher	Selectors	Yes	Researchers who study other types energy systems or technology
Funders	Selectors	No	Entities that provide financial support for the development and implementation of energy system, such as STES, projects, e.g. banks and grant providers.
General contractor	Selectors	No	Companies responsible for the overall coordination and execution of construction projects, such as the installation of STES
Landowner	Selectors	No	Individuals or entities that own land and or buildings. The group are potential end users of STES technologies.
NGO	Selectors	No	Non-governmental organizations focused on environmental conservation and landscape protection
Politician	Selectors	Yes	Elected officials who influence and create policies and regulations that impact the development and deployment of energy systems.
Property owner company/ cooperative	Selectors	Yes	Organizations that own and manage multiple housing units, office buildings, and other properties. The group are potential end users of STES technologies.
Property owner private	Selectors	No	Individual property owners. The group are potential end users of STES technologies.
STES engineering and planning office	Enactors	Yes	Specialized firms focused on the design, engineering, and planning of STES
STES installer	Enactors	Yes	Companies involved in installation of STES
STES producer/ manufacturer	Enactors	Yes	Companies involved in manufacture/production of STES
STES researcher	Enactors	Yes	Researchers focused on the study and development of STES technologies and applications.
Tenants	Selectors	No	Individuals or organizations that lease property
Utilities/ network operator/ energy provider	Selectors	Yes	Companies that generate, transmit, and distribute energy. The group are potential end users of STES technologies.

A.3. Results of the Individual Surveys (T1 and T5)

Group	Aspect	Time	mean	median	q25	q75	
Enactor	Ecological	T1	19	20	11.25	20	
		T5	3.75	0	0	10	
	Economical	T1	23.5	22.5	12.5	30	
		T5	48.125	45	38.75	52.5	
	Legal	T1	10	10	6.25	10	
		T5	13.75	15	10	20	
	Political	T1	10	10	10	10	
		T5	6.875	10	3.75	10	
	Social	T1	13.8	10	10	10	
		T5	10	7.5	3.75	12.5	
	Technological	T1	23.7	20	20	30	
		T5	17.5	20	13.75	20	
	Selector	Ecological	T1	13.2	15	10	20
			T5	8.235	10	5	10
Economical		T1	34.667	25	25	40	
		T5	39.118	40	25	50	
Legal		T1	12.467	10	7.5	17.5	
		T5	11.176	10	5	15	
Political		T1	14	10	10	17.5	
		T5	13.53	10	10	20	
Social		T1	9.667	10	2.5	15	
		T5	9.706	10	5	15	
Technological	T1	16	15	10	20		
	T5	18.235	20	20	20		

A.4. Decision criteria considered

Criteria	Criteria group	Units	Definition
Land requirement	Spatial	m ²	The area required for the installation and operation of the storage system. This includes both the area used directly and any safety distances.
Dual use of area	Spatial	qualitative scale	The area of the storage system that can be used for other purposes at the same time, such as parking or other construction uses.
Storage efficiency	Technological	%	Storage efficiency, in terms of round-trip efficiency, describes the proportion of energy that is available for reuse after a storage system has completed a full charge and discharge cycle. It encompasses all energy losses that occur during the storage process and energy withdrawal, including losses in the storage itself, and indicates how efficiently the system recovers the stored energy. A high storage efficiency indicates minimal energy loss over the entire cycle.
Lifespan	Technological	a	The life expectancy/lifespan indicates the estimated number of years that a thermal store will function reliably under normal operating conditions before it needs to be replaced or extensively refurbished.
Thermal power	Technological	MW	The maximum amount of energy that the storage system can deliver per unit of time. This value describes the system's ability to provide energy quickly and in large quantities.
Modularity	Technological	qualitative scale	The ability of the storage system to be built from flexible and modifiable units or modules, so that it can be adapted to specific requirements and easily expanded as needed. Modularity enables a step-by-step system expansion by adding additional modules, without having to restructure the entire system.
Winter electricity reduction potential	Technological	qualitative scale	The winter electricity reduction potential describes the ability of a storage technology to reduce the demand for additional electricity for heat supply in winter and thus increase the thermal self-sufficiency of the system. Storage technologies with low operating temperatures, which are often operated in combination with heat pumps, require additional electricity to reach the heating temperature. In contrast, technologies with higher storage temperatures enable direct heat supply without significant electricity demand, which reduces dependence on the power grid and increases the thermal self-sufficiency of the overall system.
Investment cost	Economic	Cost unit	The total initial costs for the acquisition and installation of the storage system, including material, construction and setup costs.
Levelized Cost of Storage (LCOS)	Economic	Cost unit /MWh	The LCOS are the standardized full costs per megawatt hour for the provision of usable heat energy from a thermal store over its lifetime. All relevant costs are considered, including investment, operating and energy costs for heating the energy from the store to the useful temperature, e.g. using a heat pump. The costs of heat generation for loading the storage tank are not included. The full costs for thermal storage enable a realistic assessment of the economic viability and efficiency of various storage technologies.
Global Warming Potential (GWP)	Ecological	kg CO ₂ eq	The GWP describes the climate impact of the emitted gases over a certain period, expressed in kilograms of CO ₂ equivalent. The specific climate impact of various greenhouse gases, such as methane, is weighted relative to CO ₂ to quantify their contribution to global warming. This value is delimited according to the cradle-to-gate approach, which only considers the emissions from the extraction of raw materials to the completion of the product and excludes emissions from operation and disposal.
Social acceptance	Social	–	The willingness of the local population to accept and support the storage system. This criterion considers public opinion, trust in the technology and willingness to accept it based on perceived benefits and possible negative impacts.
Visibility	Spatial / Social	qualitative scale	The influence of the storage system on the landscape and the aesthetics of the surroundings. Evaluated on a qualitative scale, this criterion describes the extent to which the system can be integrated into the local environment without significantly affecting the visual perception of the landscape.
Maturity	Technological	TRL	The degree of maturity, often referred to as the Technological Readiness Level (TRL), indicates the state of development of a technology on a scale of 1 to 9. TRL 1 represents the initial idea, TRL 8 describes a technology that is almost market-ready and has been successfully tested under real-world conditions, and TRL 9 represents a fully proven technology in commercial use that meets market needs.

A.5. Results of the deck-of-cards group weighing results of the homogeneous groups at T2

Group	Criterion	Median	Mean	Std_Dev	Weighting 1	Weighting 2
Enactors	Dual use of area	0.063	0.063	0.023	0.047	0.079
Enactors	Global warming potential	0.014	0.014	0	0.014	0.014
Enactors	Investment costs	0.094	0.094	0.044	0.125	0.063
Enactors	LCOS	0.146	0.146	0.045	0.114	0.178
Enactors	Land requirement	0.086	0.086	0.009	0.092	0.079
Enactors	Lifespan	0.063	0.063	0.024	0.08	0.047
Enactors	Maturity	0.091	0.091	0.077	0.036	0.145
Enactors	Modularity	0.066	0.066	0.042	0.036	0.096
Enactors	Public acceptance	0.132	0.132	0.005	0.136	0.129
Enactors	Storage efficiency	0.063	0.063	0.024	0.08	0.047
Enactors	Thermal power	0.064	0.064	0.024	0.081	0.047
Enactors	Visibility	0.029	0.029	0.022	0.045	0.014
Enactors	Winter electricity reduction potential	0.088	0.088	0.036	0.114	0.063
Selectors	Dual use of area	0.08	0.08	0.003	0.082	0.078
Selectors	Global warming potential	0.032	0.032	0.026	0.014	0.05
Selectors	Investment costs	0.083	0.083	0.001	0.082	0.083
Selectors	LCOS	0.118	0.118	0.026	0.137	0.1
Selectors	Land requirement	0.08	0.08	0.003	0.082	0.078
Selectors	Lifespan	0.11	0.11	0.038	0.137	0.083
Selectors	Maturity	0.087	0.087	0.013	0.096	0.078
Selectors	Modularity	0.057	0.057	0.022	0.041	0.072
Selectors	Public acceptance	0.084	0.084	0.017	0.096	0.072
Selectors	Storage efficiency	0.069	0.069	0.02	0.055	0.083

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Group	Criterion	Median	Mean	Std_Dev	Weighting 1	Weighting 2
Selectors	Thermal power	0.066	0.066	0.016	0.055	0.078
Selectors	Visibility	0.087	0.087	0.013	0.096	0.078
Selectors	Winter electricity reduction potential	0.047	0.047	0.028	0.027	0.067

A.6. Results of the deck-of-cards group weighing results of the mixed groups at T4

Group	Criterion	Median	Mean	Std_Dev	Weighting 1	Weighting 2	Weighting 3	Weighting 4	Weighting 5
Mixed	Dual use of area	0.07	0.08	0.015	0.07	0.07	0.069	0.09	0.103
Mixed	Global warming potential	0.015	0.02	0.018	0.015	0.013	0.017	0.051	0.004
Mixed	Investment costs	0.103	0.104	0.026	0.137	0.113	0.103	0.101	0.065
Mixed	LCOS	0.138	0.133	0.02	0.148	0.128	0.138	0.101	0.152
Mixed	Land requirement	0.09	0.081	0.026	0.103	0.042	0.069	0.09	0.103
Mixed	Lifespan	0.069	0.075	0.013	0.092	0.085	0.069	0.062	0.065
Mixed	Maturity	0.085	0.082	0.04	0.026	0.085	0.138	0.073	0.09
Mixed	Modularity	0.052	0.046	0.018	0.026	0.056	0.052	0.067	0.028
Mixed	Public acceptance	0.099	0.103	0.021	0.092	0.099	0.138	0.084	0.103
Mixed	Storage efficiency	0.059	0.056	0.013	0.059	0.056	0.034	0.067	0.065
Mixed	Thermal power	0.059	0.056	0.013	0.059	0.07	0.034	0.062	0.053
Mixed	Visibility	0.084	0.084	0.011	0.07	0.099	0.086	0.084	0.078
Mixed	Winter electricity reduction potential	0.085	0.079	0.02	0.103	0.085	0.052	0.067	0.09

Data availability

Data will be made available on request.

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