Assessment of potential for Aquifer Thermal Energy Storage Systems for Spain

Ramos-Escudero, A.; Bloemendal, M.

DOI
10.1016/j.scs.2022.103849

Publication date
2022

Document Version
Final published version

Published in
Sustainable Cities and Society

Citation (APA)
Ramos-Escudero, A., & Bloemendal, M. (2022). Assessment of potential for Aquifer Thermal Energy Storage Systems for Spain. *Sustainable Cities and Society*, *81*, Article 103849. https://doi.org/10.1016/j.scs.2022.103849

Sustainable Cities and Society 81 (2022) 103849

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Assessment of potential for Aquifer Thermal Energy Storage Systems for Spain

A. Ramos-Escudero [a,*], M. Bloemendal [b,c]

[a] Department of Electronics, Computer Architecture and Projects Engineering, Universidad Politécnica de Cartagena Spain, C/ Doctor Fleming, s/n 30201 Cartagena, Spain

[b] Department of water management, Delft University of Technology, Mekelweg 5, 2628 CD, Delft, The Netherlands

[c] KWR, Watercycle Research Institute, Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands

ARTICLE INFO

Keywords:
Aquifer Thermal Energy Storage systems
potential
Geographical Information Systems

ABSTRACT

Aquifer Thermal Energy Storage (ATES) Systems is a technology to sustainably and economically provide space heating and cooling. However, it cannot be applied everywhere because successful application depends on the presence of a suitable aquifer and favorable climatic conditions. Despite some operational ATES systems, the Spanish ATES market is immature, and there are no regulations or guidelines developed. To foster ATES adoption in Spain, this paper introduces a potential study considering the resource potential, technical, economic, and environmental aspects. The GIS-based approach is focused on the geographical identification and assessment of the aquifer potential for ATES and climatic conditions. This allows to distinguish those areas considered more suitable for ATES systems for the residential and for the tertiary sector. The results show where in Spain potential for energy and GHG savings with ATES can be found. 38% of the aquifers in Spain show potential for ATES and 63% of large urban areas in Spain are located in such areas. Also, 50% of the population lives in areas where the residential sector seems to be suitable for ATES based on the climatic conditions. Energy and GHG savings can reach up to 91% and 68% respectively, derived from the use of ATES.

1. Introduction

Aquifer Thermal Energy Storage (ATES) is a reliable low-carbon technology for space heating and cooling of buildings. Their energy and environmental benefits are proven in various studies and applications (Bloemendal and Hartog, 2018, Schüppler et al., 2019, Todorov et al., 2020). However, ATES is not a global widespread technology (Schüppler et al., 2019, Todorov et al., 2020, Surface and Energy, 2018). Information from 2009 (Bakema, 2020) and 2018 (Fleuchaus et al., 2018) revealed that approximately 85% of the ATES systems in the world are located in The Netherlands, and 10% are in Sweden, Denmark, and Belgium. However, there is an increased interest in ATES in countries such as Great Britain, Germany, Japan, Turkey, and China. Among low ATES adoption countries with technical potential for ATES, often the non-technical barriers prevent application of this technology (Pellegrini et al., 2019). Same as what happens to other emerging energy technologies, lack of knowledge and awareness among energy decision makers and general public limits adoption. In this context, better decisions can be made through better mapping (Calvert et al., 2013). To this end, a rough spatial worldwide ATES potential GIS-based assessment was done by (Bloemendal et al., 2015) and (Lu et al., 2019). They showed that within the Spanish territory areas exists with very high to very poor potential for ATES. This variability of potential is caused by the widespread in climatic and geologic conditions. In spite of this variation still many medium and large Spanish cities are situated on top of aquifers (Barcelona, Seville, Valencia, Zaragoza, Valladolid, Palma de Mallorca, Tarragona, Malaga, Almería, Oviedo, Burgos, Murcia, and Córdoba among others), cities that combined represent a considerable share of the Spanish population and industry. Many of these aquifers are fundamentally detrital, with good permeability, where the water is located a few meters deep and is easily and economically accessible through traditional drilling techniques. The potential of the Spain's aquifers for the geothermal use of its groundwater is large and should be utilized for decarburization of heating and cooling for buildings (IGME)

Abbreviations: ASHP, Air Source Heat Pump; ATES, Aquifer Thermal Energy Store; COP, Coefficient of Performance; DEM, Digital Elevation Model; GHG, Greenhouse Gas; GIS, Geographical Information System; GSHP, Ground Source Heat Pump; HP, Heat Pump.

* Corresponding author at: Universidad Politécnica de Cartagena: Universidad Politecnica de Cartagena, Calle Dr Fleming s/n, 30201 Cartagena, Murcia, Spain.
E-mail address: adela.ramos@edu.upct.es (A. Ramos-Escudero).

https://doi.org/10.1016/j.scs.2022.103849
Received 25 November 2021; Received in revised form 21 February 2022; Accepted 16 March 2022
Available online 18 March 2022

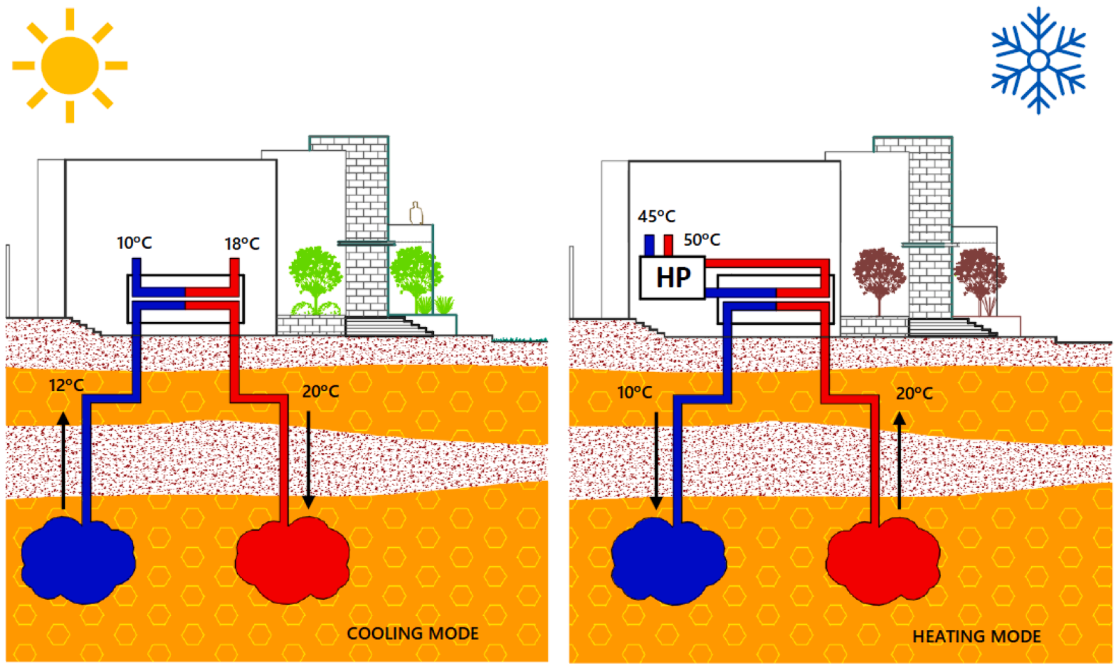

Fig. 1. ATES system operation example in cooling mode (left) and in heating mode (right). Source: (Ruiz Delgado et al., 2010).

Geological Survey of Spain 1997.

However, in Spain, the number of operational ATES systems are unknown as there is no official record for such systems. The total capacity installed is estimated to be around 120 MW_{th} ((IGME) Geological Survey of Spain 1977). In Zaragoza, though, up to 65 geothermal systems using groundwater are identified (2013), and it is the only city in Spain that counts with a regulatory system developed for ATES. Current practice in Spain already shows the potential of the development of heat pumps for ATES systems. For example, the exploitation that is currently carried out in highly productive aquifers, located on the alluvial of rivers such as the Guadalquivir and Ebro or, even other detrital formations, such as the Delta of the Llobregat river and the coastal plain of Valencia, where more and more high-power systems with heat pumps are being implemented.

In this study, a detailed insight into ATES potential and factors affecting potential are identified, assessed, and described. The two most important indicators defining the site-specific suitability for ATES systems are climatic and hydrogeological conditions. Climate determines, to a large extent, the associated heating and cooling demand of a building. To successfully apply the ATES systems, the annual heating and cooling needs to be more or less balanced so that the heat extraction during winter is similar to the heating storage during the summer (Lu et al., 2019). On the other hand, the hydrogeological conditions of the aquifer determine whether the aquifer has the accurate properties to be exploited for ATES. The presence of both a permeable aquifer and sufficient thickness is a basic precondition for aquifer characteristics. Other hydrogeological parameters provide information about the cost-effectiveness of the exploitation of the aquifer by the ATES systems.

To evaluate if the use of ATES systems in Spain can or should be increased, this work aims to improve awareness, assess technical and financial feasibility and identify the positive environmental effects for ATES in Spain. To this end, suitable ATES adoption sites are identified via spatial analysis for which methods are developed to allow for detailed level of potential assessment. To assess technical and financial feasibility, case study sites are carried out in two different places accounting for different use, climatic and subsurface characteristics.

The novelty of this work is threefold:

- firstly, a method is developed to identify and evaluate thickness, permeability of aquifers to be exploited by ATES, which are then geographically referenced in Spain. This allows for the identification of the cities in Spain that could benefit from ATES technology.
- Secondly, site-specific geohydrological characteristics are selected and observed that allow start identifying the level of feasibility of the exploitation of these aquifers with ATES systems in Spain, and the technical, economic, and environmental conditions.
- And finally, a detailed design for a business case and emission reduction is carried out, which afterward itś extrapolated and translated into the potential contribution of ATES to the Spanish energy transition.

ATES systems working principle

Aquifer Thermal Energy Storage (ATES) systems offer the possibility of storing cold and heat in an aquifer. The development of the technology began in the 1980s with the aim of storing solar energy and waste heat at high temperatures (Fleuchaus et al., 2018). The flow direction between the wells of an ATES system is changed to either store or extract heat from the aquifer. The temperature difference (ΔT) between the cold well and the warm well, together with the flow rate (Q) of the well, determine the thermal capacity of the ATES system.

During the heating mode, water is pumped from the warm well to the cold well (see Fig. 1 right). ATES provides, together with a Heat Pump (HP), the base heating demand. The peak demand can be provided too by the ATES and HP although is also often provided by a gas boiler. In the cooling mode, the groundwater is pumped from the cold well to the warm well. In the example of Fig. 1, at the left side, a cold well increases, from 10 to 12°C is observed. While the cold well temperature is lower than the return temperature (18°C), the system is able to provide free cooling using only the heat exchanger. An ATES system provides in part or completely the cooling demand. To cover any peaks in the cooling needs, the use of a compression chiller or the use of the heat pump as a chiller is common.

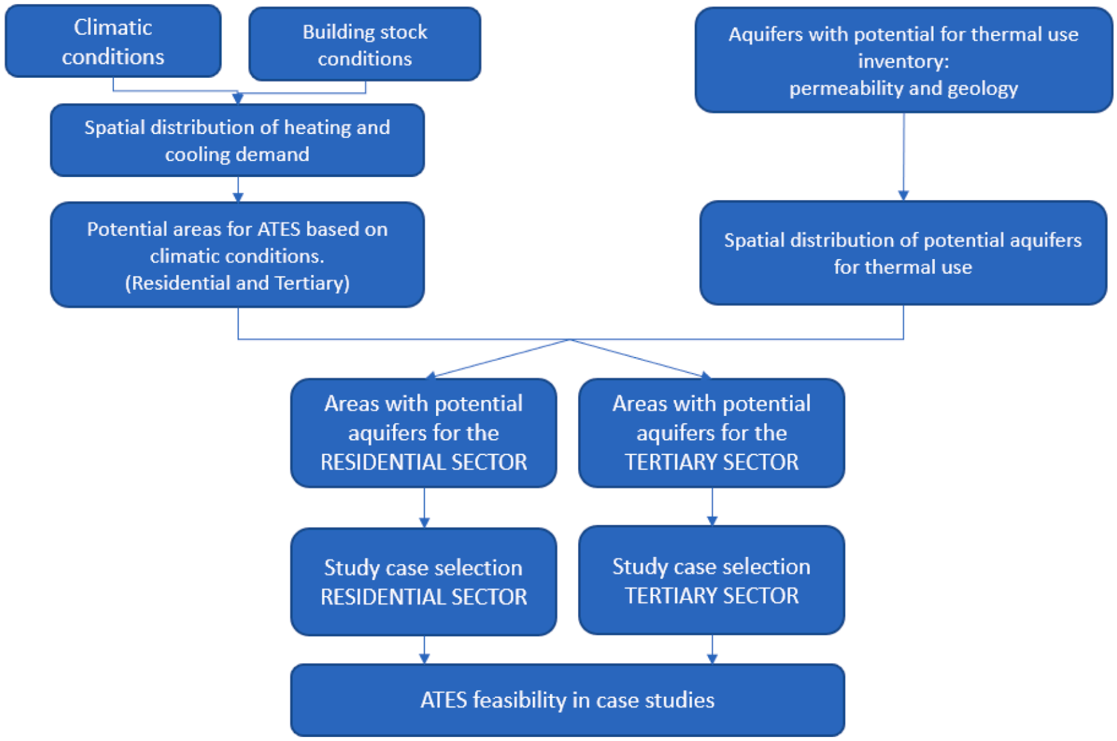

Fig. 2. Approach to determine the ATES feasibility.

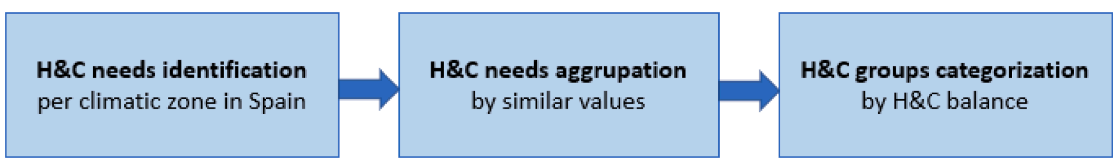

Fig. 3. H&C spatial distribution analysis steps.

2. Methodology

2.1. General approach

This study explores the feasibility of the ATES systems in the Spanish territory Fig. 2. shows the top-down methodology followed along this work. To this end, at first, a GIS-based exploration to determine those areas with favorable characteristics for ATES systems is done. This exploration consists of an initial analysis of the spatial distribution of the heating and cooling needs of buildings on the one hand and the spatial distribution of the suitable hydrogeological conditions on the other. The energy demand is based on the different climatic areas and the building stock characteristics, which allows for the identification of areas with a more or less balanced heating and cooling demand. The aquifers with hydrogeological characteristics suitable for thermal use that, in principle, could be also suitable for ATES are also mapped via a GIS-based approach. Next, two study cases are selected within the suitable areas for which ATES systems feasibility is assessed to also address technical and financial aspects of ATES suitability in Spain. Finally, the information from the exploration and the results obtained are analyzed and translated into the ATES suitability and potential in Spain.

2.2. Spatial analysis using GIS

2.2.1. Heating and cooling demand

During operation of an ATES system in winter, cooling capacity for next summer is stored, and during cooling in summer, heating capacity for next winter is stored. Hence, to sustainably exploit ATES systems, seasonal energy storage and recovery must more or less balance (Bloemendal and Hartog, 2018). Therefore, disproportionally warm or cold areas must be avoided as respectively cold or warm wells cannot be charged sufficiently to meet demand for the next season (Bloemendal and Hartog, 2018). In some European countries, such as The Netherlands, this balance is regulated so that the ratio H/C (Heating and Cooling) must be lower than 15% in the first 5 years and lower than 10% in 10 years (Hendriks, 2010). In Spain, however, there is no specific regulation that tackles this aspect and thus the allowed range can be broader. That means that thermal imbalance is likely to occur.

To be able to spatially localize these areas, a climatic characterization of Spain and the energy demand associated with the residential and tertiary building sectors is carried out (see Fig. 3).

The energy needs required for human comfort in a specific building is a function of the outdoor climatic conditions, the use of the building and the specific architectural characteristics of the building (De Carli et al., 2018). Outdoor climatic conditions can be estimated at a large scale based on the climatic zones[1] and the specific energy needs that are usually associated with the different climatic zones (Tsikaloudaki et al., 2012). This can be done by setting a reference building with a certain energy behavior so that all the buildings in the same area are supposed to behave energetically in the same way. In the present study, this

[1] A climate zone is a world area or region distinguished from a neighbor by a major physical climatic characteristic that is a global scale.

Table 1
Heating and cooling balance score.

Score	H/C	Description
1	0.5<H/C<2	Energy needs balanced. Prevailing mode can be either heating or cooling and the other energy need typology is up to 2 times higher than the other.
2	0.1<H/C<0.5 and 2<H/C<9	Heating between 3 to 6 times higher than cooling, or cooling 3 to 6 times higher than heating.
3	0.1>H/C and H/C>9	High heating needs and no cooling needs, or only cooling needs, no heating.

approach was conducted to obtain insight into the energy needs for the building sector in Spain, both for residential and tertiary buildings. To estimate the energy demands, difference has to be made between building sector uses, such as residential and office buildings, due to the resulting differences in thermal loads (IDAE 2005). For the residential sector, energy needs can be identified for every climatic zone based on existing literature. Later, energy needs were compared (heating vs cooling), allowing to spatially determine those areas with balanced and unbalanced energy needs. According to the balance level, they were categorized by comparing the heating and cooling needs and the increment of the minority mode to the majority. According to this increment, a score from 1 to 3 was assigned for every climate zone (see Table 1) proposing suitable areas that gradually fulfil the favorable requirements for ATES.

The suitability score was spatially assigned to the climatic zones in the study area. As a result, a map with the suitability for ATES based on the climatic conditions for the residential sector was created. Score-1 areas were finally selected and considered for the following step in the final selection of the study sites to develop a detailed feasibility study of the ATES systems.

For tertiary buildings, however, the lack of data per climatic zone called the use of another approach. This time, the most common tertiary building and thus, the representative building typology consumming a large amount of thermal energy, was identified. Later, average thermal energy for heating and cooling purposes was estimated based on statistics and present literature. As a main result, the spatial identification of great energy consumers in the tertiary sector buildings and their energy demands associated was obtained.

Although in Spain it is not yet binding, in the near future geothermal systems will be only applicable to those high energy efficiency buildings (Catalonia, 2010). In Spain, only after the approval of the building technical code in 2007 (de Fomento, 2017) was the energy consumption of the building stock limited. This ensured that the buildings constructed from then on were more energy efficient. Therefore, in this study, only building stock constructed from 2008 is considered.

2.2.2. Hydrogeological conditions

The amount of thermal energy that can be recovered for the ATES system defines the suitability of the aquifer for this purpose, and it depends on the hydrogeological conditions and the store volume in the subsurface (Sommer, 2015). Therefore, assessing the hydrogeological conditions of the aquifer where ATES will operate is paramount to determining its suitability. The transmissivity measures the quantity of water that the aquifer can transmit horizontally. For ATES, this parameter is also commonly used to determine the water that an aquifer can supply to the well, which eventually will determine the capacity of the aquifer. Transmissivity is the product of hydraulic conductivity and reservoir thickness. At the same time, hydraulic conductivity behavior derives from the permeability of the rock, and thus, they are to a high extent connected. Both of these two parameters can be then used to proceed with the basic evaluation of the suitability of the aquifer at a large scale.

In addition, specific hydrogeologic parameters are considered for the aquifers that determine the efficient operation and the design of an ATES system (Bloemendal et al., 2015).

The following parameters are used to assess if there is potential for ATES:

- Aquifer composition. Complex hydrogeological aquifers are not desired. Indeed, any heterogeneity, fractures or fissures in the aquifer affect the thermal efficiency of the system. On the one hand, they may cause lateral thermal losses due to localized flow paths. On the other, tilted aquifers are likely to be caused by fractured geology, and they present high groundwater flow with the undesired conditions mentioned.
- Depth. Although it does not affect the thermal energy, going to deep aquifers eventually results in higher drilling costs. Optimal length is then a commutation between system costs, water quality expected, and the system efficiency.

The following parameters are used to make a preliminary design for the ATES case studies:

- Water quality. It determines the life expectancy of the ATES systems and the maintenance of the system. Mixing different water with different qualities is likely to cause the well filter clogging. Shallow aquifers in urban areas (< 50 meters depth) are usually affected by this fact.
- Water freshness. Although ATES can be applied both in saline and fresh water, the latter option results in being cheaper as no salinity-resistance equipment is needed. Therefore, this is the preferable option, although they must compete with drinking water uses. Coastal urban areas possess saline aquifers with no use for drinking, and thus, in principle it can be considered an option. However, it usually is not allowed to prevent salinization of the freshwater aquifers.
- Groundwater flow. High groundwater flow may provoke a loss of efficiency in the system due to the thermal energy loss for advection, which has a large thermal plume affection. Besides, this affects to a larger extend to small system. Thus, high groundwater velocity aquifers are not desired.

2.2.3. Combined ATES potential

Based on the information outlined in 0, potential areas for ATES systems maps following the climatic conditions are elaborated both for the residential and the tertiary sector. Among the areas with the lowest score for climatic suitability, a selection process of the aquifers suitable for ATES, including those suitable for thermal use, is carried out following the conditions explained in 0. The process is performed in GIS so that the information must be previously converted into a shapefile GIS layer. The GIS software used in this work is the open access QGIS (QGIS 2019). From the "vector" tool package, the geoprocessing tools were used in the creation of the maps so that areas that did not fulfil the established requirements for every case were dismissed. It allowed for a rough assessment of the suitable aquifers for residential and tertiary sector separately. This information served as the basis for the selection of the study cases.

2.3. Selection of the case studies

In order to evaluate the suitability of certain technology, not only the resource availability must be assessed but also the technical and economic aspects (Lu et al., 2018). In this study, a feasibility assessment of the ATES systems is proposed in two selected cases. They must be selected among the previous potential areas identified. One study case must be selected among the areas with potential aquifers for the residential sector and the other for the tertiary sector. For every case and among the suitable areas, one aquifer must be selected based on the site-specific conditions. Here, groundwater flow and proximity to urban areas is assessed and is determined to the final selection of the areas. High underground water flow areas are avoided and proximity to urban areas is desired as they are considered energy consumption hotspots (Li, 2018). Groundwater flow assessment is based on the local Digital Elevation Model (DEM) of every aquifer, and proximity to urban areas is identified by analyzing the aquifers' location and the urban area's location in GIS.

2.4. ATES feasibility of case sites

2.4.1. ATES System dimensioning

ATES potential assessment requires a detailed design evaluation of ATES systems, as this is imperative to evaluate the technical, economic and environmental benefits (Bloemendal and Hartog, 2018). The ATES systemś efficiency depends mainly on the thermal recovery efficiency and is affected by site-specific storage and hydrological estate. When designing the ATES wells, the first parameter to be considered is the pumping capacity, which is related to the amount of thermal energy power (heating and cooling) they should deliver to the building, that is the flow rate the well must be able to produce.

The capacity of the heat pump must be sized in accordance with the heating loads (Bloemendal and Hartog, 2018). In general, ATES systems follow a seasonal pattern with heating mode in the winter and cooling mode in the summer. However, energy demands may vary in the same day and this trend can be disrupted for a specific system, so that heating is needed in the morning and cooling in the afternoon. Nonetheless, this short variation have been proven not to influence the overall thermal impact and thermal efficiency of the system (Sommer et al., 2015). In this study, the required capacity was calculated based on the specific heating and cooling needs (W/m^2) which were estimated by using an energy modelling software (University of valencia 2020) (details in 0.). Next, the capacity from well can be calculated assuming the work principle of the heat pump that can be expressed as follows:

$$Heat_{delivered} = electricity_{use} + Heat_{from\ ATES} \tag{1}$$

$$Electricity_{use} = \frac{Heat_{delivered}}{COP} \tag{2}$$

Where COP is the coefficient of performance of the heat pump, $Heat_{delivered}$ is the heat delivered from the system to the building, and the $electricity_{used}$ is the electricity needed by the pump to finally provide the heat delivered. Substituting electricity use from (2) in (1), the heat delivered by the ATES can be obtained. The heat delivered by the ATES must be calculated separately for heating and for cooling as the system operates differently in each mode. Cooling can be provided without using the heat pump, which is where one of the greatest advantages of these systems lies. Indeed, the temperature difference between the cold well and the building temperature makes it possible to cool the building without using the heat pump (Sommer et al., 2015) which translates to a great amount of energy saved. Therefore, to calculate the energy demand required from the wells to provide the cooling needs, no calculations are needed as there is no other facility involved. The energy demand that the system must produce for heating can be calculated by applying (1). In Spain, heat pumps connected to ATES operate with a COP between 3 and 5.5 (IDAE-Institute for Energy Diversification and Saving 2019). However, ATES systems providing cooling are able to operate with COP between 20 to 40 in the cooling mode since the circulating pump is the only electricity consumer device (Ruiz Delgado et al., 2010).

Well flow rate (Q_{ATES}, m^3/h) can be calculated applying (3) and output the amount of water needed per unit time by the ATES to provide the energy demanded.

$$Q_{ATES} = \frac{P}{C_w \cdot (T_{out} - T_{in})} \tag{3}$$

Where P_{th} is the heating/cooling capacity (power/flux (J/s)) of the ATES system, C_w is the volumetric heat capacity of water (4.2 MJ/m^{3}K), and $T_{out} - T_{in}$ are the extraction and infiltration water temperature, representing the average temperature difference between the warm and the cold well. These temperatures must be assessed based on the specific working temperatures of the building in heating and cooling mode and the thermal increase generated by the HP. Considering that as average, it is able to produce 5°C (Zhu et al., 2011). The temperature of the reinjected water must be in the range of 5°C to 25° to not cause negative effects on the subsurface and groundwater (Li, 2014).

Next, the distance between the well is important to be identified. This depends on the storage volume that the ATES needs to provide the required heating and cooling demand. The storage volume (m^3) of pumped groundwater can be calculated as follows, where E_{th} is the energy (heat (J)) required by the system.

$$V_{ATES} = \frac{E_{th}}{C_w \cdot (T_{out} - T_{in})} \tag{4}$$

Besides, the distance that the wells must be separated to no interfere with one another is a function of the thermal radius (R_{th}), and it can be calculated as follows:

$$R_{th} = \sqrt{\frac{C_w \cdot V_{ATES}}{C_{aq} \cdot \pi \cdot L}} \tag{5}$$

Where C_w is the volumetric heat capacity of the aquifer (about 2.8 MJ/m^{3}K) and L is the length of the well screen in meters.

In the ATES system, thermal losses in the aquifer can be diminished by reducing the surface area of the circumference and the top and bottom of the thermal cylinder (A) of the volume of the underground heat storage (V). To this end, an appropriate screen length must be identified based on the required storage volume needed and local conditions:

$$\frac{A}{V} = \frac{2}{L} + \frac{2}{R_{th}} \tag{7}$$

Optimal screen length can be also estimated based on the relation with the storage volume so that conduction and dispersion losses are minimal at the screen length when $L/R_{th}$is 2. Finally, the required borehole radius for the well (r_w) can be calculated as follows:

$$r_w = \frac{Q}{V_{\max} \cdot L \cdot 2\pi} \tag{8}$$

Where V_{max} (m/h) is the maximum velocity of entrance of the water to the well. This is a critical parameter in the well design as it addresses the possible well mechanical clogging due to the presence of particles (Ruiz Delgado et al., 2010). It can be estimated using the following equation:

$$V_{\max} = \frac{Q}{\pi \cdot d \cdot L} \tag{9}$$

d is the required borehole radius, usually varying from 0.3 to 1 meters (Ruiz Delgado et al., 2010).

Dimensioning of the ATES systems was conducted by applying this formula with the input data from the study cases selected.

2.4.2. Economic feasibility

The economic study consists of assessing the cost of the ATES installation and comparing it with other possible alternative solutions. Total cost is calculated based on the capital costs and the operational costs of the system. The ATES systemś capital costs have a strong variability as parameters used are not site-specific (Schüppler et al., 2019). According to (KWA 2018), capital costs can be estimated based on the maximum capacity of the system. For small systems (<100 kW), capital costs can be calculated following the equation: €10,000 + €525/kW. For large systems (>100kW), they can be estimated by substituting the capacity of the system in the following approximation: €69,860·ln (kW/6.69)–€109,000.

Operational costs comprise the demand-related costs and the operation-related costs. The demand related costs are the result of the heating and cooling demanded (kWh) multiplied by the cost of the electricity (€/kWh). The operation-related costs are made up by the maintenance costs, and it is estimated to be 4% of the capital costs of the ATES (Schüppler et al., 2019, KWA 2018).

The economic study has been completed by comparing the results with a reference technology. This comparison allowed for the calculation of the Net Present Value (NPV) of the ATES systems by using this equation:

$$NPV = -C_{ATES} + \sum_{t=1}^{T} R_t \cdot q^{-1} \tag{10}$$

Where $-C_{ATES}$ is the capital cost of the system, T is the period studied, and R_t is the difference between the operational costs of the ATES and of the reference technology.

2.4.3. GHG Emission reductions

The environmental analysis is based on the annual CO_2 emission resulting from the system operation and estimate the amount of CO_2 emission savings of the system compared to the reference technology. Both for the ATES system and the reference technology, the CO_2 emission can be calculated by multiplying the annual heating and cooling by the national emission factor. Emissions savings of the ATES with respect to the reference system is also calculated by the difference of their emissions.

2.5. Data used

2.5.1. Hydrogeological data

Permeability information for the selection process of the study sites was extracted from the 1:200.000 Lithostratigraphic map from the Geological Survey of Spain (Geological Survey of Spain (IGME)). This map is the result of crossing the lithology and the permeability information, resulting in 35 groups Originally, lithologies are associated with 7 groups attending to their origin formation (carbonates, quaternary detrital, detrital, volcanic, metadetrital, igneous, and evaporitic) and permeability information is divided into 5 groups (very high, high, medium, low, and very low). Aquifer thickness information, however, was extracted from different reports elaborated mainly by the Spanish Geological Survey and by the correspondent river basin authority (Todorov et al., 2020, IGME 1985, Navarro, 2006, Valle et al., 2007, Contreras et al., 2017) and (CHJ 2018). On the other side, underground water bodies aquifer spatial information of Spain is provided by (E. T. and demographic challenge Ministry) and is openly available online.

2.5.2. Energy data

For the identification of the energy needs associated with every climate zone for new buildings, the subsequent information was used. The energy performance indicators are extracted from the H2020 Tabula and Episcope (Institut Wohnen und Umwelt 2013) projects. These projects' scope is the identification of the energy building performance of the building stock in the EU Member States to be applied in refurbishment processes. The starting point is the Tabula concept of residential building typologies: single-family, terraced house, multifamily, and building block. Later, the project elaborates on a building stock energy model considering the energy behavior of the building stock from 16 countries in the EU. The Building Institute from Valencia (IVE) developed the case for Spain, although only information for Valencia province was available. However, most of the climate zones in Spain can be encountered in this region (7 out 12) (IVE 2015).

2.5.3. Other data

In the study sites selection process, strong groundwater flows aquifers were avoided so that pitch areas were identified. To this end, Digital Model of the Terrain information was extracted from the Spanish National Centre for Geographic Information (Gegraphical National Institute). Urban atlas information was extracted from the European Energy Agency (European Environment Agency (EEA) under the framework of the Copernicus programme 2012) in GIS shapefile format. The urban atlas provides pan-European comparable land use and large cover data for urban zones with more than 100,000 inhabitants in Europe.

2.5.4. Study area

The study area considered in this work is the Spanish territory. It accounts for a surface of 505,990 km^2 and an annual average temperature range from 15 to 18°C. The study area is divided in climate zones according to the location and altitude. Average energy needs for the building stock are associated to these climate zones so that buildings falling in the same zone are supposed to have similar energy needs. Extended information regarding climate zone and energy associated can be seen in (APPENDIX I. Climatic zones in Spain)

In Spain there are a total of 740 water bodies that cover around 70% of the Spanish surface (Goverment of Spain) and are divided into 22 river basin authorities. The available water resource is strictly controlled to secure the minimum water available by the annual mean value of the total recharge rate of the groundwater body to guarantee the minimum ecological water availability. Attending to the geology, four different aquifers typologies are identified in Spain:

- Areas formed by loose or semi-consolidated materials, such as gravel, sand and silt, that line the valley bottoms of the main rivers, such as the Ebro and Guadalquivir, and the deposits of a similar nature that extend through the great plateaus of the Duero and Tagus, and by coastal areas such as the Llobregat or Ebro deltas or the Plains of Castellón or Valencia, among others. They constitute detrital aquifers and are used to supply the populations and industries, especially in irrigated agriculture. They occupy an area of approximately 99,000 km^2.
- Areas with natural rocks carbonated with materials, generally limestone, more or less karstified. They appear in the eastern and southern sectors of the peninsula and the Balearic Islands. These carbonate aquifers occupy an area of 69,000 km^2.
- In the western sector of the peninsula, there are mostly terrains with igneous rocks (granites and related and metamorphic rocks (slates and similar)), materials generically cataloged as impermeable or of very low permeability, but which contain aquifers of local interest. Thousands of springs and wells in those areas that supply small population centers and agricultural and other industries have great importance for them.
- In the Canary Islands, the aquifers are linked to rocks of a volcanic nature. A large part of the water used on the islands is of underground origin. The extension of these aquifers is 7,800 km^2. In the interior of the peninsula there are also volcanic auriferous formations, although less important, in Olot and Campo de Calatrava.

The geothermal energy potential assessment guide of Spain (I. de D. y A. de la E. IDAE. 2011) elaborated an inventory of those aquifers likely to possess potential for thermal uses. The geothermal resource has a temperature range between 30 and 100°C, but they are located in areas with an average geothermal gradient between 25 to 35 °C/Km. The only geologic condition for their existence is to be at an adequate depth of permeable geologic formations (sand, sandstone, conglomerates, dolomites, limestones, etc.) that allow for storage and water circulation. These permeable formations may be constituted by consolidated rocks, fissures and fractures (metamorphic, sedimentary, or igneous). In general, the geologic constitution of the Iberian Peninsula allows for the general existence of permeable deep formations and therefore, for the low temperature geothermal resources. The use of these resources in Spain is focused on the direct heat use for heating and cooling purposes in the residential, agricultural and industrial sectors. Based on their geological location, low temperature resources in Spain are classified in

Table 2
Main characteristics of the aquifers with thermal use potential in Spain.

Origin	Quantity	Temperature (°C)	Flow rate (l/s)
Carbonated	188	10 – 20	20–200
Carbonated and metamorphic	1	16 – 20	–
Detrital	138	9 – 201	1 – 150
Detrital and carbonated	23	7 – 202	13– 50
Detrital and metamorphic	5	8 – 16	8 – 16
Volcanic	1	11 – 13	

In [1] [2] classes, two aquifers have been removed since they present thermal anomalies that do not represent the average temperatures.

two types: geothermal resources located in large sedimentary basements and those located in areas of mountain ranges and internal depressions. This listed information has been spatially identified and displayed in Fig. 5 for this study. In contrast, no existing detailed centralized aquifers dataset information has been available in Spain up to now. Instead, individual reports exist where the specific physical characteristics and measurements of the water bodies are shown. The most relevant for this study have been developed by the different river basin authorities in Spain and the Geological Survey of Spain (IGME). Both lithology and permeability information are meticulously explained in the reports, but aquifer thickness information, however, was not available in all of them. Therefore, study cases selection was subject to the existence of this data.

3. Results spatial analysis

3.1. Geohydro

The most relevant parameters concerning the accessibility and suitability of these aquifers to be exploited are summarized in (Table 2). From them, we can see that the prevailing origin of the aquifers is

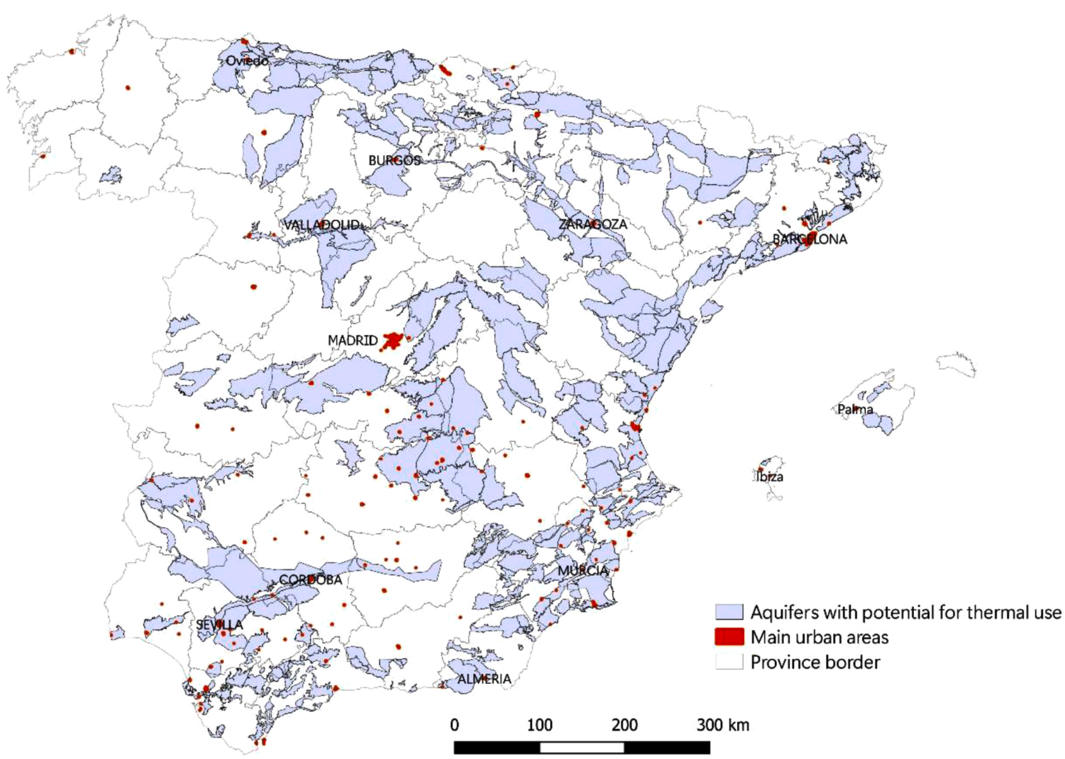

Fig. 4. Aquifers in Spain with potential for thermal use. Own elaboration. Source (I. de D. y A. de la E. IDAE. 2011).

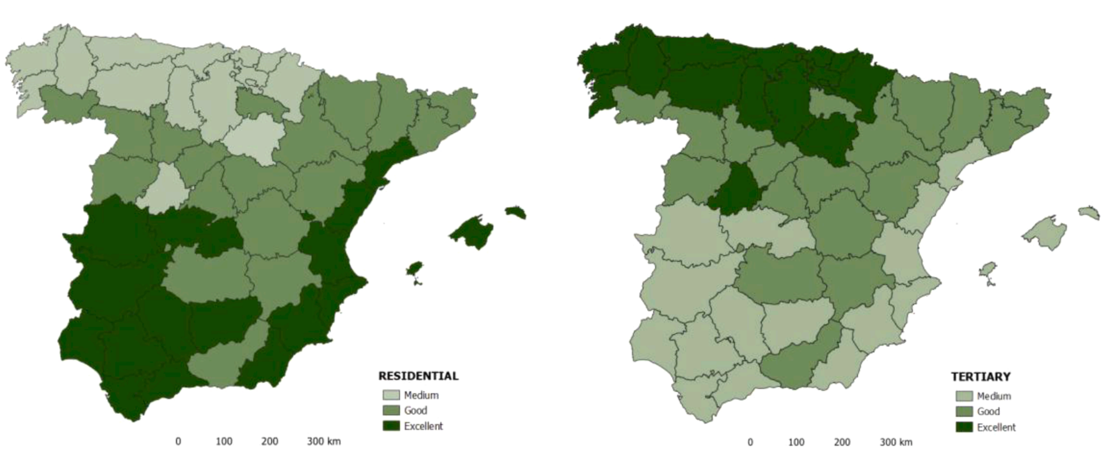

Fig. 5. Suitability of the ATES systems for the Residential (left) and Tertiary (right) based on the climatic conditions in Spain.

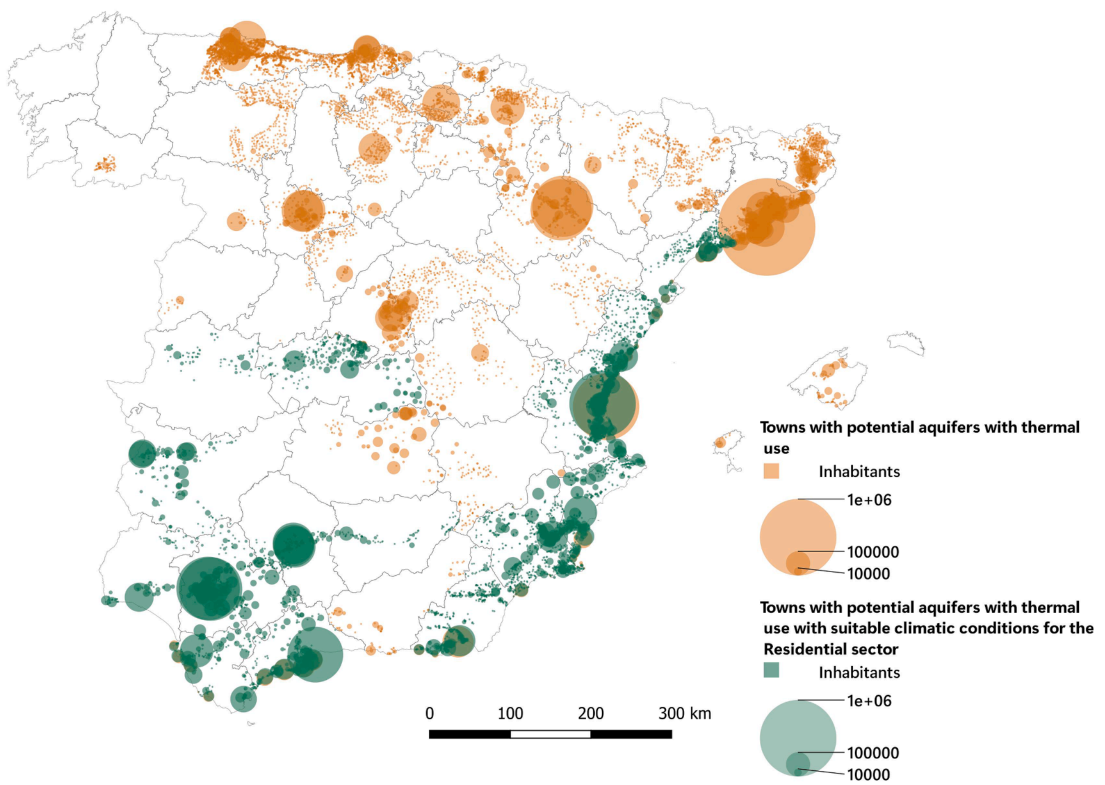

Fig. 6. Overview of the Spanish towns located in areas where the hydrogeological and the climatic conditions may be favorable for the exploitation of ATES (areas colored in green and orange). In green, towns with the most suitable conditions for the residential sector based on the climatic conditions.

carbonated and detrital, with an average temperature ranging from 7 to 20°C, and a flow rate varying from 1 to 200 l/s.

Information displayed in Fig. 4 is spatially analyzed along with other spatially relevant parameters to provide insight over the potential areas' location. From this information, it can be concluded that total groundwater bodies in Spain occupy 360,812 km^2 while those identified to have potential for thermal use account for 137,970 km^2. They represent respectively 38% of the total aquifer surface and 27% of the surface of the Spanish territory (505,990 Km^2). In Fig. 4, urban areas of Spain are also represented. As specified above, they are large urban areas that account for a minimum of 100,000 inhabitants. In Spain, a total of 136 urban areas with these characteristics are identified. After a spatial evaluation with GIS, 75 large urban areas in Spain are identified to be located above potential aquifers, representing 55% of the total large urban areas. In order to evaluate the suitable areas in Spain for ATES systems, further research must be done. Basically, climatic and site-specific hydrogeological conditions are behind it.

All aquifers possess in principle good conditions for thermal use. However, further information must be firstly consulted to finally determine its suitability for ATES applications, e.g., the aquifer thickness, hydraulic conductivity and groundwater flow.

3.2. Climatic

Total primary energy consumption for H&C purposes for the residential sector in Spain is approximately 5,800 GWh, from which 70% is for heating and 30% for cooling, and almost 50% is consumed in the Mediterranean areas (IDAE-Institute for Energy Diversification and Saving 2016). According to the Spanish technical building code (de Fomento, 2017), energy needs are expected to be the same in areas with the same climate zone classification. As explained in 0, average energy needs are associated to every climate zone. However, for this study, only energy needs from buildings constructed in 2008 onwards are considered. Although not yet mandatory in Spain, in the near future geothermal systems will be only applicable to those high energy efficiency buildings (Catalonia, 2010). To characterize the energy needs of only the new building stock, several estimations were made from information gathered that are explained in APPENDIX. Results are shown spatially in Fig. 5.

According to (ERESEE 2020. Update of the long-term Strategy for Energy Rehabilitation in the Building Sector in Spain 2020), the tertiary sector in Spain consumes for H&C purposes 7% of the total primary energy consumption in Spain, from which approximately half is for heating and half for cooling purposes. However, unlike the residential sector, there is no available information regarding the specific H&C energy needs by climatic zones for the tertiary sector. In general, ATES systems have a better feasibility in the tertiary sector because buildings are often large and require both heating and cooling. Offices are great consumers of cooling, and thus, H&C energy are expected to be more balanced for the tertiary in continental and Atlantic climates as cooling is not as high as in the Mediterranean area, with a resulting balanced energy need (see Fig. 5). Therefore, almost any potential aquifer can be considered suitable for the tertiary sector. Nevertheless, as with the residential sector, H&C needs in the tertiary are also influenced by the outdoor temperatures.

Fig. 5 shows that for the residential sector the Mediterranean area is the most suitable for the exploitation of ATES systems in terms of the building stock energy needs, while in the Atlantic area the energy demand conditions are less favorable but still possible. In contrast, areas in Spain where ATES is more appropriate for the tertiary sector follow the opposite pattern than for the residential sector.

For the residential sector, a clear tendency for the Mediterranean areas is observed, including the Balearic Islands, along with South-western areas, covering a great part of the Andalusian provinces, Extremadura and some provinces from Castilla-La Mancha. For the tertiary buildings, areas selection is not as strict as for the residential due to the considerable variety of energy needs within this sector. ATES systems then may entail from small to huge systems that can be sized in

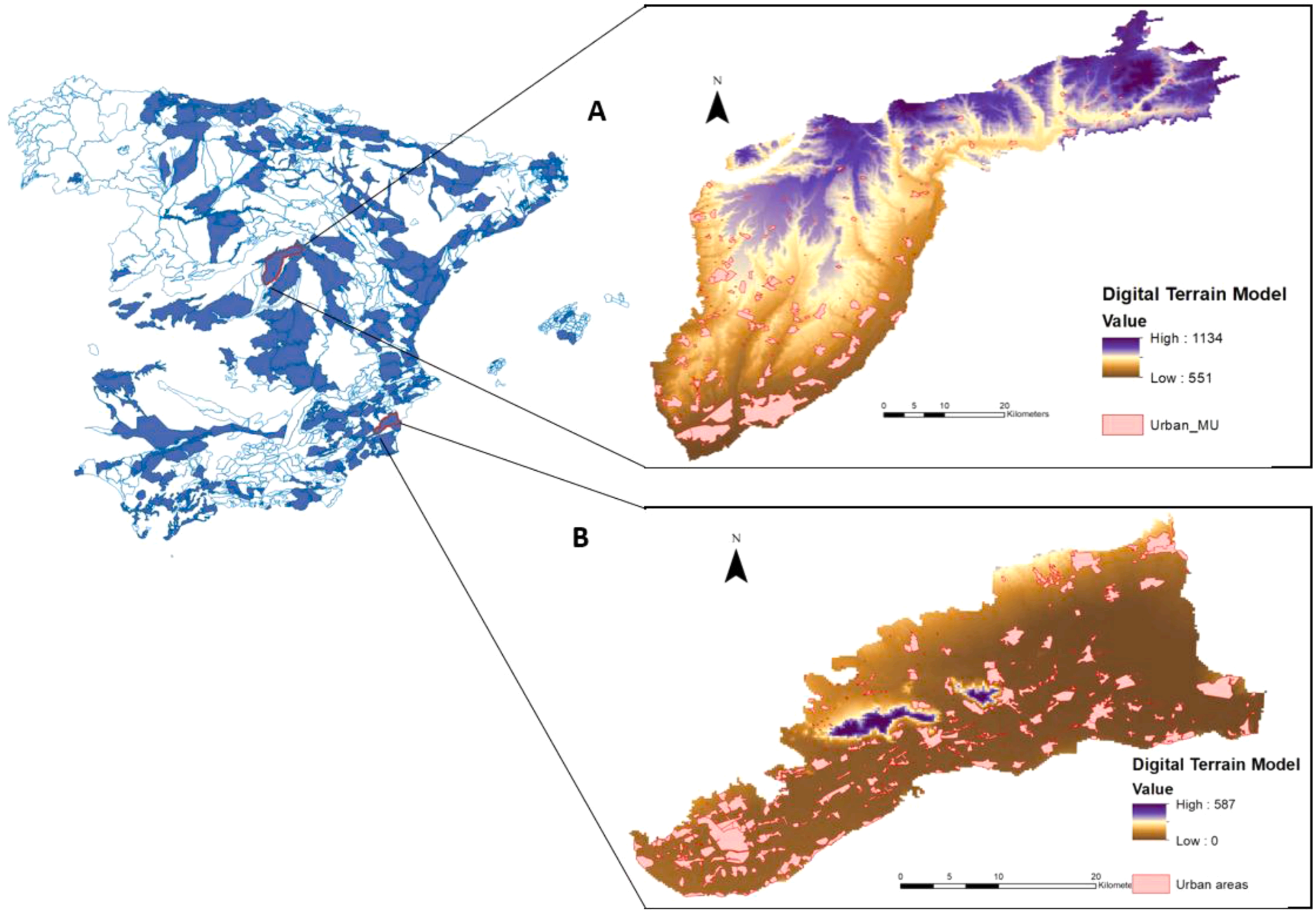

Fig. 7. Aquifer selected to develop the feasibility study of an ATES systems. A) is the "Guadalajara" aquifer located in the northeast part of Madrid and B) is the "Vega Media del Segura" aquifer located under the city of Murcia.

Table 3
Aquifer's characteristics of the main cities selected for residential areas.

City	Aquifer name	Av. Thickness (m)	T (°C)[1]	Deep[1] (m)	Origin[1]
Guadalajara	La Alcarria	110[2]	12 – 15	10 – 50	Detrital
Valencia	Pla de València Norte	200[3]	18 – 22	15 – 100	Detrital
Almería	Medio-bajo Andaráx	20 – 40[4]	15 – 40	20 – 40	Detrital
Murcia	Vega Media del Segura	200[5]	15 – 18	5 – 30	Detrital
Cartagena	Campo de Cartagena	10 – 110[6]	18 – 25	30 – 200	Det.& Carb.
Sevilla Córdoba	Aluvial del Guadalquivir	Unknown	16 – 18	5 – 30	Detrital

1 (Ramos-Escudero, 2011), 2 (Garrido et al., 2015), 3 (Geological Survey of Spain (IGME) 2009), 4 (Geological Survey of Spain (IGME)), 5 (Geological Survey of Spain (IGME) 2020), 6 (Segura River basin Authority 2015)

order to compensate any thermal load deviation.

3.3. Potential areas for ATES based on the hydrogeological conditions and energy needs

By combining both the hydrogeological information and the climatic conditions spatial information from 0 and 0, it is possible to assess the location and extension of the suitable areas for ATES. In the analysis, towns[2] location and their associated population are also considered as a measure of the market demand for heating and cooling. This analysis provides insight over the market potential for ATES systems in Spain based on the expected population where hydrogeological and climatic conditions are suitable and may benefit from ATES adoption.

Aquifers with potential for thermal use occupies 38% of the Spanish territory surface (170,000 km^2 of the total 506,030 km^2 (N. statistics survey of Spain 2021)). Within this area, 26% of the total towns in Spain are located (37,137 of the 143,221 in total (Autonomous body National Center for Geographic Information (CNIG) 2021)) (See Fig. 6, orange and green areas. In this 26%, 53% of the total population is concentrated (25.5 million of the total 47.3 million (National statistics survey of Spain 2021)). Within these areas, factoring in only those located where the climatic conditions are considered the most suitable for the residential sector (see Fig. 6 green areas), 13% of the towns are located here (18, 300), concentrating 28% of the total population (≈13 million inhabitants).

[2] According to (Autonomous body National Center for Geographic Information (CNIG) 2021), town is the geographic area that delimits the built-up or urbanized areas destined for housing and their annexed areas destined for other related uses, and that is unequivocally identified by a name.

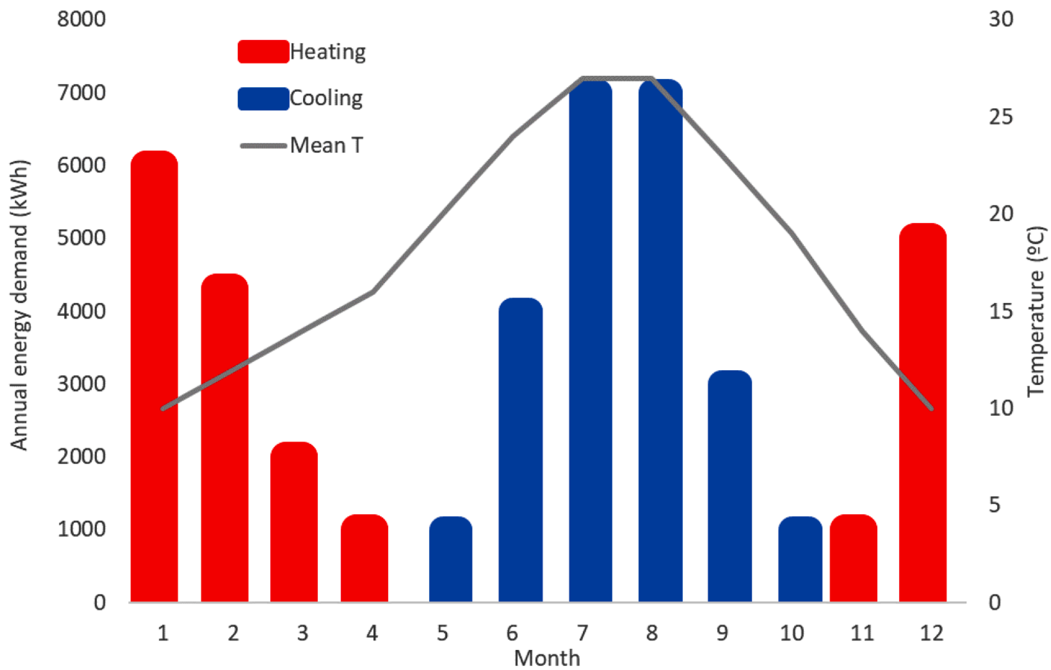

Fig. 8. Annual heating and cooling demand for tertiary.

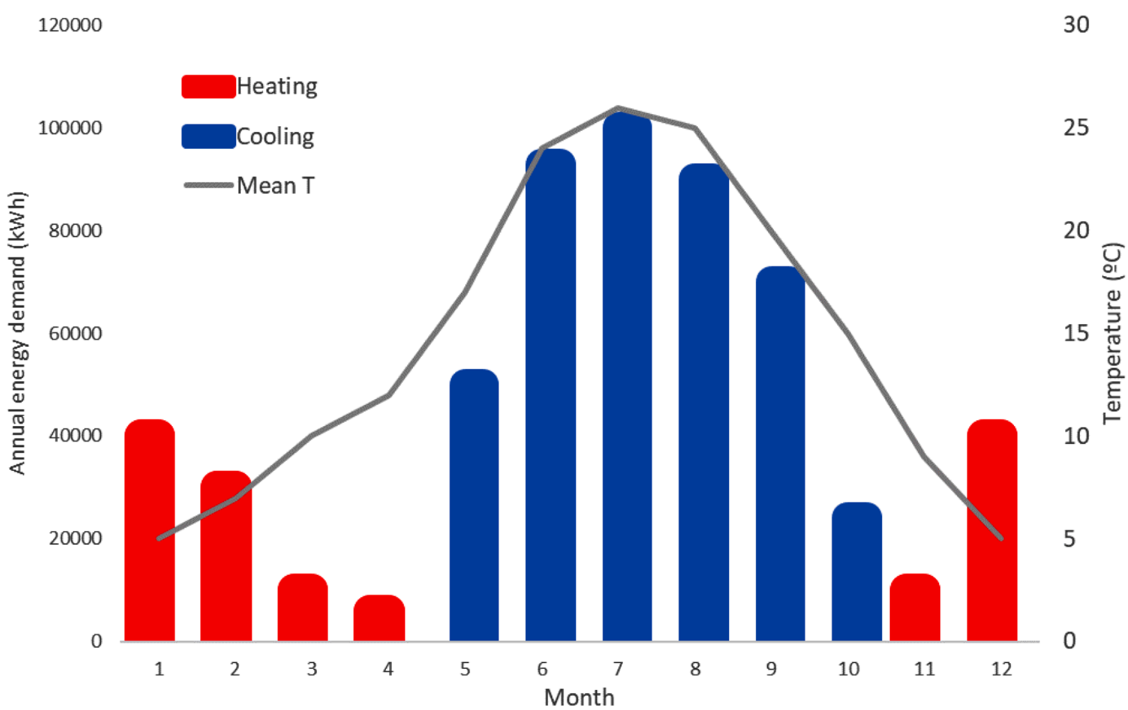

Fig. 9. Annual heating and cooling demand for residential.

4. Results ATES feasibility in the case studies

4.1. Case study site selection

Two different case studies were selected to carry out an ATES feasibility study. The selection process aims at defining a case study in the residential sector and another in the tertiary sector. Within the tertiary activities in Spain, offices buildings possess the highest concentration of surface constructed. Most of these tertiary uses are concentrated in the climatic zone D3, which correspond to the Madrid province and its surroundings. Neither of the two aquifers above the city of Madrid fall within the aquifers with potential for thermal use and were thusly dismissed. However, there are some around the city under important secondary satellite urban areas of Madrid. The "Guadalajara" (see Fig. 7) aquifer is one and is within the potential aquifers inventory for thermal uses. Aquifer thickness is 480 meters, with a temperature range from 12 to 15°C. A digital terrain model indicates that the aquifer area has a height difference of 600 meters (551 to 1,134 m.a.s.l.). However, where main urban areas are located, height difference is almost negligible. All in all, this aquifer was selected as a suitable aquifer for the exploitation of ATES for the tertiary sector.

Within the suitable areas for the residential sector, main cities were

Table 4
Heating and cooling needs of the buildings and installed GSHP capacity.

Parameter	Unit	Tertiary	Residential
Surface	m^2	10,000	2,000
Heating capacity	kW	54	6
Heating energy demand	MWh	140	19.4
Cooling capacity	kW	400	50
Cooling energy demand	MWh	420	20

Table 5
Technical parameters of the aquifer and wells.

Parameter	Unit	Tertiary	Residential
Aquifer transmissivity	m/d	0.21	5
Cold well temperature	°C	9	13
Warm well temperature	°C	16	19
Well flow rate	m^3/h	49.0	7.1
Storage volume	m^3	2,786	50,226
Maximum velocity	m/h	1.56	0.38
Required borehole radius	m	0.25	0.15
Length screen	m	20	20
Thermal radius	m	24.5	7.3

considered (Table 3). In the Mediterranean part, there are Valencia, Cartagena, Murcia and Almería. In the western part, there are Sevilla and Córdoba. In Valencia city's underground area, there are two main aquifers (Plana de Valencia Norte and Plana de Valencia Sur). Negligible slope and 200-meters' thickness make this in principle a good candidate. Cartagena is another Mediterranean coastal city located in Murcia province. In this city, the quaternary main aquifer is considered too thin, with 50-meters' average thickness, becoming even thinner nearby the city and thus was also dismissed. Moving from the coastal to the inner part within Murcia region, there is Murcia city, which is the capital of the province. There is one shallow aquifer accessible at 15 meters (Vega media del Segura aquifer) with up to 180-meters' thickness, medium permeability, and is mainly composed lithologically of gravels. Besides, the city is located in a plain, which also plays in its favor. Within the water temperature of all aquifers, in this city, the temperature range remains quite stable and not very high, compared to the others. Taking all these characteristics into account, this was the aquifer selected to develop the design of the ATES systems in the residential sector. In Fig. 7, this aquifer is represented.

The case to be developed in Guadalajara is the representative office building sector, and the Vega Media del Segura aquifer close to the city of Murcia is the case selected to represent residential buildings.

In the Vega Media del Segura, it should be noted that the materials that compose it correspond to a debris set that reaches 200 m in thickness, whose age ranges from the Pliocene to the present day. This debris set, with a high vertical and horizontal lithological heterogeneity, constitutes a single aquifer that can be outlined in two main sections, one superficial, free and with a very shallow water table, and the other deep, semi-confined multilayer. Both are hydrodynamically connected.

4.2. ATES system dimensioning

4.2.1. Energy analysis

Energy capacity and energy demand of the respective buildings have been modelled using the informatic application VPclima (University of valencia 2020). This is a practical tool that uses a national dataset of the Spanish Building Code concerning outdoor parameters, such us external humidity or temperatures. Location, size of the building, and local architectural characteristics must be set, and the program outputs the expected energy behavior of the building. A building architectural characteristic have been set so that it represents a new building with lower energy needs. Reference energy needs have been compared to those in the technical guide of the so called Ministry for the Ecological Transition and the Demographic Challenge (MITECO) (IDAE 2005). This guide evaluates the energy characteristics of the Spanish stock building, making a distinction between residential and tertiary buildings Fig. 8 and Fig. 9 show the annual energy demand of the representative buildings for space heating and cooling. In both cases, the cooling energy needs are higher than the space heating needs. Also, in both cases, heating needs are required from November to April whereas cooling is required from May to October. In the tertiary case, though, heating and cooling needs are more balanced than in the residential case.

Derived from the thermal loads of the buildings (see Table 4), the GSHP of the ATES systems is sized. Tertiary case GSHP capacity is 400 kW and residential case is 50 kW.

4.2.2. Technical analysis

For the development of a feasibility study, two ATES systems are considered with the capacity shown in Table 4. Each one has 2 wells, one for cold water storage and other for warm water storage. The specific characteristics of the wells are summarized in Table 5 and are explained in detail in this section.

In the residential case, the aquifer has medium permeability and an associated transmissivity of 100 m^2/day (Villarroya, 2009) that results in hydraulic conductivity of 0.21 m/d. In the tertiary case, the aquifer has high permeability with a mean transmissivity of 1,000 m^2/day (Villarroya, 2009) that turned out to be 5 m/d. Groundwater flow is unknown, and therefore, thermal recovery cannot be assessed based on this parameter.

Water maximum velocity in the well is estimated at 1.56 m/h for residential case and 0.38 m/h for tertiary case. This value comes from applying formula (9). Ambient water temperature is estimated to be 13°C and 16°C for tertiary and residential cases, respectively. Derived from national normative (E. T. and demographic challende M. of Spain 2007), in Spain building temperatures in the winter must be maximum 24°C and 22° C in summer. Assuming these temperatures and accounting for heat losses between the two wells, for the residential case, cold and warm well temperature is estimated to be 9°C and 16°C, and 13°C and 19°C for tertiary case. Water flow rate needed to provide the required thermal capacity for the ATES systems is 49 and 7.1 m^3/h for tertiary and residential cases. The water volume required in the aquifer to store this amount of water is estimated at 50,000 and almost 3,000 m^3.

Thermal radius in the residential case is 23 meters and 7 meters for the tertiary. The well optimal length identified is 40 meters for the residential case and 14 for tertiary case. In principle, the aquifer could be reached with shorter well lengths, which would translate into in a capital cost diminished by the reduction in drilling costs. However, optimal length will avoid undesirable heat losses in the border of the diameter of the cylindrical storage volume and by conduction and dispersion losses at the screen length, which will improve the overall efficiency of the ATES system. Resulting A/V ratio is 0.15 residential case and 0.37 for the tertiary case. As expected, the tertiary case has the highest A/V ratio, which means higher thermal losses due to dispersion losses in the underground, typical for small systems. Relation between length screen and thermal radius is 2, which is also the optimal. Finally, the required minimum borehole radius of the wells are 0.25 and 0.15 meters.

As abovementioned, COP of the GSHP selected is 5.5 for heating mode and was estimated at 30 for the free cooling mode, which correspond to the average COP for these systems (Hendriks and Godschalk, 2008).

4.3. Economic analysis

To proceed with the economic analysis, a reference system was established to compare the ATES systems results with them. In Spain, electric systems prevail in the Mediterranean areas and in the south while fossil fuel systems are already widely used in colder areas. For

Table 6
Ratios and parameters considered for the economic analysis for the ATES systems and the reference technology.

Parameter	ATES system Tertiary	Residential	Reference technology Tertiary	Residential
CAPEX	€69,860•ln (kW/6.69)-€109,000 (KWA 2018)	€10,000+€525• (kW) (KWA 2018)	200 €/kW (Sandvall et al., 2017) 0.1 €/kW (Sandvall et al., 2017)	500 €/kW (Sandvall et al., 2017)
Electricity costs	0.15 €/kWh (Goverment of Spain 2021)			
Gas cost			0.05 €/kWh (G. of Spain 2021) 4% CAPEX (Sandvall et al., 2017)	
Maintenance	4% CAPEX (Schüppler et al., 2019)	4% CAPEX (Schüppler et al., 2019)	1% CAPEX (Sandvall et al., 2017)	5%CAPEX (Sandvall et al., 2017)

Table 7
Estimated average capital costs, operational costs, and energy consumption of the ATES systems and reference technology.

Parameter	ATES system Tertiary	Residential	Reference technology Tertiary	Residential
CAPEX (€)	176,787	36,250	85,400	25,000
OPEX (€)	13,598	1,850	32,277	4,263
Electricity consumption (MWh)	69	4	140	12.6
Electricity costs (€)	6,526	404	14,023	1,263
Gas consumption (MWh)	-	-	309	-
Gas cost (€)	-	-	15,000	-
Maintenance (€)	7,071	1,450	54	3,000
Payback period (years)	10	18	-	-

cooling, only electric systems are used in the whole territory (Institute for the Diversification and Saving of Energy of Spain (IDAE), 2011; IDAE 2005). Therefore, for the tertiary case, a reference system consisting of a compression chiller for cooling and a gas boiler for heating was defined. An average 0.97 (Sandvall et al., 2017) gas boiler efficiency was used to estimate the use of gas needed to provide the required heating. For the residential case, an air-source heat pump system to provide heating and cooling was considered as a reference system. In total, 50 ASHP systems were considered, one per house in the building. Both for ATES systems and for the reference technologies, capital and operational costs were calculated based on the information summarized in Table 6. Resulting costs are summarized in Table 7, and for a better understanding, they are graphically represented in Fig. 11.

For the tertiary case, primary energy annual savings resulting from the use of ATES systems compared to the reference technology is 665 MWh, representing an annual energy reduction of 91%. Energy consumed by the ATES is 69 MWh and by the reference system is 730 MWh, from which 421 MWh are consumed for the cooling compression chillers and 300 by the gas boiler. For the residential case, ATES systems ́ annual electricity consumption is 4 MWh, and the reference system consumes 12.6 MWh, which represents a reduction of 70% of the annual energy consumed.

Fig. 10 summarizes the energy flows of the ATES systems for heating and cooling for the tertiary building (1) and the residential building (2). For the Tertiary case, an average of 245 MWh or 81% of the heating demand is covered by the energy extracted from the underground. The remaining energy is delivered by the heat pump. As for the cooling mode, despite free cooling being feasible, it is not enough to cover the cooling demand of the building. An average of 407 MWh is extracted from the underground or the 96% of the total cooling demand, and the rest is provided by the heat pump. As a consequence, the ATES for the tertiary building has an energy balance ratio between heating and cooling of 0.6. For the residential case, the heating demand supplied from the underground is 16 MWh or the 82% of the heating demand, and the cooling demand supplied is 19 MWh or the 95% of the cooling demand. Consequently, the energy balance ratio between the heating and cooling is 0.84.

From the economic analysis, the following can be mentioned (see Fig. 11). The tertiary cases ́ ATES system capital costs are 2 times the reference system's capital costs. Operational costs are clearly lower for ATES although its associated maintenance costs make this advantage smaller. Despite this high fixed annual operational cost, ATES systems can be considered a cost-effective system. Here, the installation payback period is 10 years. The residential cases ́ ATES system capital costs are around 1.5 times the reference system's cost. Annual operational costs are lower for ATES compared to the reference system although not as much as in the tertiary case. Maintenance costs here are lower for the ATES since 50 heat pump units increase the reference systems ́ costs dramatically. The payback period for the ATES systems in residential case is 18 years.

4.4. GHG emission reduction

Environmental analysis only considers CO_2 gas emissions avoided resulting from the use of the ATES systems compared to the reference systems (see Fig. 12). Thus, economic factors derived from the environmental damage provoked by CO_2 emissions are not considered in this study. CO_2 emissions have been calculated based on the national electric mix from 2019, that is, 0.15 kg CO_2/kWh (E. y T. Ministerio de Industria 2016) produced and the gas emission factor, 0.202 kgCO_2/kWh (E. y T.

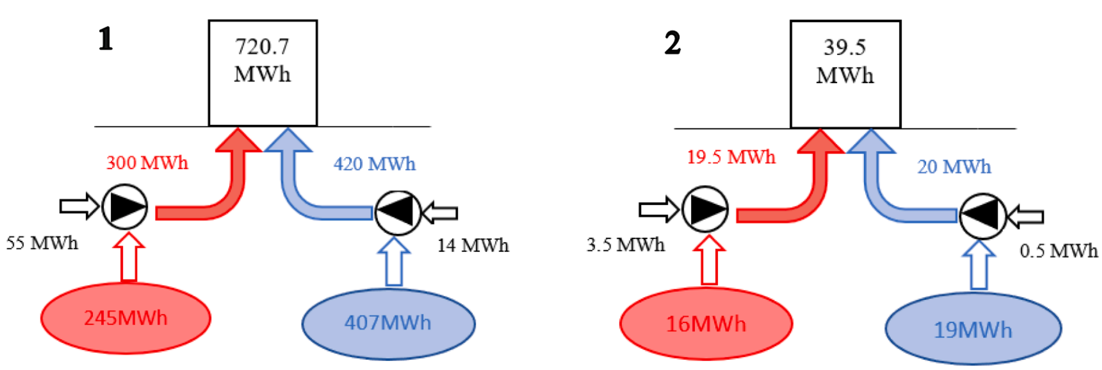

Fig. 10. Energy flows of the considered ATES systems for the Tertiary (1) and for the Residential (2) building, for heating and cooling supply.

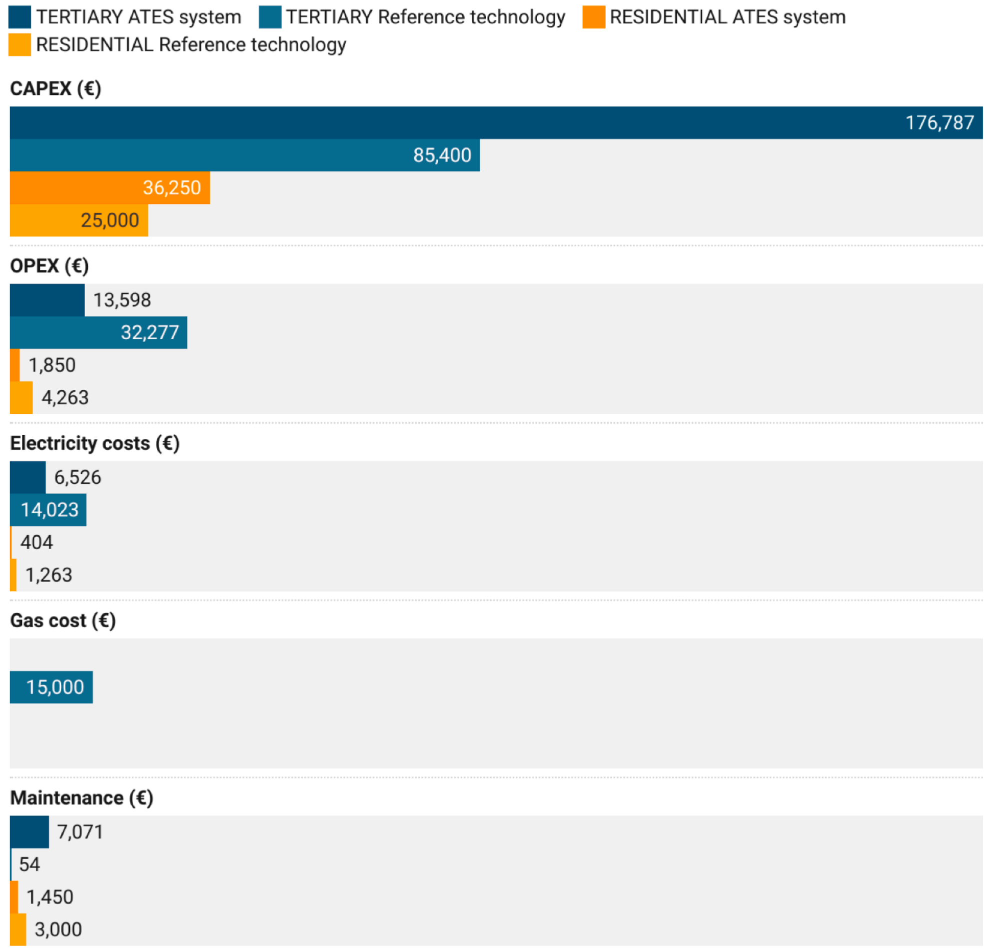

Fig. 11. Economic analysis results comparing ATES systems costs and reference technology costs for Tertiary (blue) and Residential (orange).

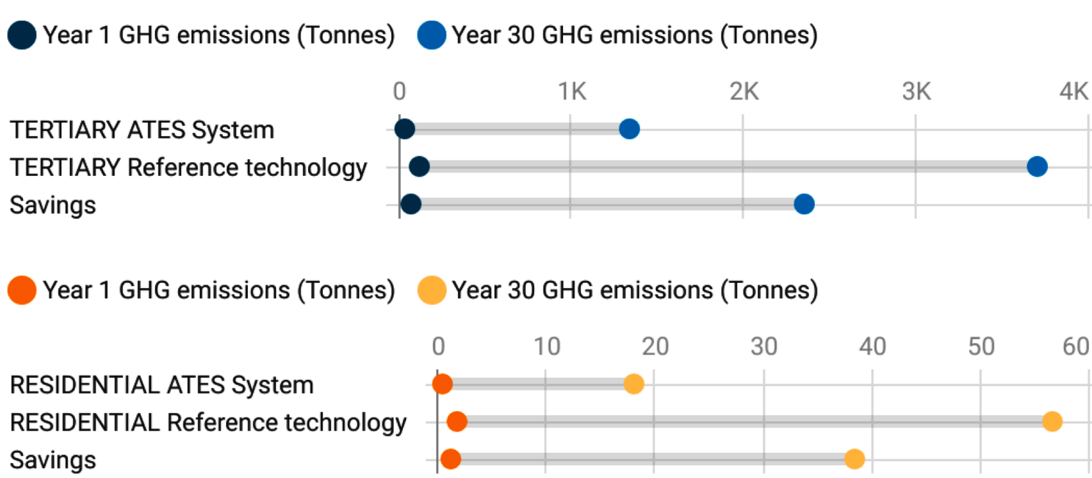

Fig. 12. GHG emissions savings of ATES systems and reference technology for Tertiary case (blue colors) and Residential case (orange colors). Information from year 1 to year 30 of operation.

Table 8
Climate severity indexes provided by the Building technical Code in Spain.

Winter severity	A	B	C	D	E
WCS	<0.3	0,3 – 0,6	0,6 – 0,95	0,95 – 1,3	>1,3
Summer severity	1	2	3	4	
SCS	< 0.6	0,6 – 0,9	0,9 – 1,25	>1,25	

Ministerio de Industria 2016) produced. The ATES system of the tertiary case could avoid 78 Ton of CO_2 annually, which represents a decrease of 63% of the emissions. The reference system's emissions are around 120 Ton, half from heating and half from cooling. In a 30-year period, considering the lifespan of the ATES system, CO_2 savings would arise up to 2,400 Ton. For the residential case, ATES annual emissions are 0.61 Ton and the reference system emissions 1.9 Ton. The result is an annual reduction in 68% of GHG emissions when using ATES. Up to 40 Ton are

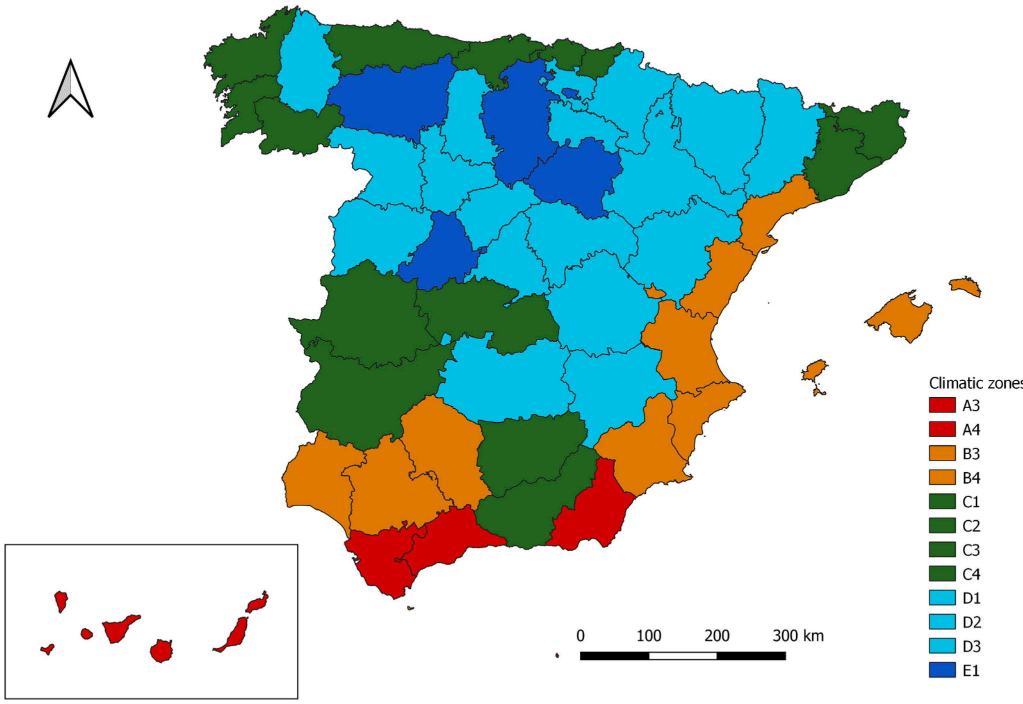

Fig. 13. Climatic zones in Spain, according to Building Technical Spanish Code.

Table 9
Heating and cooling needs per climate zone and typology building in Spain. (In orange, interpolated values, in black, real values).

Single family	A3	A4	B3	B4	C1	C2	C3	C4	D1	D2	D3	E1
Heating kWh/m^2	10	10	22	10	70	40	50	60	120	120	125	130
Cooling kWh/m^2	15	20	18	20	0	10	20	30	0	20	30	0
Terraced												
Heating kWh/m^2	5	5	10	5	35	22	28	32	60	60	65	68
Cooling kWh/m^2	17	20	17	20	0	12	17	20	0	20	30	0
Multi family												
Heating kWh/m^2	10	10	19	10	42	38	38	40	70	70	80	90
Cooling kWh/m^2	10	12	10	12	0	5	10	15	0	10	20	0
Building block												
Heating kWh/m^2	12	12	22	12	57	37	43	45	90	90	90	103
Cooling kWh/m^2	10	12	10	12	0	8	11	13	0	10	20	0

Table 10
Characterization of the climates zones based on the balance between H&C needs for the residential sector.

Energy needs	Heating kWh/m^2	Cooling kWh/m^2	Increase (points)	Score
A3	9.7	14.2	1.46	1
A4	9.7	18.4	1.90	1
B3	20.5	16.3	0.80	1
B4	9.7	18.4	1.90	1
C1	62.4	1	62.40	3
C2	37.7	9.5	3.97	2
C3	45.9	17.8	2.58	2
C4	53.7	25.8	2.08	1
D1	106	1	106.00	3
D2	106	18	5.89	2
D3	111	28	3.96	2
E1	117.1	1	117.10	3

expected to be avoided being released into the atmosphere in the lifespan of the system.

Table 11
Operational costs for ATES and the Reference system.

	Expression	Data used	Result
ATES			
Tertiary	€69,860•ln(kW/6.69)-€109,000 (Li, 2014)	400 kW	176,787€
Residential	€10,000+€525•(Li, 2014, KWA 2018](kW)	50 kW	36,250€
Reference Technology			
Tertiary			85,400€
Compression chillers	200€ • (KW)	400 kW	80,000€
Gas boiler	0.1 € • (kW)	54 kW	5,400€
Residential			
ASHP	500€ • (KW)	50 kW	25,000€

5. Discussion and conclusions

5.1. Discussion

This study shows that the utilization of the ATES systems to provide

Table 12
Energy consumption of ATES and reference technology.

	Unit	Tertiary	Residential
Energy			
Building heating demand	kWh/m^2	30	9.7
Building cooling demand	kWh/m^2	42.07	10
Heating from ATES	MWh	300	19.4
Cooling from ATES	MWh	420.7	20
Electricity used for ATES	MWh	4.17	69.02
Heating	MWh	3.5	55
Cooling	MWh	0.5	14
Elec. & gas Reference Technology			
Heating	MWh	140	6.2 +12.6*
Cooling	MWh	309	6.4

* Gas consumption

Table 13
Electricity and Maintenance costs for ATES and reference technology.

	Unit	Tertiary	Residential
ATES			
Electricity cost	€	6,526	354
Maintenance cost	€	7,071	1,813
Reference Technology			
Electricity cost	€	14,023	1,263
Gas cost	€	15,000	
Maintenance cost	€	3,200/54*	3,000

* Gas cost

heating and cooling in Spain may produce significant environmental benefits such as the savings in GHG as well as financial savings for individual building owners Section 3.3. showed that about 25% of the cities and 50% of the Spanish population live in ATES suitable areas. The exact potential of such aquifers is not yet known because their detailed characteristics are not available. However, a conservative estimation of 2-4 % ATES adoption in such regions in Spain allows to translate individual GHG savings into potential savings for Spain as a whole with ATES (in NL with many high suitable aquifers a 20% ATES adoption is expected by 2050 (Bloemendal et al., 2018)). Therefore, considering such an adoption rate (approximately 15.2 million houses) and the GHG savings rate stated in section 0, the implementation of ATES in Spain could represent a global GHG reduction ranging from 0.34 to 0.78 MTon CO_2/year.

Groundwater quality is a relevant issue in Spain since approximately 25% of the aquifers are thought to be overexploited (WWF 2019) derived from the intensive agricultural activity. However, previous research has shown that temperature changes do not negatively affect groundwater quality, mixing due to ATES wells pumping may cause some minor changes in water quality (Institute for the Diversification and Saving of Energy of Spain (IDAE) 2011). On the other hand, this research showed that ATES application could potentially mitigate GHG emission, which in turn is a positive environmental impact, which may justify minor groundwater impacts.

In this study, suitable provinces/areas in Spain for ATES systems based on climatic conditions, distinguishing between the tertiary and residential buildings, are identified (Fig. 5). It is assumed that in these regions H&C needs will be more balanced than in the other parts. However, this assumption must be carefully evaluated when considering individual buildings, as the required balance in demand may vary considerably from case to case. ATES systems in areas considered medium suitable (poorest label in this study), may perform efficiently successfully by adapting their design to the site-specific conditions or by considering adequate the incorporation of an energy support system that allows for balancing the thermal underground storage. The number of inhabitants living in suitable areas based on climatic conditions have been assessed which also must be carefully considered as they do not analyze whether the aquifers below are suitable or not. Due to the lack of information concerning the specific parameters of the aquifers (mainly the aquifer thickness), the exploration of the suitable aquifers was not extended to the whole territory but just to those with available data. Therefore, a more extended assessment is desired in order to assess the global potential for ATES systems in Spain.

Since there are no published financial studies available of the ATES systems in Spain, CAPEX of the ATES systems have been calculated based on Dutch market prices. This may cause the real costs of the systems in Spain to differ from those calculated in the work. However, according to a Spanish ATES installer company (ARCADIS), installation costs for the residential sector are expected to be quite similar in both countries.

The current high electricity production costs in Spain (only 4 countries have higher costs (Goverment of Spain 2021)) and the fact that it is a 100%-gas-dependent country are considered opportunities for ATES systems in Spain. This urges the energy market situation to change in the short to mid-term via the introduction of new low-consumption technologies in the energy market. A likely reduction of electricity production costs in Spain would cause an OPEX reduction for the ATES systems too.

In 2021, there are a few private companies installing ATES systems in Spain, but they are expected to increase. Different projects at urban scale are emerging in Spain and bring to light the available potential of various sustainable alternative sources of energy. It is expected to provoke the need of more specialized companies in the sector. Additionally, the approval of the EU Directive (2010/31/EU) that obliges the residential sector to be gas-emission neutral is also expected to demand more specialized companies throughout the country.

Given the limited level of details on the aquifers present in Spain, a first step towards utilizing the identified potential is to obtain better and more widespread available characteristics on these aquifers. On top of that, the existing regulatory framework in Spain on geothermal systems is considered deficient and specific regulations for ATES are lacking. Instead, some provinces have developed technical guidelines containing general procedures for a correct implementation and are applying rules conceived for other uses. Thus, the second step to foster the use of ATES in Spain is the creation of clear and unified specific regulations for the whole country.

5.2. Conclusion

In this study, an exploration of the potential of ATES systems in Spain

Table 14
NPV and Payback period for ATES for Tertiary and residential reference buildings.

	Years																	
Tertiary	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
OPEX ATES	13	27	41	55	69	83	97	111	125	139								
OPEX RT	32	64	96	129	161	193	22	258	290	322								
NPV	158	140	121	103	85	66	48	30	11	6								
Residential																		
OPEX ATES	2	4	6	8	10	13	15	17	19	21	23	25	28	30	32	34	36	38
OPEX RT	4	8	12	17	21	25	29	34	38	42	46	51	55	59	63	68	72	76
NPV	34	32	29	27	25	23	21	19	17	15	13	11	8	6	4	2	0.6	1

is carried out. This work includes the assessment of the underground and the climatic conditions across the Spanish territory affecting ATES systemś feasibility. The underground exploration was developed on the basis of the aquifers with potential for thermal uses, which were extracted from previous studies information. They show that at least 38% of the aquifers in Spain possess resource potential to be exploited thermally based on their hydrogeological characteristics, and among them, 26% of the towns (50% of large urban areas) present in Spain are located above one of these potential aquifers. Approximately 50% of the population in Spain lives in areas under these conditions. Due to the lack of information regarding the characteristics of the aquifers (mainly the aquifer thickness), it was not possible to globally determine the suitable aquifers in Spain. Instead, only those contained in the inventory of potential aquifers for thermal use and located nearby selected areas were considered. For optimal utilization and governance of aquifers it is of key importance to obtain such an overview.

Residential buildings located in the Mediterranean areas and south of Spain turned out to be more suitable for ATES than northern regions since heating and cooling needs are more balanced here. These conditions affect 28% of the Spanish population that lives here and 33% of the total area. In contrast, northern zones are more suited for ATES for tertiary buildings since they usually have higher cooling needs compared with the first group.

The feasibility study shows the great energy saving potential of ATES in Spain. It is concluded that up to 91% of the energy used to heat and cool a reference tertiary building and up to 70% for a residential building located in an area with suitable aquifer can be saved. This is mainly derived from the fact that cooling can be produced freely since only the water pump is used instead of the conventional compression chillers. These savings result in GHG emissions savings up to 68% compared to the reference technology. Besides, the required energy can be produced in a cost-effective way. However, the high capital costs and maintenance costs induce a payback period variation and annual operational cost increases. Payback time ranges from 10 years to 18 years for both cases. This shows that, despite the tertiary case having higher capital costs, higher thermal capacity systems are more cost-efficient.

The results of this study highlight the potential for ATES systems in Spain. Due to their energy and environmental benefits that will push Spain to reach the EU environmental goals, focus must be put on solving current barriers for its better deployment. Among them, cutting capital costs and its promotion among the stakeholders are identified in Spain as the most relevant.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Appendix I. Climatic zones in Spain

The Spanish territory is classified into major 12 groups according to their winter and summer severity which is based on the outdoor temperatures and the building stock characteristics (Spanish Building Technical Code, CTE) (Development Spanish Ministry 2019). The Winter Climate Severity (WCS) and Summer Climate Severity (SCS) are based on degree-days and solar radiation. (See Table 8). Heating and cooling demands are assumed to be the same in every climate zone.

For each province, the average winter and summer severity is identified so that, each province is given the letter and the number that fits into the WCS and SCS range. All possible combinations result in 12 different groups (see Fig. 13).

In general, the energy efficiency of the building stock in Spain is considered to be poor, due to the lack of isolation and the use of energy inefficient systems. As a result, over half of the houses has an energy label "E" or lower (ERESEE 2020. Update of the long-term Strategy for Energy Rehabilitation in the Building Sector in Spain 2020). However, the application of the EU Directive 2002/91/CE marked a turning point as, for the first time in Spain, GHG emissions in the residential sector were limited by law by means of improving the energy efficiency of the buildings. As a result, buildings constructed from 2006 onward are more energy efficient than the ones built before that.

From TABULA and EPISCOPE projects (Institut Wohnen und Umwelt 2013), the related information is gathered to estimate the annual energy needs for heating and cooling in the residential sector in the Spanish territory. The extension from regional to national data energy needs is based on the winter and summer severity of every climate zone: similar heating needs are given for zones with the same SCI and similar cooling needs for the same SCV According to CTE, energy needs are expected to be the same in areas with the same climate zone classification. B3, B4, C1, C2, C3, D1, and E1 climate zones information is available whereas A3, A4, C4, D2, and D3 are estimated by interpolating H&C values of the known anterior and posterior climate zone energy needs information is categorized by climatic zone, typology building, and building age. Although in Spain is not yet binding, in the near future geothermal systems will be only applicable to those high energy efficiency buildings (Catalonia, 2010). Therefore, annual heating and cooling needs for new buildings (>2008) per climate zone and building typology extracted from TABULA and EPISCOPE and interpolated are reflected in Table 9.

Next, average heating and cooling needs for the Spanish territory are calculated. For this purpose, the building stock typology is analyzed. Geographical differences exist, but about 67% of the houses in Spain are in building blocks, while single-family, terraced house, multifamily have a share of 13%, 17%, and 3.2% respectively (ERESEE 2020. Update of the long-term Strategy for Energy Rehabilitation in the Building Sector in Spain 2020). Taking this into consideration, a weighted average heating and cooling demands are calculated. Results are presented in Table 10. In A3, A4, and B4, cooling needs are higher than heating needs. In C2, C3, D2, and D3 heating is the prevailing mode and up to 2 times with respect to the other. Finally, in C1, D1, and E1 heating needs are quite high and there are no cooling needs, thus, energy needs are entirely unbalanced.

Appendix II. Energy consumption and costs of ATES and Reference systems

CAPEX. The capital costs have been calculated according to the expressions reflected in Table 7, and the data used correspond to the resulting heating and cooling capacities of the reference buildings, stipulated in Table 4 and 11.

Electricity and gas consumption. To determine the economic feasibility of each system, the use of the energy resource needed is previously assessed separately. Considering the capacities for both reference buildings (Table 4), and the building energy demands, the electricity demanded by the ATES systems and the reference technology are calculated (Table 12). The reference technology for the tertiary sector includes compressor chillers for cooling, therefore the use of gas is needed and counted. The COP's considered for the different technologies are for ATES 5.48 and 30 for heating and cooling respectively, 3 for the compression chiller, 0.97 for the gas condensation gas boiler, and 3.12 for the ASHP system.

OPEX. The operational costs of the different systems are calculated according to expression (11), except for the Tertiary sector and the reference technology, where expression (12) is used.

$$OPEX = Electricity\ costs\ (\in) + Maintenance\ costs\ (\in) \quad (11)$$

$$OPEX = Gas\ costs\ (\in) + Maintenance\ costs\ (\in) \quad (12)$$

The electricity cost is the result of multiplying the electricity consumption and the price of the electricity 0.1€/kWh in Spain in 2020 (EURSOSTAT 2020). The gas cost is the result of multiplying the gas consumption and the gas price in 2021, 0.05€/kWh (G. of Spain 2021). The maintenance costs are estimated using the expressions in Table 6. The electricity, gas, and maintenance costs are detailed in Table 13.

Payback period. The payback period of the ATES systems for the tertiary and residential reference buildings is calculated and reflected in Table 7. They are calculated based on the Net Present Value (NPV). The Payback period (in years) is due when NPV turns positive which is the moment the correspondent reference technology OPEX surpasses the ATES OPEX. NPV values, year after year, are reflected in Table 14.

References

Autonomous body National Center for Geographic Information (CNIG), "Towns," 2021. [Online]. Available: https://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=CAANE.

G. Bakema, "20, 000 Ates Systems in the Netherlands in 2020-Major Step," no. July 2009, 2020.

Bloemendal, M., & Hartog, N. (2018). Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. *Geothermics, 71*(June 2017), 306–319. https://doi.org/10.1016/j.geothermics.2017.10.009

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*(December 2017), 534–557. https://doi.org/10.1016/j.apenergy.2018.02.068

Calvert, K., Pearce, J. M., & Mabee, W. E. (2013). Toward renewable energy geo-information infrastructures: Applications of GIScience and remote sensing that build institutional capacity. *Renew. Sustain. Energy Rev., 18*, 416–429. https://doi.org/10.1016/j.rser.2012.10.024

W. A. Catalonia, "Building heating and cooling with underground water energy (low temperature)," pp. 1–28, 2010.

CHJ, "Documentos iniciales del tercer ciclo de planificación hidrológica (2021-2027) - ANEJO 1. Autoridades competentes.," p. 13, 2018.

S. Contreras, J. Hunink, A. Alcolea, and J. Jimenez-Martinez, "Cuantificación de la descarga subterránea al Mar Menor mediante modelización hidrogeológica del acuífero superficial cuaternario," 2017.

M. De Carli et al., "A Database for Climatic Conditions around Europe for Promoting GSHP Solutions," pp. 1–19, 2018, doi: 10.3390/geosciences8020071.

de Fomento, Ministerio (2017). Building technical Documento Básico HE. *Junio, 2013*, 1–70 [Online]. Available: https://www.codigotecnico.org/pdf/Documentos/HE/DBHE.pdf.

Development Spanish Ministry., DB-HE Ahorro de energía. Building Technical Code. 2019.

E. T. and demographic challende M. of Spain, "Thermal utilities in buildings Standar of Spain," 2007. https://energia.gob.es/desarrollo/EficienciaEnergetica/RITE/Paginas/InstalacionesTermicas.aspx.

E. T. and demographic challenge Ministry., "Water bodies of Spain spatial infromation." https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/masas-de-agua-phc-2015-2021.aspx.

E. y T. Ministerio de Industria. (2016). Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España. *Doc. Reconocido del Reglam. Instal. Térmicas en los Edif.*, 16, 17, 18[Online]. Available: http://www.minetad.gob.es/energia/desarrollo/EficienciaEnergetica/RITE/Reconocidos/Reconocidos/Otrosdocumentos/Factores_emision_CO2.pdf.

Goverment of Spain, "ERESEE 2020. Update of the long-term Strategy for Energy Rehabilitation in the Building Sector in Spain," p. 376, 2020, [Online]. Available: https://www.mitma.es/el-ministerio/planes-estrategicos/estrategia-a-largo-plazo-para-la-rehabilitacion-energetica-en-el-sector-de-la-edificacion-en-espana.

European Environment Agency (EEA) under the framework of the Copernicus programme, "Urban Atlas 2012," 2012. [Online]. Available: https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012.

EURSOSTAT, "Electricity price statistics," 2020. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics.

Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage – A review. *Renew. Sustain. Energy Rev., 94*(November 2017), 861–876. https://doi.org/10.1016/j.rser.2018.06.057

G. of Spain. (2021). Natural gas price. *Boletín Of. del Estado*, 26798–26800.

Garrido, M. Martín-Loeches, García, J. Pavón, & Martínez, M. García (2015). Origen y funcionamiento hidrogeológico del único criptohumedal subhalófilo-alcalinófilo en la facies Guadalajara del acuífero Terciario detrítico de Madrid. *Estud. Geol., 71*(2). https://doi.org/10.3989/egeol.41989.356

Gegraphical National Institute, "Geographical Information National Center of Spain." http://centrodedescargas.cnig.es/CentroDescargas/index.jsp#.

Geological Survey of Spain (IGME). (2009). Evolution and state of the undeground water bodies in the Jucar river basin authority. *World*, 1–76 [Online]. Available: http://info.igme.es/SidPDF/142000/867/142867_0000001.pdf.

Geological Survey of Spain (IGME), "Identificación y caracterización de la interrelación que se presenta entre aguas subterráneas, cursos fluviales, descarga por mananatiales, zonas húmedas y otros ecosistemas naturales de especieas interés hídrico 030.015 Talavera," 2020, [Online]. Available: http://info.igme.es/SidPDF/146000/859/146859_0000006.pdf.

Geological Survey of Spain (IGME), "Lithostratigraphy, Permeability and Hydrogeological map of Spain, scale 1:200.000." http://info.igme.es/cartografiadigital/geologica/mapa.aspx?parent=../tematica/tematicossingulares.aspx&Id=15.

Geological Survey of Spain (IGME), "Aquifer hydrogeology of the Andarax Valley," [Online]. Available: http://info.igme.es/SidPDF/142000/867/142867_0000001.pdf.

Goverment of Spain. (2021). Electricity price. *Boletín Of. del Estado*, 26798–26800.

Goverment of Spain, "A.G.U.A programme." https://www.miteco.gob.es/es/agua/temas/planificacion-hidrologica/marco-del-agua/default.aspx.

M. Hendriks and S. Godschalk, "De Pozos de Refrigeración a Almacenamiento de Energía," 2008.

M. Hendriks, "SISTEMAS GEOTÉRMICOS ABIERTOS Autores:," 2010.

(IGME) Geological Survey of Spain, "Thermal impact analysis produced by wells in the extraction of the underground water for heating and cooling in Zaragoza," pp. 68–70, 1977.

(IGME) Geological Survey of Spain, "Hydrogeological map 1:200.000 memoria." 1997.

I. de D. y A. de la E. IDAE., "Evaluacion del potencial de energía geotérmica. Estudio Técnico PER 2011-2020," 2011.

IDAE, "Evaluación del potencial de climatización con energía solar térmica en edificios. Estudio técnio PER 2011-2020.," 2005.

IDAE-Institute for Energy Diversification and Saving, "Project Sech-Spahousec, Analysis of the Energetic Consumption of the Residential Sector in Spain," 2016, [Online]. Available: www.idae.es.

IDAE-Institute for Energy Diversification and Saving, "Heat pumps statistics report," p. 2019, 2019, [Online]. Available: https://www.idae.es/noticias/idae-publica-las-estadisticas-de-bombas-de-calor.

IGME, "Memoria asociada al Mapa Hidrogeológico de España. Hoja 79. MURCIA. E. 1/200.000." p. 14, 1985.

Institut Wohnen und Umwelt, "EPISCOPE and TABULA projects website," 2013, [Online]. Available: https://episcope.eu/welcome/.

Instituto para la Diversificacion y Ahorro de la Energia (IDAE). (2011). Análisis del consumo energético del sector residencial en España. *Inst. para la Diversif. y Ahorr. la Energ.*, 76.

IVE, "Potencial de ahorro energético y reducción de emisiones de CO2 en la Comunitat Valenciana," p. 98, 2015, [Online]. Available: http://episcope.eu/fileadmin/episcope/public/docs/pilot_actions/ES_EPISCOPE_RegionalCaseStudy_IVE.pdf.

KWA, Berekening onrendabele top voor bodemenergiesystemen. 2018.

A. Q. Li, "Optimal use of the subsurface for ATES systems in busy areas," 2014.

Li, C. (2018). *GIS for Urban Energy Analysis*. Elsevier. no. December 2017.

Lu, S., Fan, M., & Zhao, Y. (2018). A system to pre-evaluate the suitability of energy-saving technology for green buildings. *Sustain, 10*(10). https://doi.org/10.3390/su10103777

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, 112*(January), 788–796. https://doi.org/10.1016/j.rser.2019.06.013

N. statistics survey of Spain, "Spanish municipalities by superficial extension," 2021. [Online]. Available: https://www.ine.es/index.htm.

National statistics survey of Spain, "Demographic data," 2021, [Online]. Available: https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176951&menu=ultiDatos&idp=1254735572981.

Navarro, A. (2006). Los acuíferos del Besòs (Barcelona): Situación actual y posibilidades de explotación. *Tecnol. del Agua, 26*(278), 58–76.

Pellegrini, M., et al. (2019). Low carbon heating and cooling by combining various technologies with Aquifer Thermal Energy Storage. *Sci. Total Environ., 665*, 1–10. https://doi.org/10.1016/j.scitotenv.2019.01.135

"QGIS. Geographic Information System. Open Source Geospatial Foundation Project." 2019, [Online]. Available: https://qgis.org/es/site/.

A. Ramos-Escudero, "Evaluación del potencial geotérmico de muy baja entalpía de la Región de Murcia mediante el uso de SIG para la implantación de sistemas de climatización y ACS.," 2011.

D. Ruiz Delgado, E. Hendriks, M. Toimil Matesanz, "Open systems technical guide," 2010. https://www.fenercom.com/publicacion/guia-tecnica-de-sistemas-geotermicos-abiertos-2010/.

Sandvall, A. F., Ahlgren, E. O., & Ekvall, T. (2017). Cost-efficiency of urban heating strategies – Modelling scale effects of low-energy building heat supply. *Energy Strateg. Rev., 18*, 212–223. https://doi.org/10.1016/j.esr.2017.10.003

Schüppler, S., Fleuchaus, P., & Blum, P. (2019). Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage (ATES) in Germany. *Geotherm. Energy, 7*(1). https://doi.org/10.1186/s40517-019-0127-6

Segura River basin Authority, "subterránea en riesgo de no cumplir los objetivos medioambientales en 2015 Demarcación Hidrográfica del Segura," 2015.

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

W. T. Sommer, Modelling and monitoring of Aquifer Thermal Energy Storage. 2015.

N. Surface and G. Energy, "A spatial explicit assessment of the economic and financial feasibility of Near Surface Geothermal Energy," 2018.

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*(November 2019), Article 101977. https://doi.org/10.1016/j.scs.2019.101977

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*(November 2019), Article 101977. https://doi.org/10.1016/j.scs.2019.101977

Tsikaloudaki, K., Laskos, K., & Bikas, D. (2012). On the establishment of climatic zones in Europe with regard to the energy performance of buildings. *Energies, 5*(1), 32–44. https://doi.org/10.3390/en5010032

University of valencia, "VPClima," 2020.

Valle, P., Delta, B. Y., & Llobregat, D. E. L. (2007). Acuíferos detríticos costeros del Litoral Mediterráneo Peninsular: Valle Bajo y Delta del Llobregat. *Enseñanza las Ciencias la Tierra, 15*(3), 295–304.

Villarroya, F. (2009). Tipos de acuíferos y parámetros hidrogeológicos. *Cent. Nac. Tecnol. Regadios*, 13.

WWF, "Agua para hoy, sed para mañana," 2019.

Zhu, K., Blum, P., Ferguson, G., Balke, K. D., & Bayer, P. (2011). The geothermal potential of urban heat Islands. *Environ. Res. Lett., 6*(1). https://doi.org/10.1088/1748-9326/6/1/019501