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ORIGINAL PAPER

Policies for aquifer thermal energy storage: international comparison, barriers and recommendations

Ruben Stemmle[1] · Richard Hanna[2] · Kathrin Menberg[1] · Poul Alberg Østergaard[3] · Matthew Jackson[4] · Iain Staffell[2] · Philipp Blum[1]

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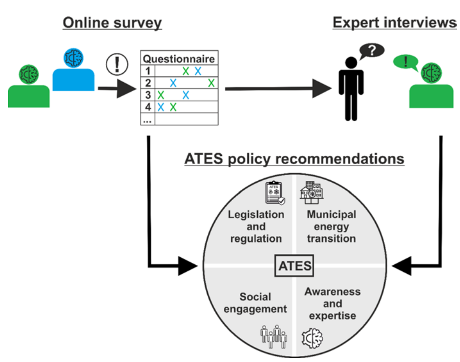
Abstract
Aquifer thermal energy storage (ATES) represents a promising solution for heating and cooling, offering lower greenhouse gas emissions and primary energy consumption than conventional technologies. Despite these benefits and the widespread availability of suitable aquifers, ATES has yet to see widespread utilisation, with uptake highly concentrated in select countries (Netherlands, Belgium, Sweden and Denmark). Beyond technical and hydrogeological feasibility, appropriate national policies are paramount in driving ATES deployment. This study provides an international comparison of ATES policies, highlighting best practices and revealing where measures are missing. It sources insights from a survey of experts across academia, industry and governmental bodies in 30 countries, complemented by semi-structured expert interviews. The study reveals significant differences in the existence and strength of supportive policy environments between countries with different ATES market maturity. A mere 33% of all survey respondents stated that there are policies designed to support ATES utilisation in their respective countries, while the existence of laws and regulations governing ATES was confirmed by 56% of the respondents. The interviews provide details on creating supportive environments (e.g. through facilitators like pre-existing groundwater technology use and building energy efficiency standards) and further barriers to ATES deployment. Ten recommendations for ATES policies are derived to address the following areas: legislative and regulatory issues, raising public awareness, ATES' role in local energy transitions, and social engagement. This work aims to steer global policy towards better harnessing the potential of ATES to decarbonise buildings.

Graphical abstract



Keywords Aquifer thermal energy storage (ATES) · Energy policy · Sustainable heating and cooling · Geothermal energy · International deployment · Energy transition

Abbreviations

ASHP	Air source heat pump
HVAC	Heating, ventilation and air conditioning
ATES	Aquifer thermal energy storage
SGE	Shallow geothermal energy
DHC	District heating and cooling
SUHI	Subsurface urban heat island

Extended author information available on the last page of the article

GSHP Ground source heat pump
UTES Underground thermal energy storage

Introduction

Aquifer thermal energy storage (ATES) is an open-loop and most often shallow geothermal system that uses groundwater for seasonal storage of thermal energy. ATES systems exploit the wide availability and high heat capacity of groundwater to supply heating and/or cooling previously stored in the subsurface to mitigate temporal mismatches between energy demand and availability (Bloemendal et al. 2015; Fleuchaus et al. 2020). ATES systems supplying both heat and cold are commonly used in large building complexes, such as offices, airports, universities or hospitals (Birhanu et al. 2015; Fleuchaus et al. 2018; Lu et al. 2019). This kind of ATES typically stores waste heat and cold from the cooling and heating process itself and therefore benefits from balanced heating and cooling demands of the connected buildings, which ensures sustainable system operation.

Another type of ATES operation is to store excess heat from external sources, such as industrial waste heat and surplus solar thermal energy. These systems can also be used in a decentralised way as described above or in centralised applications in district heating and/or cooling (DHC) networks. This allows them to compensate for fluctuating energy supply and to increase the share of renewable energy sources in the network which can further contribute to the energy transition at the municipal level (Fleuchaus et al. 2018; Schmidt et al. 2018; Todorov et al. 2020).

Compared to conventional heating and cooling technologies, such as gas boilers and compression chillers, ATES can reduce greenhouse gas emissions by up to 74% (Stemmle et al. 2021). Similar reductions were shown regarding primary energy consumption (Fleuchaus et al. 2018; Vanhoudt et al. 2011). These environmental benefits are accompanied by lower operational costs compared to conventional technologies, leading to typical payback times of ATES systems ranging from 2 to 10 years (Fleuchaus et al. 2018; Ghaebi et al. 2017; Schüppler et al. 2019). Nevertheless, ATES uptake remains limited. The more than 3000 systems installed globally are highly concentrated in the Netherlands with 85% and a further 10% in Sweden, Denmark and Belgium (Fleuchaus et al. 2018), despite suitable aquifers being widespread across the globe (Bloemendal et al. 2015; Lu et al. 2019; Ramos-Escudero and Bloemendal 2022; Stemmle et al. 2022).

Like other technologies such as wind and solar power (Best and Burke 2018; Saidur et al. 2010; Timilsina et al. 2012), international adoption of ATES requires appropriate energy policies. This is evident from the high number of Dutch ATES systems, supported by a sophisticated ATES legislative and regulatory framework. Building on successful government-subsidised pilot projects in the late 1980s, Dutch ATES numbers grew rapidly post-2000. These first systems required permits governed mainly by the Dutch Water Act (Drijver and Godschalk 2018). By the early 2010s growing adoptions in the Netherlands required a revised legislative and regulatory framework for ATES, leading to a more specific ATES policy. The resulting Geo Energy Systems Amendment (Dutch: *Wijzigingsbesluit bodemenergiesystemen*) features a simplified eight-week permit process, company certifications to ensure high system quality and standardised system monitoring requirements (Bloemendal et al. 2023; Drijver and Godschalk 2018). More specific operational regulations were also established, including upper and lower storage temperature limits of 25 °C and 5 °C, respectively, and a required energetic balance between injected heat and cold.

Besides ensuring efficient system operation, these regulations aim to protect the subsurface environment (Drijver et al. 2010; Drijver and Godschalk 2018). As systems numbers grew, authorities also addressed increasing scarcity of subsurface space in urban areas and potentially detrimental thermal interferences between systems. They introduced geothermal energy master plans for coordinated spatial subsurface and energy planning of ATES systems in dense urban areas, ensuring optimal and sustainable use of the available subsurface (Beernink et al. 2022; Bloemendal et al. 2014; Drijver and Godschalk 2018; Sommer et al. 2015). An interactive online map by the Dutch Ministry of Economic Affairs and Climate Policy allows municipalities to mark designated areas for geothermal use, aiding ATES planning.

The extensive Dutch ATES legal and regulatory framework stands out internationally, while for countries with a limited ATES deployment available literature, reports or other pieces of information about country-specific ATES policies is often lacking. While not specifically dealing with ATES, some publications discuss the legislative framework for shallow geothermal energy (SGE) utilisation in European countries. These studies highlight a heterogeneous landscape of country-specific legislation and regulations governed by a plethora of national and regional laws, decrees and guidelines. This diversity hinders the uptake of SGE systems, suggesting a need for standardised policy approaches and regulations (García-Gil et al. 2020; Haehnlein et al. 2010; Hähnlein et al. 2013; Somogyi et al. 2017; Tsagarakis et al. 2020). ATES faces similar constraints as other SGE systems, and inadequate policy can also stifle uptake of ATES.

To address the lack of information about ATES-specific policies in many countries, this study presents an international comparison of market barriers, policies, and regulations for ATES. It highlights best practices for policy approaches, explores success factors and challenges in

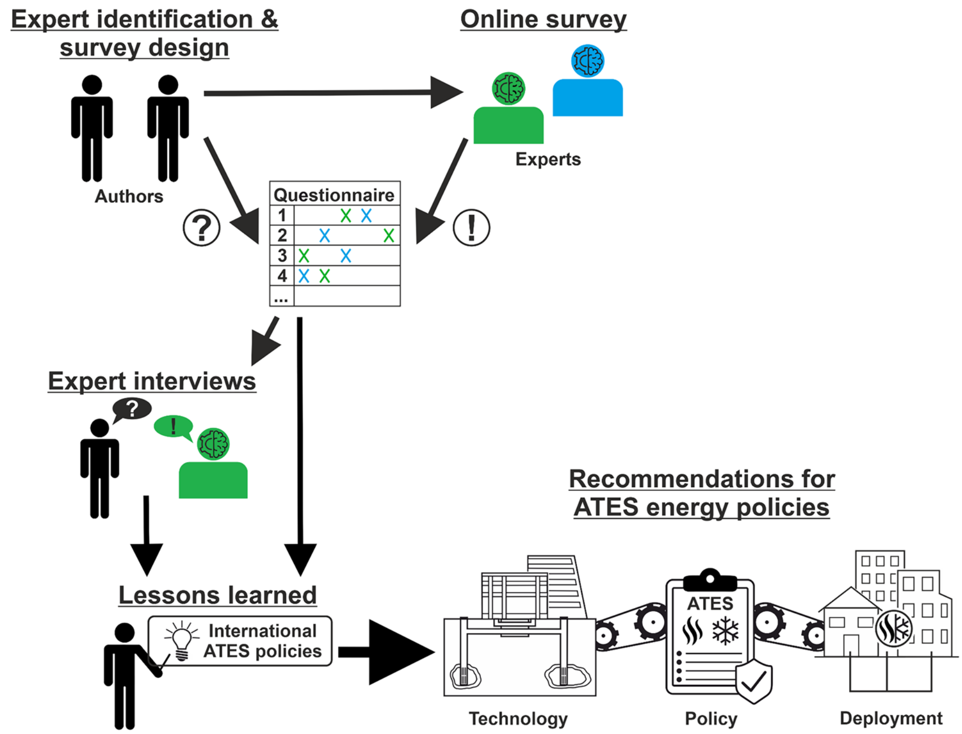


Fig. 1 Overview of this study's workflow

increasing ATES adoption, and identifies areas where appropriate policies are missing. From these insights, recommendations are derived for a comprehensive ATES policy approach to overcome legislative, regulatory and socio-economic barriers to wider international ATES deployment.

Methodology

To gather comprehensive information on the current status of ATES policies and regulations internationally, we conducted an online survey and a series of online interviews (Fig. 1). The survey was sent to experts and practitioners in ATES, geothermal energy and geoscience. Additional contacts were compiled from publicly available membership lists of European heating and cooling industry and trade associations. Given that all recipients were identified for their relevant expertise, it is appropriate to assume that they possessed sufficient knowledge to answer the survey questions, and in cases where they did not, they were instructed to answer 'don't know'. The survey was emailed to 333 contacts from academia, consultancies, installation companies, government authorities, national geological surveys and industrial associations working on geothermal energy and ATES from 47 countries. 82 experts across 30 countries completed the survey, yielding a 25% response rate. We followed recommendations in survey methods literature (Dillman et al. 2015; Frandell et al. 2021) on maximising the sample size by emailing a pre-notification letter,[1] initial survey invitation and three reminders to recipients over one month.

The survey's questionnaire was sent via Qualtrics (version March 2023) and sought information on country-specific policies, legal, technical, economic and societal conditions relevant to ATES, important market enablers and barriers and the existence of laws and regulations governing ATES installation and operation. Following good practice in survey design (Clark et al. 2021; Dillman et al. 2015), we developed closed questions with fixed-choice responses and open-ended questions allowing respondents to write their own answers. The phrasing of questions, fixed responses and Likert scales were formulated carefully to avoid leading answers in a particular direction. At the end of the survey, respondents were asked if they would be willing to participate in a follow-up interview. Subsequently, we conducted a set of 16 semi-structured interviews with a set of these experts to collect further country-specific information. Most interviews were conducted using Microsoft Teams or Zoom. Respondents consented to take part and to be audio and video recorded. Interviews were recorded, transcribed and detailed notes taken. Quotations and attributions used in this paper were sent to interviewees to obtain their permission

[1] Pre-notification emails may however be less effective in raising web survey response rates compared to pre-notification postal letters (Clark et al. 2021; Daikeler et al. 2020).

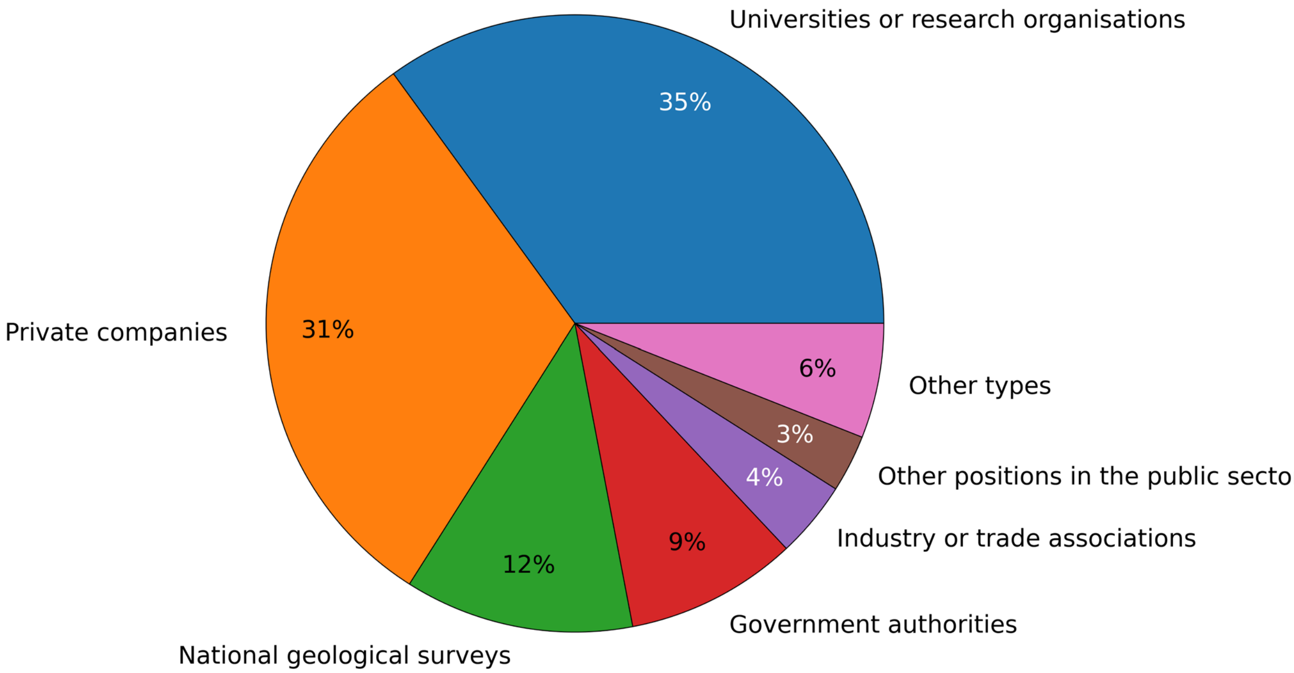


Fig. 2 Pie charts showing the shares of the survey respondents' type of organisation. It should be noted that respondents were able to select more than one type of organisation. Appendix C states the absolute numbers of survey responses on a country per country basis

to include them. The online survey's questionnaire and the interview guide are presented in Appendices A and B.

Insights and lessons learned from the survey and interviews were used as a basis for developing recommendations for a sophisticated ATES policy that aims to foster a wider international ATES deployment.

Results and discussion

Results of the online survey

A total of 82 experts from different countries and types of organisations completed the survey (Fig. 2, Appendix C). For 17 countries, no responses were received. While not complete, the collected set of data is the most extensive to have been produced.

A key finding is that legislative and regulatory frameworks relevant to ATES vary widely among different countries in both their existence and design. This confirms earlier findings from broader studies of shallow geothermal energy (García-Gil et al. 2020; Haehnlein et al. 2010; Hähnlein et al. 2013; Somogyi et al. 2017; Tsagarakis et al. 2020).

Sects. "Importance of market factors" to "Access to technical knowledge and qualified workers for ATES installation" highlight specific survey questions in more detail. For these analyses, we categorise countries by ATES market development levels to identify potential influences on market factors, policy and regulatory frameworks, and other survey aspects (Table 1). The categorisation is based on Fleuchaus et al. (2018) and extended from survey results. With only 7 responses from the Netherlands, the only mature ATES market, Dutch responses were combined with those from growing markets into a *"mature & growing markets"* group with 4 countries. The *"emerging markets"* group includes 14 countries, while the *"countries without ATES"* group includes 12 countries. To facilitate more straightforward comparisons, responses of 'don't know' are omitted from the following evaluations. Sect. "Country comparison" compares results from the Netherlands, Denmark and Germany being mature, growing and emerging markets, respectively. These countries also had the highest response numbers.

Importance of market factors

Survey questions 4 (& 4.a): *At the present time and in your view, how important are the following market factors in influencing the uptake (the potential adoption) of ATES in your country?*

Different market factors can act as barriers or enablers for a wider use of ATES. The influence of these factors on technology progression varies based on the country-specific market development level (Fleuchaus et al. 2018). Respondents' importance ratings of ATES market factors are therefore presented as a function of the ATES market

Table 1 Countries represented in the survey results grouped according to their ATES market development levels. Number of ATES systems based on survey responses and Fleuchaus et al. (2018)

Mature & growing markets	ATES systems	Emerging markets	ATES systems	Countries without ATES
Mature:		Australia	< 10	Albania
Netherlands	> 3000	China	6–10	Austria
		Finland	1	Czech Republic
Growing:		France	Unknown	Estonia
Belgium	100–340	Germany	2–4	Greece
Denmark	50–80	Hungary	Unknown	Italy
Sweden	220–300	Norway	25–40	Lithuania
		Poland	Unknown	Portugal
		Romania	Unknown	Russia
		Slovakia	Unknown	Serbia
		South Korea	< 10	Slovenia
		Switzerland	2–3	Spain
		UK	11–12	
		USA	2	

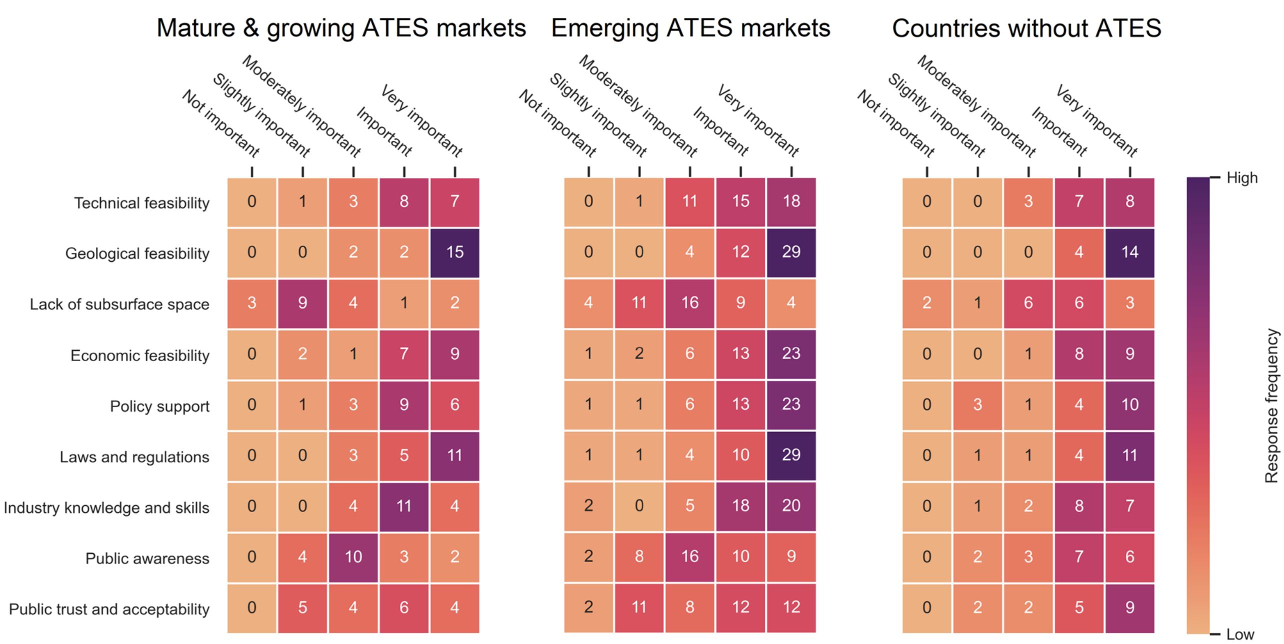


Fig. 3 Relative survey response frequencies of the importance ratings grouped by ATES market factors. The three heat maps show responses for the three groups of countries outlined in Table 1. Inset numbers inside each grid square give the numbers of responses

development level (Fig. 3). *Geological feasibility* and *laws and regulations* were rated as the most critical factors for the uptake or the adoption of ATES across all country groups (Table 2). In contrast, *lack of subsurface space* and *public awareness* received the lowest ratings across all groups, suggesting that the two most and two least important market factors are universal, rather than country-specific.

However, the importance ratings of other market factors differ between country groups. *Countries without ATES* have relatively uniform ratings, with most factors classed *important* or *very important*. In contrast, *mature & growing markets* and *emerging markets* see more differentiated views on ATES market factors (Fig. 3).

Existence of ATES policies

Survey questions 5 (& 5.a): *Are there any policies being applied currently in your country to increase the*

Table 2 Average score of the Importance Rating of ATES market factors for each country group

Mature & growing markets		Emerging markets		Countries without ATES	
ATES market factor	Rating	ATES market factor	Rating	ATES market factor	Rating
Geological feasibility	4.68	Geological feasibility	4.56	Geological feasibility	4.78
Laws and regulations	4.42	Laws and regulations	4.44	Laws and regulations	4.47
Economic feasibility	4.21	Policy support	4.27	Economic feasibility	4.44
Technical feasibility	4.11	Economic feasibility	4.22	Technical feasibility	4.28
Policy support	4.05	Industry knowledge and skills	4.20	Industry knowledge and skills	4.17
Industry knowledge and skills	4.00	Technical feasibility	4.11	Policy support	4.17
Public trust and acceptability	3.47	Public trust and acceptability	3.47	Public trust and acceptability	4.17
Public awareness	3.16	Public awareness	3.36	Public awareness	3.94
Lack of subsurface space	2.47	Lack of subsurface space	2.95	Lack of subsurface space	3.39

Scores are the arithmetic means across all survey responses. Scores correspond to ratings as 1: *not important*; 2: *slightly important*; 3: *moderately important*; 4: *important*; 5: *very important*

installation and use (to encourage the adoption and use) of ATES?

33% of respondents state that policies exist in their country to increase or adopt ATES use (Fig. 4). These responses all came from *mature & growing ATES markets* or *emerging ATES markets*. For *countries without ATES*, all responses indicate no policies to promote its adoption. Fisher's exact test with a 0.05 significance level indicates a statistically significant dependence between ATES market maturity and policy existence. As response numbers vary between countries (Appendix C), countries with many responses, such as Germany, have a greater impact on the significance assessment than countries with single responses.

Existence of ATES laws and regulations

Survey questions 7 & 7.a: *Are there any laws or regulations currently in effect or active in your country to govern the installation and use of ATES systems?*

Overall, 56% of respondents reported active laws and regulations for ATES in their countries (Fig. 4). Survey results suggest that the ATES market development level significantly affects the existence of laws or regulations for ATES. In *mature & growing markets* most answers confirm existing governance of ATES systems. Most respondents from *emerging markets* also stated 'yes'. Conversely, 80% from *countries without ATES* indicated no legal and regulatory basis for ATES.

Ease and speed of ATES application process

Survey question 10: *In your country, how do you rate the ease or difficulty and speed of the application process to gain planning permission for new ATES installations?* (for mature & growing markets and emerging markets only)

Respondents from *mature & growing markets* and *emerging markets* rated their country's ATES planning application process frequently (39%) as 'poor' (Fig. 4). Statistically significant differences between the two groups were not evident. This suggests there is scope even in *mature & growing markets* to reduce barriers for ATES resulting from lengthy and difficult permitting processes.

Quantity of available information on ATES

Survey questions 12 & 12.a: *How do you rate the quantity (amount) of information about ATES available to the public and system or energy planners in your country?*

Limited availability of ATES information can hinder deployment. 63% of responses rated the information quantity as 'poor' or 'very poor' (Fig. 4), with a significant influence of ATES market development level on the ratings. The Netherlands stands out with the highest amount of information available, with 86% of all Dutch responses being 'high' or 'very high'.

Public awareness of ATES

Survey questions 14 & 14.a: *How do you rate the level of public awareness of ATES in your country?*

81% of responses rated public awareness of ATES as 'very low or none' or 'low' (Fig. 4). However, ATES public awareness was also rated the second least important factor for its uptake (Sect. "Importance of market factors"), suggesting that high public awareness may not be a priority

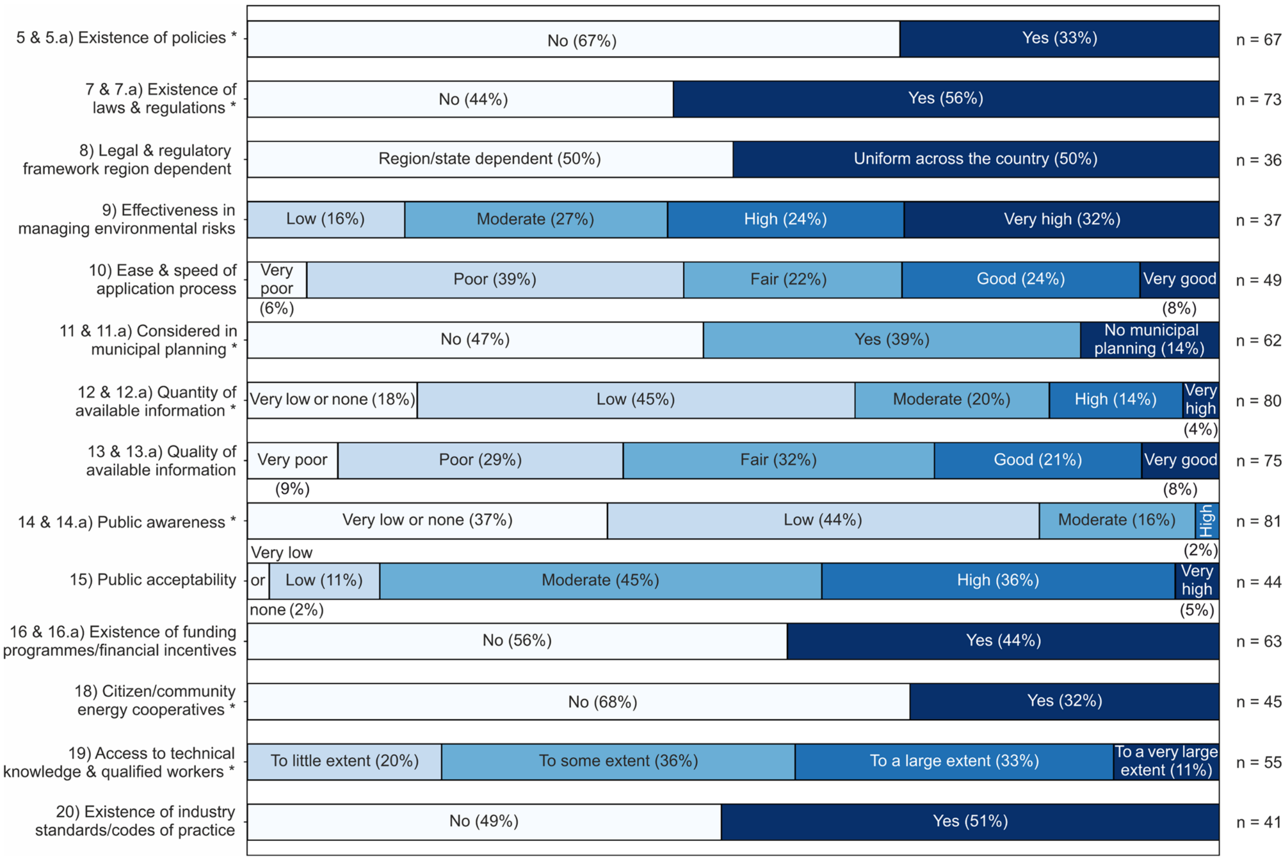


Fig. 4 Survey responses to further questions and their shares of the total number of responses (*n*) per question. Response numbers differ between questions due to the survey design and the disregard of 'don't know' responses. Questions marked with an asterisk suggest a statistically significant dependence between ATES market development level (Table 1) and the question's topic when using a significance level of 0.05. Sects. "Existence of ATES policies" to "Access to technical knowledge and qualified workers for ATES installation". describe the results of some questions in more detail

for increased adoption. This is supported by 86% of Dutch responses rating public awareness of ATES as low or moderate, despite it being an established technology (Fleuchaus et al. 2018).

Existence of funding programmes for ATES

> **Survey questions 16 & 16.a:** *Are there any currently active funding programmes or financial incentives which provide support for ATES systems in your country?*

Around 56% of respondents said their country lacks funding programmes or incentives for ATES (Fig. 4). This rises to 82% in countries with no installed ATES systems, compared to 46% in countries with ATES.

Access to technical knowledge and qualified workers for ATES installation

> **Survey question 19:** *To what extent does your country have access to enough technical knowledge and qualified workers for the installation of ATES systems? (for mature & growing markets and emerging markets only)*

Around 69% of respondents state that there is access to sufficient technical knowledge and qualified workers 'to some extent' or 'to a large extent' (Fig. 4). ATES market development level has a significant influence on the responses reflected in more ratings 'to a large extent' from *mature & growing markets*.

Country comparison

This section provides a condensed comparison of the survey results from the only mature (the Netherlands, 7 responses),

Table 3 Comparison of survey results for the Netherlands (mature ATES market), Denmark (growing ATES market) and Germany (emerging ATES market)

	Netherlands	Denmark	Germany
Existence of policies	Y (100%)	N (100%)	Y (50%) N (50%)
Existence of laws & regulations	Y (100%)	Y (100%)	Y (71%) N (29%)
Legal & regulatory framework region dependent	Region/state dependent (50%) Uniform across the country (50%)	Uniform across the country (100%)	Region/state dependent (100%)
Considered in municipal planning	Y (83%) N (17%)	Y (50%) N (50%)	Y (60%) N (40%)
Existence of funding programmes/financial incentives	Y (50%) N (50%)	N (100%)	Y (75%) N (25%)
Citizen/community energy cooperatives	Y (60%) N (30%)	Y (80%) N (20%)	Y (17%) N (83%)
Existence of industry standards/codes of practice	Y (100%)	N (100%)	Y (60%) N (40%)
Effectiveness in managing environmental risks	+	+	o
Ease & speed application process	o	o	–
Quantity of available information	+	o	–
Quality of available information	+	o	o
Public awareness	–	–	–
Public acceptability	+	o	o
Access to technical knowledge & qualified workers	+	o	o

Percentages indicate the shares of corresponding responses with regard to total response number for the respective question and country. The lower half of the table shows results from the average ratings of all responses from the respective country (Y yes; N no; + high; o moderate; – low)

a growing (Denmark, 7 responses) and an emerging market (Germany, 15 responses). The sophisticated Dutch ATES policy and accompanying beneficial conditions are acknowledged by the Dutch respondents leading to the overall most favourable and affirming responses (Table 3). Furthermore, only in the Netherlands legally binding technical regulations regarding drilling work and installation of the subsurface and surface parts of ATES exist.

Conversely, despite being a growing market, no distinct ATES policy, funding and industry standards exist in Denmark. Increasing Danish ATES numbers therefore may result from economic and environmental benefits compared to conventional types of heating and cooling (Schüppler et al. 2019; Stemmle et al. 2021; Vanhoudt et al. 2011). It might also be related to Denmark's historically progressive heat planning strategies, which led to an internationally outstandingly high share of district heating supply (Johansen and Werner 2022; Werner 2017). This contrasts with the Netherlands where there is a stronger focus on individual heat and cold supply fostering the high adoption of decentralised ATES systems. However, the Danish district heating systems can also benefit from ATES on the ambitious way to full decarbonisation by 2030 through integration of large-scale thermal storage into the heat grids and utilisation of unused industrial waste heat (Johansen and Werner 2022). Thus, while not specifically tailored towards ATES, the Danish energy and climate protection policy appears to have created a favourable environment for emerging sustainable technologies. This also reflects in a high share of responses stating that citizen or community energy cooperatives play a role in the Danish ATES market (Table 3). Cooperative ownership of district heating grids ensured a local heating supply in many Danish municipalities (Johansen and Werner 2022).

In contrast to policies, laws and regulations for ATES exist in all three countries. The introduction of technology regulation governing the installation and use of ATES thus seems to be of higher priority than establishing a policy stimulating ATES. For Germany, several survey respondents mentioned the engineering standard on underground thermal energy storage (UTES) VDI 4640 Part 3, developed by the Association of German Engineers (German: *Verein Deutscher Ingenieure*, VDI). Other than the Dutch industry protocols, this technical standard for operational strategies, system dimensioning and well drilling for ATES and other types of UTES is only voluntary and recommended. A legally binding framework for authorisation of planning,

Table 4 Expert interviews: Participants, countries and organisation types

Interview participant(s)	Country	Organisation name	Organisation type
David Simpson	Belgium	AGT—Advanced Groundwater Techniques	Private company: Hydrogeological consultancy
Xiaobo Wu	China	CEEC Geothermal Co., LTD (China Energy Engineering Corporation)	State-owned enterprise: Geothermal energy engineering
Rasmus Aaen & Anders Juhl Kallesøe	Denmark	NIRAS A/S	Private company: Engineering consultancy
Teppo Arola	Finland	Geological Survey of Finland	National geological survey
Guillaume Attard	France	Ageoce Solutions	Private company: Geoscience consultancy
Christian Boissavy	France	Cabinet Boissavy	Private company: Geothermal energy consultancy
Paul Fleuchaus	Germany	tewag GmbH	Private company: Geoscience consultancy
Frank Agterberg	Netherlands	Branchevereniging Bodemenergie Nederland (Dutch shallow geothermal energy association)	Industry/trade association
Martin Bloemendal	Netherlands	Delft University of Technology	University/academia
Bas Godschalk	Netherlands	IF Technology	Private company: Geothermal energy engineering
Bjørn Frengstad	Norway	NTNU Norwegian University of Science and Technology	University/academia
Horia Ban	Romania	Termoline	Private company: Renewable heating and cooling
Vincent Badoux	Switzerland	GEOTEST Ltd	Private company: Geoscience consultancy
Edward Hough	United Kingdom	British Geological Survey	National geological survey
Anonymous	United Kingdom	N/A	Public sector organisation
Erick Burns	USA	N/A	Public sector organisation

installing and operating ATES in Germany is provided by the German Water Resources Act (German: *Wasserhaushaltsgesetz*, WHG). It is, however, embedded in a much broader context and aims at protecting water as basis for life, ecosystem and usable asset (Hähnlein et al. 2011; Neidig 2022). According to several respondents, an opportunity to stimulate ATES in Germany is the existence of funding programmes supporting the installation of energy-efficient buildings and district heating networks with a high share of renewable energies. These programmes consider technologies for large-scale heat storage including ATES. Nevertheless, the lower half of Table 3 shows that Germany has the least favourable environment for growing ATES diffusion in this comparison. For Denmark and the Netherlands progressively improving conditions for ATES are indicated.

Results of expert interviews

16 interviews were conducted with select experts or practitioners who had participated in the survey, to gather more detailed information on ATES policies and regulations and current obstructive and beneficial factors for ATES deployment (Table 4). The expert interviews were limited to countries with existing ATES, since the survey finds that laws, regulations and policies for ATES are mainly absent in countries without installations. The interview results are synthesised in the following sections.

Current factors benefiting ATES deployment

Once again, Dutch interviewees confirmed the sophisticated Dutch policy described in the introduction. Besides this purposeful ATES policy, there are further factors benefiting ATES in the Netherlands and partially in countries with *growing markets* as well (Table 1). They include the pre-existing expertise regarding the use of groundwater for other purposes, such as drinking water production, which has served as a technological driver for ATES implementation as stated during interviews with Dutch and Danish experts. This led to a mostly high quality of early ATES systems resulting in good reputation and growing awareness amongst the professional field (e.g. policy makers, municipalities, heating and cooling sectors).

Policy drivers indirectly promoting ATES in *mature & growing markets* are strict building energy efficiency requirements, mandatory local heat planning and a general focus on heat pumps and district heating. A sufficient workforce and an overall open-minded or even favourable attitude towards ATES among local authorities were also stressed as benefiting factors. Increasing interest in ATES was also attributed to rising gas prices and the desire for primary energy savings.

For countries with *emerging markets*, several interviewees acknowledged the presence of suitable aquifers for ATES and further beneficial factors (Table 5). Interviews with French and Finnish experts revealed existing water and environmental acts already largely suitable for handling ATES.

Table 5 Some beneficial and obstructing factors for increased ATES deployment reported during expert interviews

Mature & growing markets		Emerging markets	
Beneficial factors	Obstructive factors	Beneficial factors	Obstructing factors
Suitable aquifers	No coordinated planning (Netherlands, Belgium)	Suitable aquifers	Region-dependent legislation in some countries
Suitable laws and regulations	Slow permit process (Denmark, Belgium)	Suitable laws and regulations in some countries	Slow permit process
Uniform legislation (Netherlands, Denmark)	No industry standards (Denmark, Belgium)	Some existing demonstration systems	Technical problems with early systems
Fast permit processes (Netherlands)	ASHP as a strong competitor	Funding available (some countries)	No funding available (some countries)
Abundance of available information		Pre-existing expertise in groundwater utilisation	Lack of available information
High awareness in professional field			Low awareness in professional field
High quality of systems			Lacking workforce
Industry standards (Netherlands)			Lacking capacity and expertise within local authorities
Sufficient workforce			Focus on other types of renewable energy
Favourable attitude and expertise in local authorities			
High building efficiency requirements			
Pre-existing expertise in groundwater utilisation			
Focus on related technologies			

For some *emerging markets*, such as Germany, available funding options for individual systems and ATES research were reported as means to initiate a phase of growing ATES utilisation.

Current barriers to ATES deployment

Obstructing factors to an increasing use of ATES are found to be more numerous in *emerging ATES markets* than in *mature & growing markets* (Table 5). For example, interviewees from Norway and France described insufficient installation quality of early ATES systems causing technical problems and bad publicity. The few systems in *emerging markets* typically face lengthy permit procedures, sometimes more than a year, which reduces the appeal of ATES. Lacking availability of information on ATES, low awareness among practitioners, such as heat pump sellers and heating engineers, as well as missing financial incentives were further highlighted as barriers which effective ATES policies should address. Some structural problems pointed out during interviews include lacking capacity and expertise within local authorities and insufficient planning and installation workforce. The greater policy focus on other renewable technologies, such as wind and solar power, also contributes to low ATES uptake in *emerging markets*.

An exemplary barrier mentioned by experts from the Netherlands and Belgium reflecting the already more widespread ATES application in these *mature & growing markets* is the prevailing individual approach of ATES planning and permission. Especially in dense urban areas, this might lead to inefficient subsurface utilisation in the future compared to a coordinated district-level approach. Despite growing numbers of ATES installations in Denmark and Belgium, interviewees from these countries criticised the slow permitting process and missing industry-wide installation and operation standards. The much faster growth of air source heat pumps (ASHP) as a competing option for meeting building energy requirements was also pointed out as an impeding factor in these markets.

Policy recommendations

Based on the online survey results and the insights from the expert interviews and complemented by relevant literature, this subsection develops policy recommendations on how to overcome legislative, regulatory and socio-economic barriers to a wider international ATES deployment. The following sections cover a variety of important elements constituting a sophisticated ATES policy (Fig. 5). For each of these elements, recommendations as well as key actions to achieve

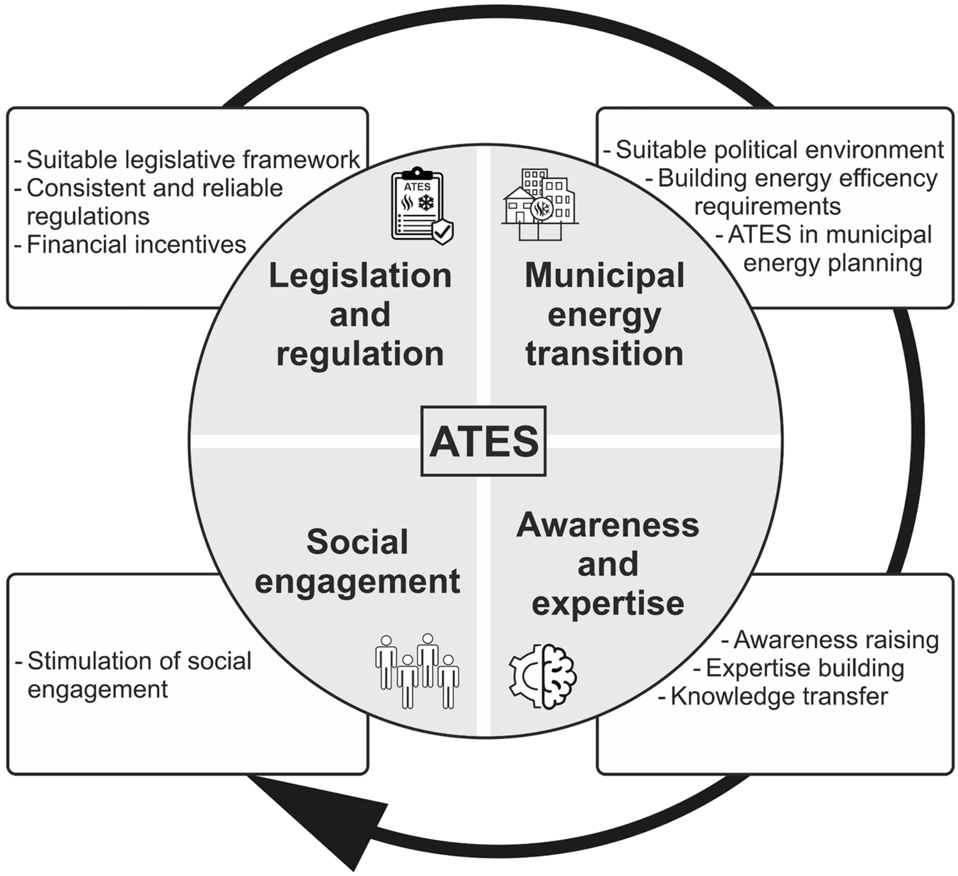


Fig. 5 Recommendations for a sophisticated ATES policy consisting of different policy elements. Detailed key actions for each element are described in the text. The arrow indicates a coarse practical order of actions, which provides the structure to the following subsections

them are presented. Where available, relevant quotes from the interviews introduce new aspects which are discussed below the quotes.

Legislation and regulation of ATES

The online survey revealed suitable legislation for and regulation of ATES as one of the most important market factors (Fig. 3). A lack of a reliable legislative framework and suitable regulations has previously been described as a threat to technology introduction, increasing diffusion and widespread economic application in the context of ATES and SGE in general (Drijver and Godschalk 2018; García-Gil et al. 2020; Neidig 2022).

Recommendation 1: Creation of a suitable legislative framework for ATES In many countries, ATES is legally governed by national water acts and environmental protection acts, accompanied by various regional or local laws and directives. Being not specifically designed for ATES, these laws commonly cover all types of groundwater actions which have varying requirements for a suitable legislation. In a first step, it is therefore necessary to check, if existing water and environmental protection acts sufficiently address specific requirements of ATES, such as handling re-injection of heated and cooled groundwater. With only few installed systems, Finland represents an exemplary country where ATES is considered a niche technology and no specific legislative framework is in effect. Nevertheless, existing Finnish water and environmental acts proved suitable in providing necessary tools governing the first ATES applications. In countries where this is not the case, a legislative reform of existing laws or the purposeful creation of a specific ATES legal framework are necessary. The latter happened in the Netherlands in 2013 when existing acts were combined and improved upon creating a single Geo Energy Systems Amendment which governs the thermal use of groundwater.

> *"The harmonisation […] made it much easier to get the permits."* – Martin Bloemendal, Delft University of Technology, Netherlands.

A suitable ATES legislation should allow for an easy and rapid permitting. This was repeatedly highlighted as a critical point during the interviews. Half of all survey respondents pointed out regional or federal differences in the legal framework including permit procedure variations. A unified procedure across an entire country holds great potential to reduce permit duration and complexity. Harmonising scattered permitting rules directly affects potential system adopters and benefits consultancies and public authorities in decision making and thus can contribute to a favourable perception of ATES among all relevant stakeholders.

Recommendation 2: Creation of consistent and reliable ATES regulations A successful set of ATES regulations must ensure a high ATES installation quality and operational performance as well as addressing environmental risks. Detrimental impacts of ATES on the environment can result from mixing of groundwater with different physical–chemical composition (Bonte et al. 2011; McClean and Pedersen 2023; Possemiers et al. 2014; Regnier et al. 2023). Changes in groundwater temperature can further alter physical–chemical properties and geochemical equilibria with adverse implications for drinking water quality (Hähnlein et al. 2013). Temperature changes can also affect the ecological conditions and biological processes of groundwater ecosystems and their respective ecosystem services (Blum et al. 2021; Griebler and Avramov 2015; Koch et al. 2021; Ni et al. 2016).

Risk management should therefore include preliminary evaluations of the expected extent of thermal impact. A regulatory framework for ATES should also address inefficiencies in the permission procedure due to approval of excessively large capacities often not fully used and thus hindering future installations (Bloemendal et al. 2014; García-Gil et al. 2020; Perego et al. 2022). While based on a countrywide harmonised set of regulations, permission procedures should ideally contain some reasonable flexibility and public authority discretion in approving storage temperatures in already thermally influenced urban aquifers (i.e. subsurface heat islands, SUHI) (Hähnlein et al. 2013; Menberg et al. 2013). System operation monitoring and reporting should be made mandatory in any ATES regulatory framework to control operational compliance with permitted temperature limits, extraction volumes and energy balance requirements.

> *"It took us a couple of years to get to the point where we are."* – Martin Bloemendal, Delft University of Technology, Netherlands.

At the same time, it became clear from the interviews that the regulatory regime should not be too restrictive and burdensome. Overly complex and lengthy permit procedures could otherwise hinder an increasing ATES deployment. This was realised in the Netherlands, where regulatory maintenance and monitoring requirements were originally introduced for environmental protection purposes. Over time, Dutch ATES regulations were expanded and complemented by legally binding industry standards aiming for high system installation and operation standards. Despite the extensive regulations, rapid permission times of eight weeks are common and lightweight permit procedures for smaller systems (<50 m^3/h) lower bureaucratic barriers for potential system owners (Drijver and Godschalk 2018). This way, the reasonable and reliable Dutch regulatory framework supports decisions and actions among planners, installation companies and local authorities alike.

ATES regulations should account for the country-specific ATES market development level (Table 1) and include space for dynamic adjustments. Past changes in Dutch regulations due to an increasing number of ATES installations serve as a good illustration. Currently, newly created systems must adhere to strict rules stating that extraction temperatures of already existing neighbouring systems cannot be affected by more than ± 0.5 K. Especially in dense urban areas this might hinder further ATES deployment in the long term. A Dutch interviewee accordingly hoped for further adjustments introducing a more flexible approach towards system spacings and a coordinated planning of multiple systems which can achieve an overall higher system performance in dense urban settings (Bloemendal et al. 2018; Sommer et al. 2015).

Recommendation 3: Provision of financial incentives for ATES Space heating and cooling with ATES is commonly subject to higher upfront capital costs than other types of heating and cooling such as ASHPs, gas boilers or compression chillers (Schüppler et al. 2019). The high importance of economic feasibility as an ATES market factor was underlined in the online survey responses (Fig. 3). The availability of funding schemes tailored towards ATES can significantly reduce financial risks and can constitute a crucial part of ATES policies to attract financial interest of potential system owners. Besides decentralised ATES systems for single building complexes, centralised ATES feeding into district grids can profit from funding, too.

> *"If you lower the costs, that will remove one of the main barriers."* – Rasmus Aaen, NIRAS A/S, Denmark.

Funding schemes for individual installations might cover different ATES deployment stages. Besides subsidising system installation, funding for site-specific feasibility studies, hydrogeological exploration and thermo-hydraulic simulations can lower financial barriers during system planning. Other financial allocation mechanisms such as low-interest loans and reduced electricity prices for heat pump operation are also conceivable. Funding of ATES research projects and demonstration sites can further help in stimulating a broad ATES market uptake.

The specific design of financial incentives for ATES provided through national funding programmes or tax deduction schemes is subject to the country-specific fiscal policy and institutional environment. It can also be adapted over time as happened in the Netherlands where financial support during the start-up phase of market implementation in the 1990s was granted for early ATES systems through a market uptake programme by the Dutch Ministry of Economic Affairs (now the Ministry of Economic Affairs and Climate Policy). Today, however, in the context of a mature and fully commercialised ATES market, no financial incentives specific to ATES are available or required any more.

Besides ATES-specific funding, more general funding schemes and financial incentives supporting building energy efficiency, high-efficiency heat pumps, seasonal thermal storage or storage systems feeding into heating grids can indirectly foster a higher ATES deployment rate. In this case, ATES should specifically be included in a technology portfolio eligible for funding.

Role of ATES in the municipal energy transition

Municipalities are key actors for a successful heat transition in the built environment (Beauchampet and Walsh 2021). Municipal engagement with energy includes holistic municipal energy planning, building energy retrofitting and the uptake of sustainable technologies such as low-carbon district heating grids and high-efficiency heat pumps, all of which can facilitate increased ATES deployment (Coy et al. 2021; Herreras Martínez et al. 2022).

Recommendation 1: Establishing a suitable political environment National governments are responsible to create the right policy framework for the heat transition and, in this course, establish political drivers encouraging an increased ATES implementation. This starts with clearly communicating climate protection targets, the heat transition's urgency and suitable transformation strategies for the built environment (Herreras Martínez et al. 2022; Sillak 2023). Reliable and consistent governmental strategies and information on suitable technological solutions are crucial for long-term planning security of municipal, business and private stakeholders.

Mandatory municipal heat planning is an important example for legally binding instruments supporting the leading role of local authorities in the heat transition (Herreras Martínez et al. 2022). Local empowerment facilitated by central governments can further encourage this leading role (Coy et al. 2021, 2022; Vringer et al. 2021). This way, municipalities can substantially engage in the transformation of the heating and cooling infrastructure reflected by their own transformation from solely consumers of heat and cold to active prosumers, i.e. a combined role of producers and consumers. A supporting central governance should clearly outline the energy planning role of municipalities and increase municipal competences in finding the best technological solutions accounting for local opportunities and barriers. The unique Danish energy policy granting far-reaching autonomy to municipalities in making long-term decisions on their supply of thermal energy could potentially serve as an exemplary practice model for other countries (Bulkeley 2010; Chittum and Østergaard 2014; Johansen and Werner 2022; Sperling et al. 2011).

Recommendation 2: Establishing building energy efficiency requirements Increasingly strict building energy efficiency requirements are considered an integral part of an overarching policy framework for sustainable space heating and cooling concerning building energy retrofitting as well as the construction of new buildings.

> *"That [building energy efficiency] policy worked out quite well to increase market demand."* – Martin Bloemendal, Delft University of Technology, Netherlands.

As pointed out by several interviewees in the Netherlands and Belgium, strict efficiency standards of newly constructed buildings can effectively foster a widespread ATES deployment since ATES is a well-suited technology to substantially reduce the primary energy consumption for space heating and cooling. ATES and its energetic and cost benefits should therefore be promoted within the portfolio of efficient technological solutions.

Recommendation 3: Integrating ATES into municipal energy planning Municipal energy planning accounts for local chances and barriers in advancing the energy transition at a local level. Accompanying the increasingly decentralised and climate friendly generation and supply of electricity and thermal energy, municipal energy plans aim to find the right technological solutions district by district (Brandoni and Polonara 2012; Sperling et al. 2011). Seasonal thermal storage can be an important component of municipal energy plans (Kauko et al. 2022; Paiho et al. 2017) which therefore might stipulate increased ATES deployment including the integration of ATES into DHC grids.

National or regional governments can assist municipalities in considering ATES in municipal energy planning by providing information services, energy planning guides and tools. These could include government-operated online map applications that show suitable regions for ATES across the country including some preliminary statements on site-specific feasibility and existing installations including operational information such as permitted extraction volumes. This can also benefit early design considerations of individual systems. The freely accessible services in Belgium (www.dov.vlaanderen.be/portaal/?module=verkenner) and the Netherlands (www.wkotool.nl) can serve as inspirations for similar services in other countries. Free and easy online access to hydrogeological subsurface data can also facilitate consideration of ATES in municipal energy plans.

"The municipalities can make a kind of [ATES] master plan." – Bas Godschalk, IF Technology, Netherlands.

Accompanying the legal obligation for municipalities to prepare energy plans, a holistic and coordinated approach of managing ATES and other shallow geothermal systems is to be encouraged as it can prevent thermal interferences between installations early on or even intentionally allow them to achieve overall higher system performance on the district level (Bloemendal et al. 2018; Sommer et al. 2015). Especially in countries with higher installation densities such as Belgium and the Netherlands, interviewees stressed the advantages of such a coordinated planning over individual system planning. Structural expertise building in local authorities might be necessary to adequately address this level of urban energy planning potentially involving heat transport modelling and other sophisticated management measures.

ATES awareness and expertise

While not being rated as important market factors for an increased ATES uptake in the online survey (Fig. 3), the low level of public ATES awareness and lacking hydrogeological and technological expertise regarding ATES were repeatedly stressed during several interviews as severe barriers to a broader ATES development. This is in line with past experience with other renewable energy technologies, such as photovoltaics, solar thermal energy, ASHPs and ground source heat pumps (GSHPs) (Briggs et al. 2022; Karytsas and Theodoropoulou 2014; Peñaloza et al. 2022; Seetharaman et al. 2016).

Recommendation 1: Raising awareness of ATES A sophisticated and thorough ATES policy in a given country should make a wide variety of stakeholders aware of ATES, such as potential consumers, energy planners, installation companies, the national heating, ventilation and air conditioning (HVAC) and heat pump industry as well as regional and local authorities. Indeed, relevant policy makers have to be aware of ATES for this to happen in the first place, which is often lacking. As some interviewees pointed out, initial awareness raising initiatives could therefore come from governmental energy agencies, national heat pump associations or national geothermal associations. These organisations can take a crucial role in increasing awareness in the responsible governmental bodies.

"You need to talk about ATES and […] improve awareness." – Anonymous interviewee, public sector organisation, UK.

Awareness building measures raised by interviewees include workshops, conferences and online courses organised by governmental energy and environmental agencies in cooperation with industry associations or universities. Aiming at different target audiences, these events can explain ATES operation principle and suitable use cases as well as stressing its benefits. Informing the public can help reducing adverse impressions of an overly high technological complexity of ATES linked to the widely unfamiliar term 'aquifer'.

"Go and advertise it." – Teppo Arola, Geological Survey of Finland, Finland.

Another great leverage effect in raising public awareness can be attributed to existing ATES installations, both demonstration projects and pioneering commercial systems, the existence and benefits of which should be communicated to all stakeholders (Fleuchaus et al. 2021). National or regional geological surveys and energy agencies can provide information about existing systems via web pages and similar distribution channels. The unique example of façade plaques for Dutch buildings highlighting space heating and cooling with ATES could also set a precedent in illustrating a subsurface technology that is otherwise not visible.

"Energetically, ATES is the best source of a heat pump, including […] passive cooling." – Frank Agterberg, Branchevereniging Bodemenergie Nederland, Netherlands.

In recent years, heat pumps have been a central part of many energy transition strategies in the building sector and corresponding supportive national and international policies (Grubler and Wilson 2014; IEA 2022). Besides presenting ATES as a distinct new technology, ATES policies could use this ongoing political and societal focus on heat pumps as a starting point to promote heat stored in the underground as the ideal heat source for heat pump operation. Communicating the environmental and economic benefits due to primary energy savings compared to other heat sources, such as the outside air, could help increasing ATES popularity. This includes stressing its capability of passive cooling during summer, i.e. without running the heat pump's compressor (Fleuchaus et al. 2018; Schüppler et al. 2019). Benefits of centralised ATES application as storage components of district heating grids should be emphasised as well.

Recommendation 2: Building up ATES expertise The online survey results presented in Fig. 3 illustrate the high importance of knowledge and expertise among relevant stakeholders in industry and government authorities. Especially in emerging ATES markets, skill shortages and insufficient training and qualifications were often pointed out as significant barriers to a wider ATES deployment. This problem is not unique to ATES and can be observed for other related areas as well, such as building energy retrofits, photovoltaic and heat pump installation (Branford and Roberts 2022; Briggs et al. 2022; Jagger et al. 2013; Zekira and Chitchyan 2019).

"There are courses and trainings for people to get into this business." – Bas Godschalk, IF Technology, Netherlands.

Policies fostering a coordinated approach of government and industry to build up sufficient education and training capacities are needed for a rapid workforce upskilling (Briggs et al. 2022). Governmental education programmes and training infrastructure can take the form of information campaigns and skills boot camps focusing on various groups in the workforce along the supply chain of ATES deployment.

"They don't see the opportunity, even if they are situated on top of it." – Teppo Arola, Geological Survey of Finland, Finland.

Government-controlled capacity building initiatives should also address knowledge on subsurface utilisation opportunities and basic hydrogeological processes that is often lacking amongst energy planners, building architects and heat pump sellers since these groups arguably have the highest impact on promoting ATES commercialisation.

"A lot of those […] who do similar things could be re-trained." – Erick Burns, USA.

Additionally, a higher number of qualified personnel could potentially be generated by a systematic skill shift in technologically related sectors. Especially in countries with a high share of groundwater resources in drinking water production, such as Germany and Denmark, ATES education and training could benefit from already existing expertise and high-quality standards in the water industry. This skill shift might also be conceivable for pre-existing expertise in hydrocarbon exploration in some countries. Speeding up permission procedures for ATES requires capacity development in government authorities as well since a robust knowledge on reasonable system spacing and temperature limits is necessary including special considerations in already thermally affected urban aquifers.

"Hopefully you plant some seeds [in the universities] and it starts to grow in five or ten years." – Bjørn Frengstad, Norwegian University of Science and Technology, Norway.

Besides upskilling amongst practitioners and public authorities, adjusted education in relevant disciplines at universities can also build up ATES expertise in the long term.

"The market follows the successful projects." – Teppo Arola, Geological Survey of Finland, Finland.

Especially in emerging markets, the importance of successful ATES systems early on was stressed during several interviews due to the pioneering role of early lighthouse projects. Industry standards and codes of practice in the form of guidelines on ATES design, installation and operation can ensure system quality. Ideally policy makers should implement such standards as legally binding protocols as enforced in the Netherlands in 2013. These protocols are designed to dynamically incorporate new research findings to further improve ATES quality. The Netherlands can also serve as a best practice model in establishing mandatory national certifications for specialist companies active in ATES consultation, design and construction. Such certifications can pose an integral element of a sophisticated ATES policy leading to higher system quality, decreasing installation costs, increasing reputation and ultimately fully commercialising the ATES market.

Recommendation 3: Establishing ATES knowledge transfer Policy-initiated expertise development for ATES as described above could be supplemented by establishing different platforms for knowledge exchange, both on national and an international level.

"Owners of ATES systems have unified themselves in the user platform." – Martin Bloemendal, Delft University of Technology, Netherlands.

Again, the Netherlands provides an example for a successful knowledge exchange platform among individual ATES users. This platform (gebruikersplatform.bodemenergie.nl) by the Dutch industry association for geothermal systems consists of an online member forum and a knowledge platform offering consultation for end users and webinars on a regular basis providing valuable information on optimal system operation.

"We are open for [international] collaboration." – Bas Godschalk, IF Technology, Netherlands.

ATES knowledge transfer on the international level is currently mostly limited to academic research projects. Technical assistance or collaboration programmes could address a more systematic transfer of ATES expertise and knowledge on a broader level. Such transfer could take place in the frame of existing structures, such as the Technology Collaboration Programme on Heat Pump Technologies (HPT TCP) by the International Energy Agency (IEA). As pointed out during some interviews, national geological surveys could also significantly contribute to ATES knowledge transfer between different countries generating important shared expertise especially between neighbouring countries with similar hydrogeological subsurface characteristics. Examples of this already happening are the Nordic countries Norway, Sweden and Finland. However, this exchange was described as being limited and rather unstructured indicating potential for a more systematic exchange between geological surveys. This is also true for collaborations and research projects between national heat pump associations organised under the auspices of the European Heat Pump Association (EHPA), which could be expanded for topics more specific to ATES.

> *"It's easy to copy and paste this legislation."* – Horia Ban, TermoLine, Romania.

Besides addressing technical challenges and research findings on ATES, insights into suitable and practically proven ATES legislation and regulation could also be part of international knowledge transfer. Especially countries with emerging ATES markets and countries that have yet to see first ATES installations could benefit from already implemented and successful legislative and regulatory ATES frameworks from other countries. In the long-term, this might also encourage a harmonised ATES legislation across national borders, for example, in the context of the European Union.

Social engagement with ATES

Active participation of citizens in transforming the energy system is often described as a meaningful part of the energy transition and a way to increase acceptance of renewable energies. Such social engagement allows meaningful citizen interactions with the energy system and thereby empowers formerly marginalised actors (Beauchampet and Walsh 2021; Hartmann and Palm 2023; Wüstenhagen et al. 2007). In some countries, citizen-led community initiatives have already contributed to a wider acceptance and larger share of renewable energies in electricity supply (Fouladvand et al. 2022; Hartmann and Palm 2023). This can serve as a model for social engagement with sustainable heating and cooling solutions as well. It should be noted, however, that the research participants provided very little information about social engagement with ATES during the online survey and the interviews.

Recommendation: Stimulation of social engagement with ATES A common form of collective social engagement is a citizen energy cooperative which describes local communities with joint investments in technologies to generate and consume or sell renewable energy (Dóci et al. 2015; Fouladvand et al. 2022). Since ATES is not commonly applied for individual residential buildings, especially large-scale ATES applications feeding into heating and cooling grids are conceivable for energy cooperatives. Integrating ATES into these grids allows for a flexible use of locally generated renewable energy and available waste heat increasing local value added (Todorov et al. 2020). The sense of ownership provoked by such an energy system collectively owned by the consumers themselves might serve as a key motivation for social engagement with ATES.

A sophisticated ATES policy should encourage local authorities to explicitly create space for citizen engagement in their urban heat planning. Creating awareness of the citizen energy business model in municipalities and local governments contributes to a supportive mindset and promotes the involvement of the local community early on (Hartmann and Palm 2023). Some other policy measures mentioned above are also relevant for increasing social engagement coordinated in citizen energy cooperatives. The importance of public awareness raising and provision of necessary information on ATES to different groups of stakeholders must be reiterated here since a proper information basis allows citizens to make informed decisions. Citizen workshops, information campaigns and community energy roadshows can bring citizen energy cooperatives and ATES to the public attention (Coy et al. 2022). In addition, financial incentives specifically designed for collective community engagement such as citizen energy cooperatives can reduce financial barriers.

Conclusions

This study presents an international comparison of ATES policies regarding their existence and suitability to overcome legislative, regulatory and socio-economic barriers to a wider international ATES deployment. For this, an online survey of experts and practitioners in relevant sectors, such as universities, private companies and government authorities from a total of 30 countries, was conducted. Additional information was collected through 16 semi-structured expert interviews. For the survey evaluation, countries were aggregated to three distinct groups to identify similarities and differences between different ATES market development levels.

Across all market development levels, geological feasibility of ATES as well as suitable laws and regulations were rated as the most important market factors. The existence of laws and regulations governing ATES was confirmed by 56% of all survey respondents. In contrast, a mere 33% of all respondents stated that there are policies designed to support increased ATES deployment in their respective countries. Especially survey participants from countries with a mature or growing ATES market predominantly confirmed distinct ATES policies and a legislative and regulatory framework. A dependence on the ATES market development level could also be inferred for other aspects such as public awareness and access to sufficient technical knowledge and qualified workers.

The expert interviews confirmed the overall favourable conditions for an increased use of ATES in mature or growing markets. This applies to both ATES policy elements as well as indirect drivers benefiting ATES deployment including existing widespread utilisation of groundwater technologies for other purposes and strict building energy efficiency requirements. In contrast, interviewees from emerging ATES markets pointed out many obstructing factors, such as lengthy ATES permit procedures, low awareness among relevant stakeholders and a general lack of expertise and skilled workers for planning and installing ATES systems. Overall, the online survey and expert interviews revealed significant shortcomings in many countries regarding the existence and suitability of policies and regulations for reducing market barriers and promoting benefits of ATES.

Based on our findings from the online survey and expert interviews, policy recommendations were developed which can reduce identified barriers and advance ATES market development. The recommendations cover legislative and regulatory topics on the governance of ATES and highlight ways of raising awareness of the technology, its application cases and benefits. A sophisticated ATES policy should furthermore acknowledge the potentially substantial role of ATES in the municipal energy transition and therefore include measures to promote ATES in local urban and energy planning as well as encourage social engagement with ATES. We hope that our proposed ATES policy can contribute to establishing suitable legislative, regulatory and socio-economic conditions for a wider international ATES deployment.

Appendix A Online survey questionnaire

All online survey questions and possible answers are listed below:

1. Before receiving this survey, were you aware of aquifer thermal energy storage (ATES)?

   - Yes
   - No

2. Have aquifer thermal energy storage (ATES) systems been installed in your country?

   - Yes
   - No
   - Don't know

3. Do you think that ATES is a promising technology that could be widely deployed in your country?

   - Yes
   - No
   - ATES is already widely employed in my country
   - Don't know

4. At the present time and in your view, how important are the following market factors in influencing the uptake of ATES in your country?

   - Technical (engineering) feasibility
   - Geological feasibility including presence of suitable aquifers
   - Lack of (limited) subsurface space due to other subsurface uses
   - Economic feasibility including investment and operational costs
   - Policy support
   - Laws and regulations
   - Industry knowledge and skills
   - Public awareness
   - Public trust and acceptability

     - Five-point scale from 'not important' to 'very important'
     - Don't know

5. Are there any policies being applied currently in your country to increase the installation and use of ATES?

   - Yes
   - No
   - Don't know

6. If known, please provide brief details about any policies being applied currently in your country to increase the installation and use of ATES.
7. Are there any laws or regulations currently in effect or active in your country to govern the installation and use of ATES systems?

   - Yes
   - No
   - Don't know

8. Is the legal and regulatory framework concerning ATES uniform across the country or are there differences between regions?

   - Uniform across the country
   - Region/state dependent
   - Don't know

9. In your country, how do you rate the effectiveness of planning laws and regulations to manage environmental risks (e.g. groundwater quality impacts or subsurface temperature changes) associated with ATES installation and use?

   - Five-point scale from 'very low or none' to 'very high'
   - Don't know

10. In your country, how do you rate the ease or difficulty and speed of the application process to gain planning permission for new ATES installations?

    - Five-point scale from 'very poor' to 'very good'
    - Don't know
    - Not applicable

11. Is ATES considered as part of municipal or local authority heat (energy) plans in your country?

    - Yes
    - No
    - My country does not have municipal or local authority heat (energy) plans
    - Don't know

12. How do you rate the quantity (amount) of information about ATES available to the public and system or energy planners in your country?

    - Five-point scale from 'very low or none' to 'very high'
    - Don't know

13. How do you rate the quality of information about ATES available to the public and system or energy planners in your country?

    - Five-point scale from 'very poor' to 'very good'
    - Don't know

14. How do you rate the level of public awareness of ATES in your country?

    - Five-point scale from 'very low or none' to 'very high'
    - Don't know

15. How do you rate the level of public acceptability of ATES in your country?

    - Five-point scale from 'very low or none' to 'very high'
    - Don't know

16. Are there any currently active funding programmes or financial incentives which provide support for ATES systems in your country?

    - Yes
    - No
    - Don't know

17. If known, please provide brief details about any currently active funding programmes or financial incentives for ATES in your country, particularly on what is funded or incentivised.
18. Do citizen or community energy cooperatives play a role in your country's ATES market?

    - Yes
    - No
    - Don't know

19. To what extent does your country have access to enough technical knowledge and qualified workers for the installation and operation of ATES systems?

    - Five-point scale from 'Not at all' to 'To a very large extent'
    - Don't know

20. Are there any industry standards or codes of practice to manage the quality of ATES installations and operation in your country?

    - Yes
    - No
    - Don't know

21. If known, please provide brief details about any industry standards or codes of practice to manage the quality of ATES installations and operation in your country.
22. Optional: If known, please state the/an approximate number of ATES installations in your country.

If respondents answer 'no' or 'don't know' to question 2, they are presented a smaller number of partially slightly modified questions:

3.a • Yes
- No
- Don't know

4.a At the present time and in your view, how important are the following market factors in influencing the potential adoption of ATES in your country?

– Technical (engineering) feasibility
– Geological feasibility including presence of suitable aquifers
– Lack of (limited) subsurface space due to other subsurface uses
– Economic feasibility including investment and operational costs
– Policy support
– Laws and regulations
– Industry knowledge and skills
– Public awareness
– Public trust and acceptability

• Five-point scale from 'not important' to 'very important'
• Don't know

5.a Are there any policies being applied currently in your country to encourage the adoption and use of ATES?

• Yes
• No
• Don't know

6.a If known, please provide brief details about any policies being applied currently in your country to encourage the adoption and use of ATES.

7.a Are there any laws or regulations currently in effect or active in your country to govern the installation and use of ATES systems?

• Yes
• No
• Don't know

9.a To what extent do you think that planning laws and regulations in your country are adequate to support the adoption of ATES systems?

• Five-point scale from 'Not at all' to 'To a very large extent'
• Don't know

11.a Is ATES considered as part of municipal or local authority heat (energy) plans in your country?

• Yes
• No
• My country does not have municipal or local authority heat (energy) plans
• Don't know

12.a How do you rate the quantity (amount) of information about ATES available to the public and system or energy planners in your country?

• Five-point scale from 'very low or none' to 'very high'
• Don't know

13.a How do you rate the quality of information about ATES available to the public and system or energy planners in your country?

• Five-point scale from 'very poor' to 'very good'
• Don't know

14.a How do you rate the level of public awareness of ATES in your country?

• Five-point scale from 'very low or none' to 'very high'
• Don't know

16.a Are there any currently active funding programmes or financial incentives which provide support for ATES systems in your country?

• Yes
• No
• Don't know

17.a If known, please provide brief details about active currently active funding programmes or financial incentives for ATES in your country, particularly on what is funded or incentivised.

Appendix B Expert interviews guide

Questions used as an interview guide for the semi-structured expert interviews are listed below:

I. How would you describe the current situation and history with respect to the deployment and installation of ATES in your country?
II. To what extent do you think ATES has potential to be more widely deployed in your country?
III. In the survey you indicated that […] and […] are the most important market factors influencing whether ATES could be more widely deployed in your country. Could you explain your reasons for this?
IV. In the survey you indicated that […] and […] are the least important market factors influencing whether ATES could be more widely deployed in your country. Could you explain your reasons for this?

V. *[If relevant policies exist]* How effective have any policies been in increasing the installation and use of ATES in your country?
VI. *[If relevant policies do not exist]* Which types of policies could be effective for encouraging wider deployment and use of ATES in your country?
VII. *[If funding programmes or financial incentives exist]* How effective are any funding programmes or financial incentives in supporting the installation of ATES systems in your country?
VIII. *[If funding programmes or financial incentives do not exist]* How do you think funding programmes or financial incentives could be designed to effectively support the installation of ATES in your country?
IX. [*If relevant laws or regulations exist]* How effective are any laws or regulations in governing the installation and use of ATES systems in your country? To what extent could this legal and regulatory framework be improved?
X. *[If relevant laws or regulations do not exist]* How could laws or regulations be designed to effectively govern the installation and use of ATES systems in your country? What could an effective legal and regulatory framework for ATES look like?
XI. *[If legal and regulatory framework is region or state dependent]* How do regional or state differences in laws and regulations relevant to ATES affect the ease or difficulty of installing it?
XII. *[If applicable]* In the survey you indicated that ATES is considered as part of municipal or local authority heat (energy) plans in your country. Can you explain more about how ATES is considered in these plans?
XIII. Can you explain more about the quantity, quality and types of information available to the public and system planners about ATES in your country?
XIV. *[survey response to question 14 or 14.a was 'very low' to 'moderate']* How could the level of public awareness of ATES in your country be improved?
XV. Are there any strategies in your country to maximise public trust and acceptance of ATES?
XVI. *[If citizen or community energy cooperatives play a role]* What role do citizen or community energy cooperatives have in ATES deployment in your country?
XVII. *[If survey response to question 19 was 'to little extent' or 'to some extent']* How could jobs, skills and technical knowledge for ATES design, installation and use be further developed in your country?
XVIII. *[If survey response to question 19 was 'to a large extent' or 'to a very large extent']* In the survey, you indicated that your country has a high level of access to technical knowledge and qualified workers for ATES installation. To what extent is this a result of particular initiatives to develop skills, knowledge and labour for ATES, or inherited from other industries already existing in your country?
XIX. *[For emerging markets only]* Have you or others in your country benefited from knowledge transfer from countries with greater experience in ATES, and if so from which countries?
XX. *[For mature or growing markets only]* Do you or other ATES specialists in your country provide knowledge transfer to other countries, and if so which ones?
XXI. *[If industry standards or codes of practice exist]* How effective are any industry standards or codes of practice in managing the quality of ATES installations and operation in your country?
XXII. *[If industry standards or codes of practice do not exist]* How do you think industry standards or codes of practice could be designed to effectively manage the quality of ATES installations and operation in your country?
XXIII. Is there any requirement for the performance of ATES systems to be monitored after installation?

Appendix C Response rate of online survey

Country	Invitations	Responses	Response rate [%]
Albania	2	1	50
Australia	5	5	100
Austria	12	5	42
Belarus	1	0	0
Belgium	11	3	27
Bosnia and Herzegovina	4	0	0
Bulgaria	5	0	0
Canada	7	0	0
China	3	1	33
Croatia	8	0	0
Cyprus	1	0	0
Czech Republic	4	1	25
Denmark	26	7	27
Estonia	5	1	20
Finland	8	2	25
France	15	3	20
Germany	32	15	47
Greece	4	1	25
Hungary	7	2	29
Iceland	7	0	0
Ireland	6	0	0
Italy	9	2	22

Country	Invitations	Responses	Response rate [%]
Japan	2	0	0
Kazakhstan	1	0	0
Kosovo	2	0	0
Latvia	2	0	0
Lithuania	5	1	20
Moldova	1	0	0
Montenegro	1	0	0
Netherlands	17	7	41
North Macedonia	2	0	0
Norway	10	2	20
Poland	7	1	14
Portugal	5	2	40
Romania	2	1	50
Russia	5	1	20
Serbia	3	1	33
Slovakia	3	1	33
Slovenia	5	1	20
South Korea	4	2	50
Spain	10	1	10
Sweden	19	2	11
Switzerland	15	5	33
Turkey	4	0	0
Ukraine	3	0	0
United Kingdom	16	4	25
USA	7	1	14

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Declarations

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References

Beauchampet I, Walsh B (2021) Energy citizenship in the Netherlands: the complexities of public engagement in a large-scale energy transition. Energy Res Soc Sci 76:102056. https://doi.org/10.1016/j.erss.2021.102056

Beernink S, Bloemendal M, Kleinlugtenbelt R, Hartog N (2022) Maximizing the use of aquifer thermal energy storage systems in urban areas: effects on individual system primary energy use and overall GHG emissions. Appl Energy 311:118587. https://doi.org/10.1016/j.apenergy.2022.118587

Best R, Burke PJ (2018) Adoption of solar and wind energy: the roles of carbon pricing and aggregate policy support. Energy Policy 118:404–417. https://doi.org/10.1016/j.enpol.2018.03.050

Birhanu ZK, Kitterød N-O, Krogstad HE, Kværnø A (2015) Numerical modeling of aquifer thermal energy efficiency under regional groundwater flow: a case study at Oslo Airport. Hydrol Res 46:721–734. https://doi.org/10.2166/nh.2015.119

Bloemendal M, Olsthoorn T, Boons F (2014) How to achieve optimal and sustainable use of the subsurface for aquifer thermal energy storage. Energy Policy 66:104–114. https://doi.org/10.1016/j.enpol.2013.11.034

Bloemendal M, Olsthoorn T, van de Ven F (2015) Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage. Sci Total Environ 538:621–633. https://doi.org/10.1016/j.scitotenv.2015.07.084

Bloemendal M, Jaxa-Rozen M, Olsthoorn T (2018) Methods for planning of ATES systems. Appl Energy 216:534–557. https://doi.org/10.1016/j.apenergy.2018.02.068

Bloemendal M, van der Schans M, Beernink S, Hartog N, Vardon PJ (2023) Drivers to allow widespread adoption of ATES systems: a reflection on 40 years experience in The Netherlands. In: Symposium on Energy Geotechnics, Delft, the Netherlands, pp 3–5

Blum P, Menberg K, Koch F, Benz SA, Tissen C, Hemmerle H, Bayer P (2021) Is thermal use of groundwater a pollution? J Contam Hydrol 239:103791. https://doi.org/10.1016/j.jconhyd.2021.103791

Bonte M, Stuyfzand PJ, van den Berg GA, Hijnen WAM (2011) Effects of aquifer thermal energy storage on groundwater quality and the consequences for drinking water production: a case study from The Netherlands. Water Sci Technol 63:1922–1931. https://doi.org/10.2166/wst.2011.189

Brandoni C, Polonara F (2012) The role of municipal energy planning in the regional energy-planning process. Energy 48:323–338. https://doi.org/10.1016/j.energy.2012.06.061

Branford Z, Roberts J (2022) The installer skills gap in the UK heat pump sector and the impacts on a just transition to net-zeo. In: Research Brief University of Strathclyde Engineering 2022

Briggs C, Atherton A, Gill J, Langdon R, Rutovitz J, Nagrath K (2022) Building a 'Fair and Fast' energy transition? Renewable energy employment, skill shortages and social licence in regional areas. Renew Sust Energy Trans 2:100039. https://doi.org/10.1016/j.rset.2022.100039

Bulkeley H (2010) Cities and the governing of climate change. Annu Rev Environ Resour 35:229–253. https://doi.org/10.1146/annurev-environ-072809-101747

Chittum A, Østergaard PA (2014) How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Policy 74:465–474. https://doi.org/10.1016/j.enpol.2014.08.001

Clark T, Foster L, Sloan L (2021) Bryman's social research methods. Oxford University Press, Oxford

Coy D, Malekpour S, Saeri AK, Dargaville R (2021) Rethinking community empowerment in the energy transformation: a critical review of the definitions, drivers and outcomes. Energy Res Soc Sci 72:101871. https://doi.org/10.1016/j.erss.2020.101871

Coy D, Malekpour S, Saeri AK (2022) From little things, big things grow: facilitating community empowerment in the energy transformation. Energy Res Soc Sci 84:102353. https://doi.org/10.1016/j.erss.2021.102353

Daikeler J, Bošnjak M, Lozar Manfreda K (2020) Web versus other survey modes: an updated and extended meta-analysis comparing response rates. J Survey Stat Methodol 8:513–539. https://doi.org/10.1093/jssam/smz008

Dillman DA, Smyth JD, Christian LM (2015) Internet, phone, mail, and mixed-mode surveys: the tailored design method, 4th edn. Wiley, Hoboken

Dóci G, Vasileiadou E, Petersen AC (2015) Exploring the transition potential of renewable energy communities. Futures 66:85–95. https://doi.org/10.1016/j.futures.2015.01.002

Drijver BC, Henssen M, Dinkla I, Gehrels H, van Nieuwkerk E, Grotenhuis J (2010) National research program on the effects of UTES – Use of the subsoil in a sustainable way. In: Proceedings Consoil, Salzburg, Austria

Drijver B, Godschalk B (2018) Important criteria for ATES legislation. EnerSTOCK 2018. In: 14th International Conference on Energy Storage, Adana, Turkey

Fleuchaus P, Godschalk B, Stober I, Blum P (2018) Worldwide application of aquifer thermal energy storage—a review. Renew Sustain Energy Rev 94:861–876. https://doi.org/10.1016/j.rser.2018.06.057

Fleuchaus P, Schüppler S, Godschalk B, Bakema G, Blum P (2020) Performance analysis of aquifer thermal energy storage (ATES). Renew Energy 146:1536–1548. https://doi.org/10.1016/j.renene.2019.07.030

Fleuchaus P, Schüppler S, Stemmle R, Menberg K, Blum P (2021) Aquiferspeicher in deutschland. Grundwasser - Zeitschrift Der Fachsektion Hydrogeol 26:123–134. https://doi.org/10.1007/s00767-021-00478-y

Fouladvand J, Ghorbani A, Mouter N, Herder P (2022) Analysing community-based initiatives for heating and cooling: a systematic and critical review. Energy Res Soc Sci 88:102507. https://doi.org/10.1016/j.erss.2022.102507

Frandell A, Feeney MK, Johnson TP, Welch EW, Michalegko L, Jung H (2021) The effects of electronic alert letters for internet surveys of academic scientists. Scientometrics 126:7167–7181. https://doi.org/10.1007/s11192-021-04029-3

García-Gil A, Goetzl G, Kłonowski MR, Borovic S, Boon DP, Abesser C, Janza M, Herms I, Petitclerc E, Erlström M, Holecek J, Hunter T, Vandeweijer VP, Cernak R, Mejías Moreno M, Epting J (2020) Governance of shallow geothermal energy resources. Energy Policy 138:111283. https://doi.org/10.1016/j.enpol.2020.111283

Ghaebi H, Bahadori MN, Saidi MH (2017) Economic and environmental evaluation of different operation alternatives to aquifer thermal energy storage in Tehran, Iran. Sci Iranica 24:610–623

Griebler C, Avramov M (2015) Groundwater ecosystem services: a review. Freshw Sci 34:355–367. https://doi.org/10.1086/679903

Grubler A, Wilson C (2014) Energy technology innovation: Learning from historical successes and failures. Cambridge University Press, Cambridge

Haehnlein S, Bayer P, Blum P (2010) International legal status of the use of shallow geothermal energy. Renew Sustain Energy Rev 14:2611–2625. https://doi.org/10.1016/j.rser.2010.07.069

Hähnlein S, Blum P, Bayer P (2011) Oberflächennahe geothermie – aktuelle rechtliche situation in Deutschland. Grundwasser 16:69–75. https://doi.org/10.1007/s00767-011-0162-0

Hähnlein S, Bayer P, Ferguson G, Blum P (2013) Sustainability and policy for the thermal use of shallow geothermal energy. Energy Policy 59:914–925. https://doi.org/10.1016/j.enpol.2013.04.040

Hartmann K, Palm J (2023) The role of thermal energy communities in Germany's heating transition. Front Sustain. https://doi.org/10.3389/frsc.2022.1027148

Herreras Martínez S, Harmsen R, Menkveld M, Faaij A, Kramer GJ (2022) Municipalities as key actors in the heat transition to decarbonise buildings: experiences from local planning and implementation in a learning context. Energy Policy 169:113169. https://doi.org/10.1016/j.enpol.2022.113169

IEA (2022) The Future of Heat Pumps, IEA, Paris. https://www.iea.org/reports/the-future-of-heat-pumps

Jagger N, Foxon T, Gouldson A (2013) Skills constraints and the low carbon transition. Climate Policy 13:43–57. https://doi.org/10.1080/14693062.2012.709079

Johansen K, Werner S (2022) Something is sustainable in the state of Denmark: a review of the Danish district heating sector. Renew Sustain Energy Rev 158:112117. https://doi.org/10.1016/j.rser.2022.112117

Karytsas S, Theodoropoulou H (2014) Public awareness and willingness to adopt ground source heat pumps for domestic heating and cooling. Renew Sustain Energy Rev 34:49–57. https://doi.org/10.1016/j.rser.2014.02.008

Kauko H, Pinel D, Graabak I, Wolfgang O (2022) Assessing the potential of seasonal thermal storage for local energy systems: case study for a neighborhood in Norway. Smart Energy 6:100075. https://doi.org/10.1016/j.segy.2022.100075

Koch F, Menberg K, Schweikert S, Spengler C, Hahn HJ, Blum P (2021) Groundwater fauna in an urban area – natural or affected? Hydrol Earth Syst Sci 25:3053–3070. https://doi.org/10.5194/hess-25-3053-2021

Lu H, Tian P, He L (2019) Evaluating the global potential of aquifer thermal energy storage and determining the potential worldwide hotspots driven by socio-economic, geo-hydrologic and climatic conditions. Renew Sustain Energy Rev 112:788–796. https://doi.org/10.1016/j.rser.2019.06.013

McClean A, Pedersen OW (2023) The role of regulation in geothermal energy in the UK. Energy Policy 173:113378. https://doi.org/10.1016/j.enpol.2022.113378

Menberg K, Bayer P, Zosseder K, Rumohr S, Blum P (2013) Subsurface urban heat islands in German cities. Sci Total Environ 442:123–133. https://doi.org/10.1016/j.scitotenv.2012.10.043

Neidig P (2022) Rechtsfragen saisonaler Aquifer-Wärmespeicher: Hemmnisse und Lösungsmöglichkeiten aus Sicht des Berg- und Umweltrechts, 1st edn. BSER Berliner Schriften zum Energierecht, vol 5. Erich Schmidt Verlag GmbH & Co, Berlin

Ni Z, van Gaans P, Smit M, Rijnaarts H, Grotenhuis T (2016) Combination of aquifer thermal energy storage and enhanced bioremediation: resilience of reductive dechlorination to redox changes. Appl Microbiol Biotechnol 100:3767–3780. https://doi.org/10.1007/s00253-015-7241-6

Paiho S, Hoang H, Hukkalainen M (2017) Energy and emission analyses of solar assisted local energy solutions with seasonal heat storage in a Finnish case district. Renew Energy 107:147–155. https://doi.org/10.1016/j.renene.2017.02.003

Peñaloza D, Mata É, Fransson N, Fridén H, Samperio Á, Quijano A, Cuneo A (2022) Social and market acceptance of photovoltaic panels and heat pumps in Europe: a literature review and survey. Renew Sustain Energy Rev 155:111867. https://doi.org/10.1016/j.rser.2021.111867

Perego R, Dalla Santa G, Galgaro A, Pera S (2022) Intensive thermal exploitation from closed and open shallow geothermal systems at urban scale: unmanaged conflicts and potential synergies. Geothermics 103:102417. https://doi.org/10.1016/j.geothermics.2022.102417

Possemiers M, Huysmans M, Batelaan O (2014) Influence of aquifer thermal energy storage on groundwater quality: a review illustrated by seven case studies from Belgium. J Hydrol Regional Stud 2:20–34. https://doi.org/10.1016/j.ejrh.2014.08.001

Ramos-Escudero A, Bloemendal M (2022) Assessment of potential for aquifer thermal energy storage systems for Spain. Sust Cities Soc. https://doi.org/10.1016/j.scs.2022.103849

Regnier G, Salinas P, Jackson MD (2023) Predicting the risk of saltwater contamination of freshwater aquifers during aquifer thermal energy storage. Hydrogeol J 31:1067–1082. https://doi.org/10.1007/s10040-023-02630-9

Saidur R, Islam MR, Rahim NA, Solangi KH (2010) A review on global wind energy policy. Renew Sustain Energy Rev 14:1744–1762. https://doi.org/10.1016/j.rser.2010.03.007

Schmidt T, Pauschinger T, Sørensen PA, Snijders A, Djebbar R, Boulter R, Thornton J (2018) Design aspects for large-scale pit and aquifer thermal energy storage for district heating and cooling. Energy Procedia 149:585–594. https://doi.org/10.1016/j.egypro.2018.08.223

Schüppler S, Fleuchaus P, Blum P (2019) Techno-economic and environmental analysis of an aquifer thermal energy storage (ATES) in Germany. Geotherm Energy 7:669. https://doi.org/10.1186/s40517-019-0127-6

Seetharaman A, Sandanaraj LL, Moorthy MK, Saravanan AS (2016) Enterprise framework for renewable energy. Renew Sustain Energy Rev 54:1368–1381. https://doi.org/10.1016/j.rser.2015.10.127

Sillak S (2023) All talk, and (no) action? Collaborative implementation of the renewable energy transition in two frontrunner municipalities in Denmark. Energ Strat Rev 45:101051. https://doi.org/10.1016/j.esr.2023.101051

Sommer W, Valstar J, Leusbrock I, Grotenhuis T, Rijnaarts H (2015) Optimization and spatial pattern of large-scale aquifer thermal energy storage. Appl Energy 137:322–337. https://doi.org/10.1016/j.apenergy.2014.10.019

Somogyi V, Sebestyén V, Nagy G (2017) Scientific achievements and regulation of shallow geothermal systems in six European countries—a review. Renew Sustain Energy Rev 68:934–952. https://doi.org/10.1016/j.rser.2016.02.014

Sperling K, Hvelplund F, Mathiesen BV (2011) Centralisation and decentralisation in strategic municipal energy planning in Denmark. Energy Policy 39:1338–1351. https://doi.org/10.1016/j.enpol.2010.12.006

Stemmle R, Blum P, Schüppler S, Fleuchaus P, Limoges M, Bayer P, Menberg K (2021) Environmental impacts of aquifer thermal energy storage (ATES). Renew Sustain Energy Rev 151:111560. https://doi.org/10.1016/j.rser.2021.111560

Stemmle R, Hammer V, Blum P, Menberg K (2022) Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany. Geotherm Energy. https://doi.org/10.1186/s40517-022-00234-2

Timilsina GR, Kurdgelashvili L, Narbel PA (2012) Solar energy: markets, economics and policies. Renew Sustain Energy Rev 16:449–465. https://doi.org/10.1016/j.rser.2011.08.009

Todorov O, Alanne K, Virtanen M, Kosonen R (2020) A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: a case study in Finland. Sustain Cities Soc 53:101977. https://doi.org/10.1016/j.scs.2019.101977

Tsagarakis KP, Efthymiou L, Michopoulos A, Mavragani A, Anđelković AS, Antolini F, Bacic M, Bajare D, Baralis M, Bogusz W, Burlon S, Figueira J, Genç MS, Javed S, Jurelionis A, Koca K, Ryżyński G, Urchueguia JF, Žlender B (2020) A review of the legal framework in shallow geothermal energy in selected European countries: need for guidelines. Renew Energy 147:2556–2571. https://doi.org/10.1016/j.renene.2018.10.007

Vanhoudt D, Desmedt J, van Bael J, Robeyn N, Hoes H (2011) An aquifer thermal storage system in a Belgian hospital: long-term experimental evaluation of energy and cost savings. Energy Build 43:3657–3665. https://doi.org/10.1016/j.enbuild.2011.09.040

Vringer K, de Vries R, Visser H (2021) Measuring governing capacity for the energy transition of Dutch municipalities. Energy Policy 149:112002. https://doi.org/10.1016/j.enpol.2020.112002

Werner S (2017) International review of district heating and cooling. Energy 137:617–631. https://doi.org/10.1016/j.energy.2017.04.045

Wüstenhagen R, Wolsink M, Bürer MJ (2007) Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy 35:2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001

Zekira Y, Chitchyan R (2019) Exploring Future Skills Shortage in the Transition to Localised and Low-Carbon Energy Systems. In: Paper presented at 6th International Conference on ICT for Suistainability, ICT4S, Lappeenranta, Finland

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Authors and Affiliations

Ruben Stemmle[1] · Richard Hanna[2] · Kathrin Menberg[1] · Poul Alberg Østergaard[3] · Matthew Jackson[4] · Iain Staffell[2] · Philipp Blum[1]

✉ Ruben Stemmle
ruben.stemmle@kit.edu

[1] Institute of Applied Geosciences (AGW), Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

[2] Centre for Environmental Policy, Imperial College London, London SW7 1NE, UK

[3] Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

[4] Department of Earth Science and Engineering, Imperial College London, Prince Consort Road, London SW7 2BP, UK