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Rethinking Residential Cooling in Europe: Leveraging Shallow Geothermal Energy Amidst Historical Architectural Challenges and Modern Heat Waves

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ABSTRACT

As climate change drives up temperatures and the frequency of heatwaves, European cities face escalating demand for sustainable cooling solutions. Conventional air conditioning methods not only fail to meet these demands efficiently but also exacerbate environmental challenges. Shallow geothermal energy (SGE) offers a promising, sustainable alternative, yet architectural and infrastructural limitations, especially in historical urban landscapes, hinder its broader application. This paper examines the potential of SGE for urban cooling, identifying architectural barriers and presenting a comprehensive framework of solutions—ranging from retrofitting and district cooling systems to innovative policy incentives and data collection methods. By advancing these approaches, SGE can be positioned as a cornerstone of sustainable cooling in European urban planning.

1. INTRODUCTION

The study begins with a critical examination of the Paris Agreement goals, questioning the optimism surrounding the current global efforts to limit warming to well below 2°C. As the world grapples with the increasing challenges posed by climate change, it becomes clear that traditional architectural practices and energy systems are insufficient for addressing the environmental and climatic shifts already underway. Europe, in particular, is facing the impacts of rising temperatures, especially in its urban areas, where both historical and modern architecture are struggling to adapt to more frequent and severe heatwaves.

A significant focus of this report is the architectural challenges that hinder the adoption of sustainable cooling solutions, such as shallow geothermal energy. In countries like Germany, homes are often not designed for central cooling systems, complicating the installation of geothermal cooling units. Additionally, the absence of widespread central cooling systems means that comprehensive cooling demand data is lacking. This gap in data makes it difficult to accurately plan and simulate shallow geothermal cooling solutions for existing buildings.

Despite these obstacles, the paper explores potential solutions that address these architectural limitations and promote the integration of shallow geothermal systems. It argues that while the ambitious goals of the Paris Agreement may be difficult to achieve, the shallow geothermal energy industry can play a critical role in helping cities adapt to future conditions. It will be discussed how these systems can mitigate the effects of heatwaves and contribute to urban decarbonization efforts.

Furthermore, drawing lessons from ancient civilizations such as Iran, which pioneered passive cooling methods, the paper advocates for innovative ways to blend traditional and modern architectural practices. By rethinking the synergy between architecture and energy solutions, cities can better protect their environments and residents in an era of increasingly intense climate conditions.

2. CONSEQUENCES OF CLIMATE CHANGE, ARE WE DOING ENOUGH?

The effects of climate change are particularly noticeable in the increasing frequency and intensity of heatwaves across Europe. Projections indicate that global warming will continue to drive both a rise in the occurrence and severity of heatwaves while gradually reducing the frequency and extremity of cold spells. These shifts are evident across the EU and the UK, with southern European countries experiencing the greatest impacts. Figure 1 depicts how frequently a heatwave may occur at different levels of global warming, with the baseline climate (1981-2010) showing a 20-year return period for such events. For example, a value of 4 on these maps indicates that a heatwave currently expected once every 20 years would occur every 4 years at that warming level, representing a fivefold increase. In a climate 3°C warmer than today, a heatwave that now happens once every 20 years could occur nearly every year in Spain and parts of Portugal, every 3 years across much of southern Europe, and at least every 5 years in other regions of Europe.

Even in an ideal scenario where global warming is limited to 1.5°C by 2100, extreme heatwave frequency is anticipated to increase threefold across nearly all of Europe (Gustavo et al., 2020). This rise would lead to a significant increase in the population exposed to extreme heat, potentially impacting 105 million people annually by the century's end (see Tables 1 and 2) and raising annual fatalities from the current 2,750 to 30,000. According to the IPCC’s Sixth Assessment Report (AR6, 2021), even with a very low emissions pathway (SSP1-1.9) targeting net-zero CO_2 by 2050, there remains a "more likely than not" chance of exceeding 1.5°C of global warming around 2035, meaning this threefold increase in heatwave frequency could be felt as soon as the next decade (Schleussner et al., 20223).

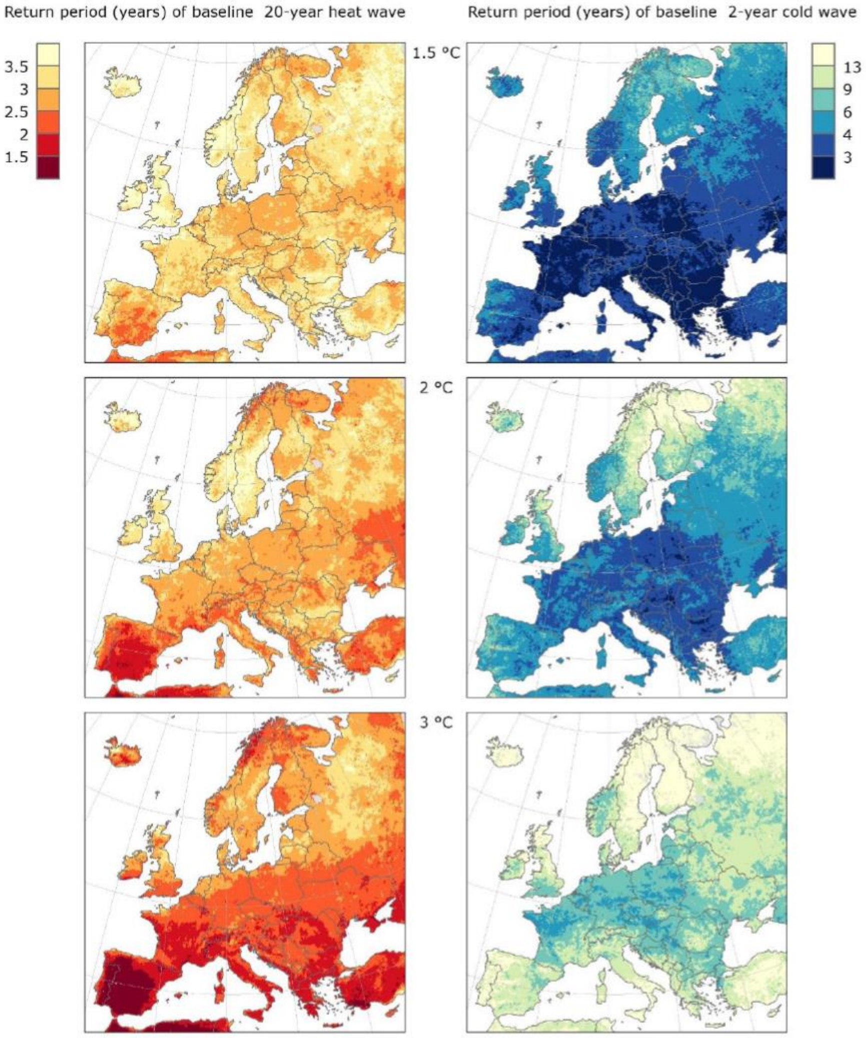
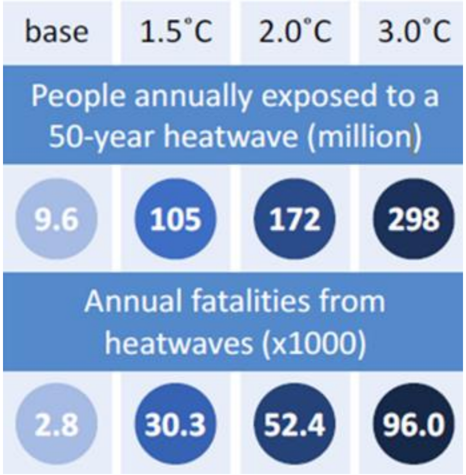
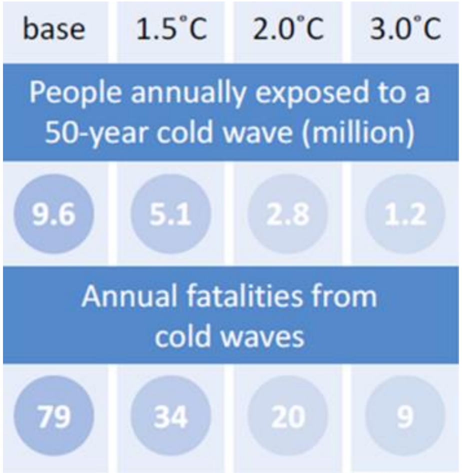


Figure 1: Return period (in years) of baseline 20-year heatwave and a 2-year cold wave for 1.5°C, 2°C and 3°C global warming (Gustavo et al., 2020)

It’s important to note that these estimates assume a relatively optimistic scenario. Without adaptation measures or vulnerability reduction, fatalities from extreme heat in 2100 could increase from 30,000 at 1.5°C of warming to 52,000 at 2°C and reach 96,000 at 3°C. Southern European countries, especially France, Italy, and Spain, are expected to see the largest increases in heat-related deaths. Conversely, milder winters will likely reduce exposure to severe cold, potentially decreasing cold-related fatalities by over 80% at a 3°C global warming scenario (Gustavo et al., 2020).



base	1.5˚C	2.0˚C	3.0˚C
People annually exposed to a 50-year heatwave (million)			
9.6	105	172	298
Annual fatalities from heatwaves (x1000)			
2.8	30.3	52.4	96.0



base	1.5˚C	2.0˚C	3.0˚C
People annually exposed to a 50-year cold wave (million)			
9.6	5.1	2.8	1.2
Annual fatalities from cold waves			
79	34	20	9

Table1: Human exposure to and fatalities from heatwaves in the EU and UK for different warming levels in 2100 (Gustavo et al., 2020)

Table2: Human exposure to and fatalities from cold waves in the EU and UK for different warming levels in 2100 (Gustavo et al., 2020)

The European Energy Agency (EEA) reports that heatwaves represent the deadliest type of climate extreme in Europe, having caused an estimated 77,000 to 129,000 deaths in EEA member countries between 1980 and 2020. The social and health impacts of heatwaves are not evenly distributed, with the most affected groups including the elderly, people with chronic conditions or disabilities, children, and those living in inadequate housing. Population vulnerability to heat extremes is likely to rise due to demographic trends, such as an increase in the elderly population (from 21% aged 65 and older in 2021 to a projected 30% by 2050) and urbanization, which is expected to grow from 75% in 2021 to 80% by 2050 (Cooling Buildings Sustainably in Europe). While well-designed, constructed, renovated, and maintained buildings can protect against extreme heat with minimal energy use, around 75% of Europe’s building stock is currently energy inefficient, and over 85% of these buildings are expected to remain in use by 2050 (Buildings and Construction, 2024). Although energy renovations of buildings are underway, progress is slow, with only about 1% of buildings being renovated each year (European Technology and Innovation Platform on Renewable Heating and Cooling, 2022). As a result, between 9% and 20% of the population may face overheating risks in buildings.

The energy demand for cooling purposes in buildings is rapidly rising. The European Energy Agency reports that energy consumption for cooling residential buildings surged by 212% between 2010 and 2019 (Cooling Buildings Sustainably in Europe, n.d.). This growth is primarily driven by increasing global temperatures and rising wealth in developing regions. According to the International Energy Agency (IEA), energy requirements for building cooling systems are expected to triple from 2018 to 2050, which equates to adding ten new air conditioning units to the power grid every second until 2050. In recent summers, we have experienced unprecedented high temperatures, further boosting the demand for air conditioning, fans, and cooling equipment. However, this increase in cooling demand presents a paradox: conventional cooling systems wastefully emit heat to their surroundings. In urban settings, air conditioning units can elevate street temperatures by up to 1°C. Additionally, since these systems are often powered by electricity derived from fossil fuels, their widespread utilization aggravates greenhouse gas (GHG) emission rates. If current trends continue unchecked, air conditioning could contribute an additional 1.5 billion tons of CO_2 emissions annually by 2030, more than triple the emissions of countries such as the UK or Brazil (Loportail, 2024b). Moreover, traditional cooling systems emit direct and indirect GHGs also due to their reliance on fluorinated gases (F-gases), such as HFCs, which can be thousands of times more potent than CO_2 (Eisbrenner, 2023).

To mitigate these effects, European policymakers should increasingly look towards sustainable cooling solutions (Figure 2), including improving building insulation, retrofitting old structures, shallow geothermal cooling, and incorporating nature-based cooling solutions like green roofs and increased urban greenery (Lampe & Connecting Europe, 2023) (World Bank et al., 2020).

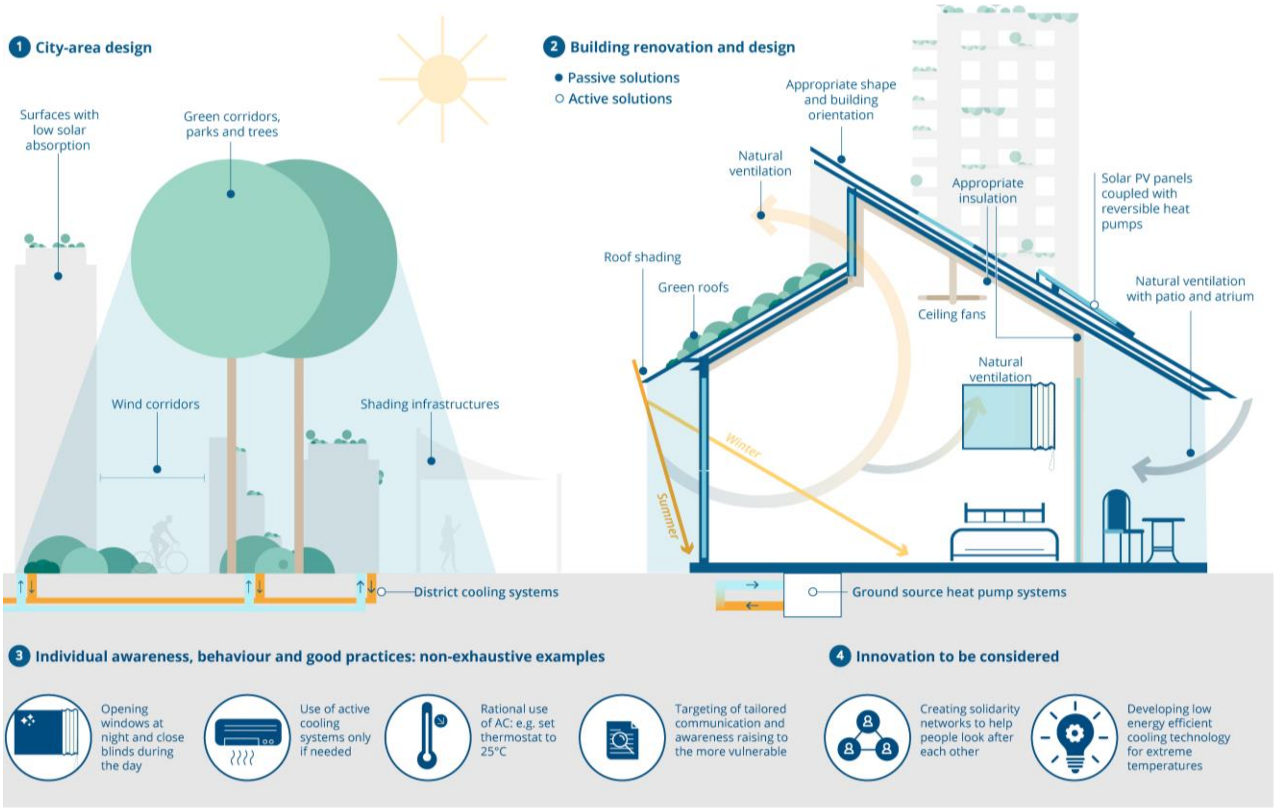


Figure 2: How to combat heat waves (Cooling Buildings Sustainably in Europe: Exploring the Links Between Climate Change Mitigation and Adaptation, and Their Social Impacts, n.d.)

This paper emphasizes the critical role of shallow geothermal cooling in addressing rising temperatures due to climate change. However, a significant barrier to its broader adoption is the architecture and design of existing buildings, a challenge that will also be explored in depth.

2. SHALLOW GEOTHERMAL SYSTEMS FOR COOLING

Shallow geothermal energy (SGE) has emerged as a key technology for sustainable heating and cooling, offering a reliable, low-carbon alternative to conventional energy systems. Its potential for both district and individual applications makes it a cornerstone in urban planning for energy transition across Europe. SGE systems utilize the thermal energy stored in the shallow subsurface, typically ranging from 10°C to 25°C, making it a viable resource for both heating and cooling. The efficiency of SGE lies in its ability to tap into this stable temperature to provide year-round energy through ground-source heat pumps (GSHPs). These systems can be categorized into closed-loop systems, such as Borehole Heat Exchangers (BHEs), and open-loop systems, such as groundwater heat pumps (GWHPs) (Walch et al., 2022). Closed-loop systems, especially vertical BHEs, are commonly used in urban areas due to their space efficiency and minimal surface footprint. Recent advances in borehole technology, such as multi-tube configurations, have significantly increased the performance of these systems. (Ahmed et al., 2022) (Walch et al., 2022).

Heat sources/sinks in shallow geothermal energy systems can be:

- Geothermal Probes: These consist of vertical boreholes with pipes inserted into them. A heat transfer fluid circulates through the pipes, transporting the heat to/from the surface.
- Geothermal Collectors: These horizontal systems are installed at shallow depths (approximately 1–2 meters) and are particularly suitable for larger properties.
- Well Systems/Groundwater Heat Pumps: These systems use groundwater as a heat source. Water is extracted from one well, passed through a heat pump, and returned to a second well.
- Energy Piles: These systems integrate geothermal technology into building foundations, serving as both structural elements and heat sources/sinks.

One of the most promising applications of SGE is its integration into District Heating and Cooling (DHC) networks. These networks distribute heating and cooling across multiple buildings through centralized infrastructure, making them ideal for urban settings. By connecting SGE systems to DHC networks, cities can leverage the stable temperatures of the subsurface to provide a renewable and efficient energy supply throughout the year (Walch et al., 2022). Fifth-generation DHC networks, which operate at lower temperatures than traditional systems, are particularly suited for SGE integration. These low-temperature networks minimize energy loss and are compatible with renewable sources such as shallow geothermal energy. Case studies from cities like Basel and Vienna illustrate how DHC systems, powered by SGE, can reduce greenhouse gas emissions and improve overall energy efficiency (Walch et al., 2022).

While the initial installation costs of SGE systems are higher than those of conventional systems, their long-term benefits make them an economically viable solution for urban environments. Studies indicate that the payback period for SGE installations can range from 2.5 to 17 years, depending on geological conditions, energy prices, and government subsidies (Ahmed et al., 2022). In regions with favorable geological conditions, SGE systems achieve higher efficiency, lowering operational costs over time.

By 2050, GSHPs are projected to cover up to 85% of heating and cooling demand in certain European regions, particularly when integrated into DHC systems . Several European cities have already demonstrated the feasibility of SGE systems for both individual buildings and district-wide applications. For instance, in western Switzerland, SGE systems with seasonal regeneration have been shown to cover up to 57% of cooling demand and 55% of heating demand in service-sector buildings. Looking forward, the expansion of shallow geothermal energy systems will play an essential role in the energy transition across Europe. As cities increasingly adopt low-temperature DHC networks, SGE will become an integral part of urban energy planning, helping meet both heating and cooling needs while significantly reducing greenhouse gas emissions (Walch et al., 2022).

Shallow geothermal cooling leverages the stable, lower temperatures of the subsurface, using circulating fluid to transfer heat and effectively acting as a ground heat sink. This cooled fluid is then recirculated to manage higher ambient temperatures (as shown in Figure 1). Shallow geothermal cooling provides several key benefits, including sustainability, environmental friendliness, and reliability. Because subsurface temperatures remain stable throughout the year, geothermal cooling ensures a consistent and reliable source of cooling—especially valuable in hot and humid climates where conventional air conditioning may fall short. Additionally, geothermal cooling is energy-efficient, with potential energy savings of up to 50% compared to traditional air conditioning systems. While most geothermal cooling systems require a heat pump powered by electricity that might introduce some carbon emissions, they still represent a greener and more sustainable choice than conventional cooling methods. One of the main reasons for that is the process of seasonal regeneration. This involves re-injecting excess heat from cooling applications back into the ground, thereby enhancing its capacity for heat extraction during the winter. This cyclical method not only ensures efficient year-round energy use but also increases the technical potential of Shallow Geothermal Energy (SGE) systems (Walch et al., 2022). When compared to conventional air conditioning (AC) units, which wastefully release heat into the surrounding environment and exacerbate the urban heat island effect, thereby further raising urban temperatures and cooling demand, it becomes clear why shallow geothermal energy (SGE) cooling systems represent a more efficient and sustainable choice for cooling.

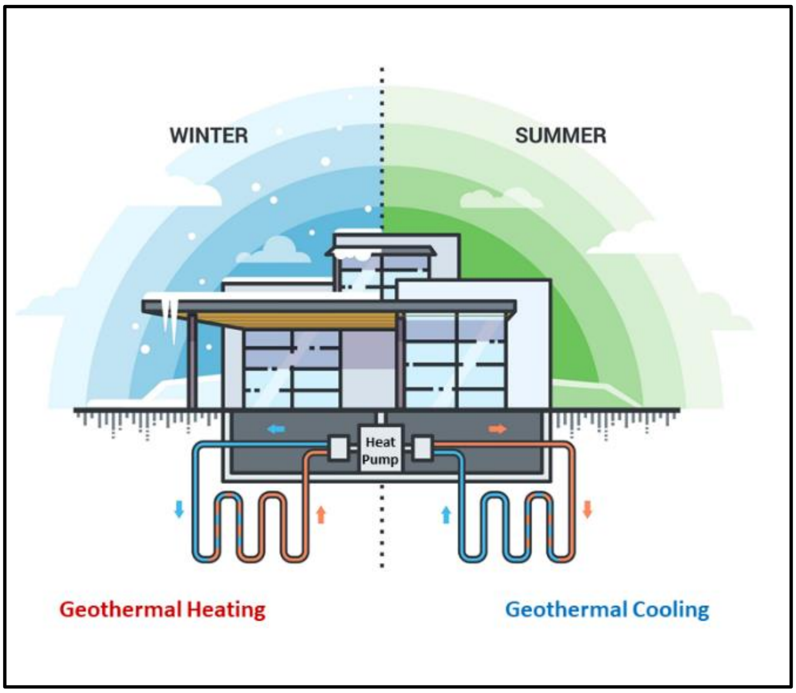


Figure 3: Geothermal cooling and heating (Sasha 2023)

3. ARCHITECTURAL CHALLENGES

European cities, shaped by complex histories, display a rich array of architectural styles that include ancient, medieval, post-war, and modern designs. This diversity is especially prominent in German cities, where medieval structures stand alongside buildings from the post-World War II period and ambitious projects from the post-reunification era. For instance, Berlin's division left visible contrasts between the East and West, and reunification spurred extensive modernization. Cities like Berlin, Munich, and Frankfurt blend medieval timber-framed houses, post-war modernism, and contemporary sleek buildings, each of which presents unique challenges when adapting to Europe's increasingly hot summers (World Bank et al., 2020) (De Toldi, 2024).

As heatwaves grow more intense and frequent, addressing the limitations of both old and new buildings in managing rising temperatures becomes essential. Despite their charm and cultural importance, historical buildings are often ill-equipped to withstand Europe's severe heatwaves, as many lack sufficient insulation and effective passive cooling mechanisms. This shortfall leads to rising energy demands for artificial cooling during summer months. For example, in Austria, older buildings have seen their cooling demand rise by up to 90% during extended heatwaves (Mukati, 2021) (Lampe & Connecting Europe, 2023) (Fürtön et al., 2022).

Post-World War architecture, especially in Germany, is characterized by modernist and industrial designs that rely heavily on concrete and glass, materials that absorb and retain heat. In cities like Berlin, the varied construction standards of post-war East and West buildings add complexity to implementing a cohesive climate adaptation strategy (Fürtön et al., 2022) (Lampe & Connecting Europe, 2023).

Modern architectural practices from the late 20th century, influenced by industrial and minimalistic aesthetics, focused more on heating needs than cooling. While visually appealing, these designs—featuring extensive glass facades, open spaces, and minimal insulation—contribute to buildings trapping heat, which, in turn, exacerbates urban heat islands, causing city centers to become significantly hotter than surrounding areas. The urban heat island effect further complicates this issue in densely populated cities. Studies show that during heatwaves, urban areas can experience temperatures several degrees higher than neighboring rural regions. This discrepancy is primarily due to heat-retaining materials like concrete and asphalt, coupled with a lack of green spaces (World Bank et al., 2020) (De Toldi, 2024).

The energy inefficiency of existing buildings is another barrier to cooling adaptation in Europe. Currently, nearly 75% of the EU's residential buildings are energy inefficient, yet only about 1% undergo renovation annually (RHC). This slow renovation rate stifles efforts to prepare cities for higher temperatures, underscoring the urgency of implementing energy-efficient and cooling technologies. Traditional cooling methods—such as shading, thicker walls, and ventilation—are increasingly insufficient against the escalating heatwaves (World Bank et al., 2020) (De Toldi, 2024).

Expanding the use of shallow geothermal cooling also faces architectural challenges across many European regions. Buildings were typically constructed without central cooling systems, which complicates retrofitting and limits the availability of comprehensive cooling demand data. Without this data, it is challenging to plan and simulate shallow geothermal units effectively for existing structures. Additionally, older buildings often have architectural constraints that hinder the straightforward installation of ground-source heat pumps and similar technologies. Historical and heritage buildings present added complexities, as any modifications must carefully balance modern needs with preservation of cultural and architectural integrity.

4. WHAT CAN BE LEARNED FROM THE PAST ABOUT CLIMATE-RESPONSIVE ARCHITECTURE

The design of buildings and homes has always been intrinsically linked to the climate of a region. Historically, civilizations adapted their architectural styles to ensure that homes were suited to the specific climatic challenges of their environments. In places with extreme heat, such as the Middle East, North Africa, and Southern Europe, innovative designs emerged to mitigate the harsh effects of the sun while maximizing natural ventilation and cooling. Conversely, in colder regions, buildings were designed to retain heat, using thicker walls and insulation.

In intensely warm regions, traditional architecture often utilized passive cooling techniques. A notable example is ancient Iranian architecture, where *Badgirs* (windcatchers) and *Qanats* (underground water channels) were cleverly incorporated into structures to enable natural cooling without relying on energy-intensive methods. Ancient Persian cooling systems applied shallow geothermal principles by using underground channels to cool the air that is drawn in through windcatchers, which is then circulated throughout the building. This approach was carbon free, energy-efficient and environmentally sustainable, demonstrating how architectural designs can be tailored to a region’s natural landscape and resources. Ancient Persia was the only civilization known to have utilized the subsurface as a ground-coupled heat exchanger to harness geothermal energy for cooling purposes (Sangin, 2023).

Other ancient civilizations, such as those in Egypt, Greece, China, and Rome, developed their own innovative cooling methods, often using natural mechanisms like shading, ventilation, and subterranean systems. The Egyptians, as early as 2500 BCE, utilized evaporative cooling techniques with wind catchers and underground ducts. Similarly, from the 8th century BCE, the Greeks incorporated cooling features like wind towers, open courtyards, and water elements to keep homes and public spaces comfortable. In China, by the 5th century BCE, cooling solutions included yin-yang roofs, underground channels, wind catchers, and courtyards. The Romans developed the hypocaust system, which primarily served as underfloor heating but also aided in maintaining comfortable indoor temperatures. They further employed shading devices like awnings and advanced ventilation strategies to enhance cooling in their buildings (Sangin, 2023).

Modern architectural trends have largely abandoned these traditional cooling solutions, opting instead for more energy-intensive methods such as air conditioning. However, as climate change drives more frequent and intense heatwaves, there is increasing awareness that incorporating these historical architectural features into contemporary designs could offer effective cooling and energy savings, while also lowering the carbon footprint of buildings (Sangin, 2023).

5. LET’S PLAY IT COOL; THE PERSIAN WAY

Ancient Persian cooling systems were renewable, eco-friendly, and sustainable, operating solely through natural forces without the need for electricity. These systems relied on the *Badgir* (windcatchers) combined with the *Qanat* (underground water channels) and/or the *Ab-Anbar* (underground water storage cisterns). In an integrated energy system framework that incorporates geothermal, wind, and hydrothermic thermal energy storage, the Qanat represents the shallow geothermal component, the *Badgir* is the wind component, and the *Ab-Anbar* acts as the Hydrothermic energy system (Sangin, 2023).

5.1. Qanat Systems, The Shallow Geothermal Component

The Persian *Qanat* system (Figures 4 and 5) is an ancient water management method historically utilized across much of the Middle East, including Iraq, Afghanistan, and Central Asia, and has also been implemented in parts of North Africa, Spain, and South Asia. Even today, *Qanats* remain in use in various arid regions with limited water availability. This system has been vital for sustainable water supply management in Iran for centuries (Manuel, Lightfoot, and Fattahi, 2018). *Qanats* consist of gently sloping underground canals that draw water from an aquifer situated at a higher elevation than the land to be irrigated. These canals are linked by horizontal tunnels, with a series of vertical wells spaced across an elevated field. The initial shaft, called the mother well, is excavated below the groundwater level of an alluvial fan aquifer, while additional wells are dug at intervals of 20 to 200 meters along a line that can extend from 300 meters to 65 kilometers between the recharge zone and the irrigated area (Figures 6 and 7).

Constructed manually and operating solely through gravity, the *Qanat* system is an eco-friendly water management solution with zero carbon emissions. This system also effectively manages groundwater overflow without disrupting the aquifer's natural balance of inflow and outflow (ICOMOS, 2016). Highly esteemed in ancient Persia, the *Qanat* was considered a technological marvel that enabled sustainable agriculture and the development of prosperous cities in arid regions. Additionally, the cool water, typically between 10 and 15 degrees Celsius, combined with underground ducts or wind towers (*Badgirs*), provided a natural method for cooling homes and public spaces, making the *Qanat* essential for climate control and temperature regulation.

The exact location and date of the earliest *Qanat* construction remain unclear, though it is generally believed that *Qanats* originated in Persia, now Iran, during the early 1st millennium BCE. Evidence of *Qanat* systems can be found throughout Iranian history, spanning from the Elamites and Assyrians (1400-550 BCE) through the Achaemenid Empire (550-330 BCE), the Seleucid Era (312-250 BCE), Parthian (250 BCE-150 CE), Sassanid (226-650 CE), and into the Islamic period beginning in 621 CE (Lightfoot, 2000). Each successive civilization rediscovered, built, maintained, destroyed, and reconstructed these systems. Outside of Iran, similar *Qanat* systems have been found in countries such as Afghanistan, Azerbaijan, Iraq, Oman, Pakistan, China, Algeria, Morocco, Spain, and Italy.

Figure 4 (Left): Inside of a *Qanat* in Shahdad, Iran (Marshall 2016)

Figure 5 (Right): Outside of a *Qanat* in Ramsheh, Iran (Geo 2018)

Figure 6: An aerial view of the *Qanat* system (Rashedi 2014)

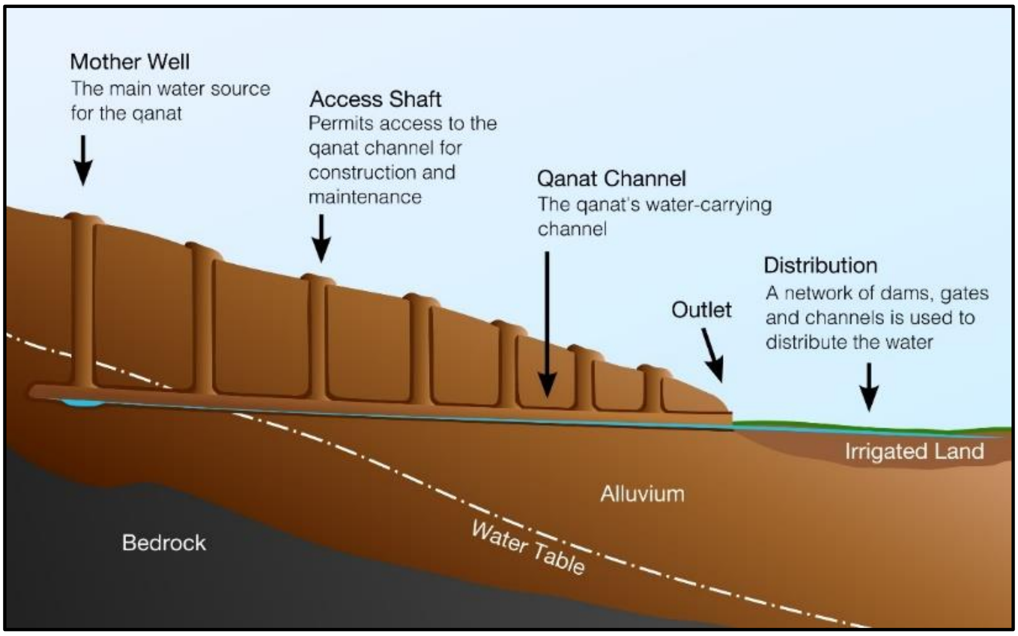


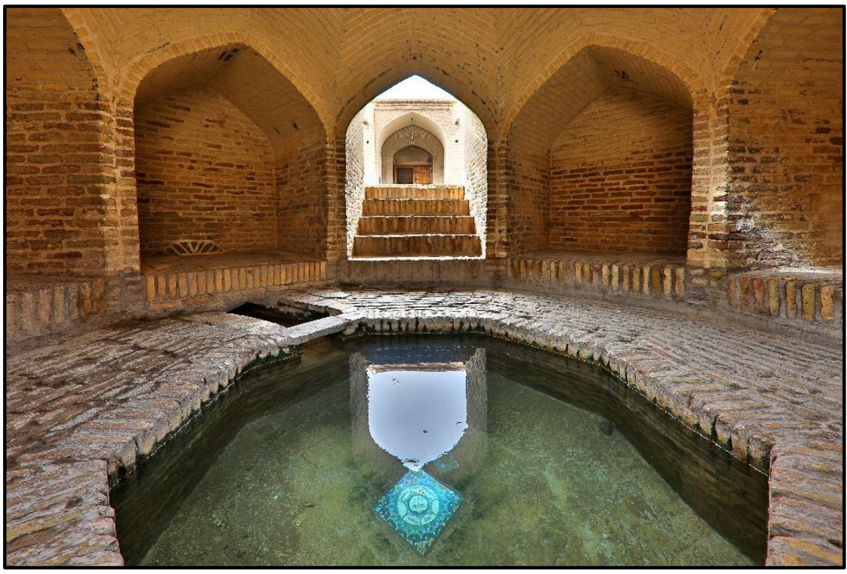
Figure 7: A cross section of the *Qanat* system (Bailey 2009)

5.2. Ab-Anbar, The Hydrothermic Energy Storage Aspect

The *Ab-Anbar* (Figures 8 and 9) is an underground water storage structure commonly found in various environments across Iran, including urban areas, villages, forts, caravan paths, and mountainous locales (Yousefi and Nocera, 2021; Yousefi et al., 2021). These cisterns are built below ground level with a domed roof and often include several ducts known as *Badgirs*. Water, typically sourced from *Qanats*, is stored at depths of 10 to 20 meters, allowing it to remain cool throughout the hot summer months (Saeidian 2013). Rainwater is also collected and stored. The unique design of *Ab-Anbars* takes advantage of seasonal temperature shifts and the insulating properties of the earth to facilitate evaporation from the water's surface, which exits through the dome with assistance from an air trap (Yousefi and Nocera, 2021).

The origins of *Ab-Anbars* can be traced to early Iranian civilizations, such as the Elamite city of Duravantash and the Achaemenid era, with remnants still visible in the Takht-e Jamshid region (Le Strange 2011). These cisterns were not only essential for daily life but also held cultural and spiritual significance, with some regarded as sacred structures.

The varied architectural features of *Ab-Anbars* reflect Iran's diverse climates, highlighting the remarkable skill in Persian architecture and engineering (Memarian, 2009). Research indicates that arched roofs absorb less radiant heat than flat roofs (Bahadori and Haghighat 1986), and the shape of the roof impacts both the average absorbed radiation and the indoor air temperature (Gómez-Muñoz, Porta-Gándara, and Heard 2003). Additionally, studies have compared the shadowing effects on domed versus flat roofs, revealing that a hemispherical dome absorbs nearly 35% less solar energy than a flat roof (Velayati and Yaghoubi 2004). In hot, arid regions like Yazd, a higher dome-to-span ratio further reduces internal heat (Figure 10), making the *Ab-Anbar* a practical choice for water storage (Yousefi and Nocera, 2021). Overall, the *Ab-Anbar* exemplifies the adaptability and innovation of Persian architectural and engineering practices.



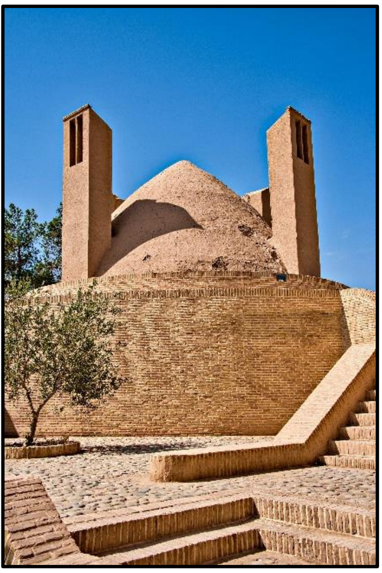


Figure 8 (Left): Inside of the Klar *Ab-Anbar* in the Shah Abbasi Caravanserai, Meybod, Iran (MehmetO 2018)

Figure 9 (Right): Outside of the Klar *Ab-Anbar* in the Shah Abbasi Caravanserai, Meybod, Iran (Dealbert 2018)

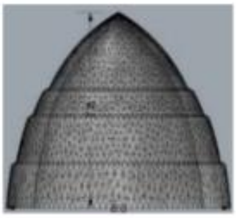
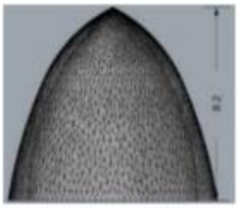
Shah vali Taft	Haj Ghazi	Barsuie Taft	Sahraie Dasti	Haj Nasir
				
185m^2	249m^2	281m^2	265m^2	196m^2

Figure 10: Different types of *Ab-Anbar* domes (Shiri, Didehban, and Taban, 2022)

5.3. Badgir, the wind aspect

The *Badgir* (Figure 11), commonly referred to as the Persian wind catcher, is a distinctive element of Iranian architecture designed for hot and humid climates. This passive cooling system utilizes natural airflow to create a comfortable indoor environment. Its main purpose is to capture fresh air, directing it into the building to lower indoor temperatures. Figure 12 demonstrates the airflow process: air enters through the wind catcher's inlet openings, circulates within the structure, and ventilates the interior before exiting through the outlet (Aboui, Mozafar, and Ameli, 2012).

In addition to cooling, *Badgirs* function as efficient ventilators, channeling fresh air from ground-level courtyards up to the top of the wind tower (Hejazi and Hejazi, 2014). For centuries, these structures have been employed as traditional systems for ventilation and cooling across various regions in the Middle East and North Africa, with their design and cooling capabilities becoming a significant focus of research in recent decades (Hejazi and Hejazi, 2014). Evidence of *Badgirs* dates back to 4000 BCE, as shown by excavations at the site of Masouda in Shahrud, Northern Iran (Masouda, 1974).

The significance of *Badgirs* extends beyond their cooling and ventilation functions. In hot and arid regions like Kashan, Yazd, Kerman, and the northern coastlines of the Persian Gulf, they are emblematic of the region’s architectural identity (Yarshater, 1989). Moreover, *Badgirs* stand as a testament to the ingenuity and adaptability of ancient Persians, who skillfully harnessed natural elements to create sustainable, comfortable living environments. They represent the seamless integration of architecture, culture, and climate.

Figure 11: Traditional house with the *Badgir*s, Aghazadeh, Abarkuh, Yazd, Iran (Morandi 2016)

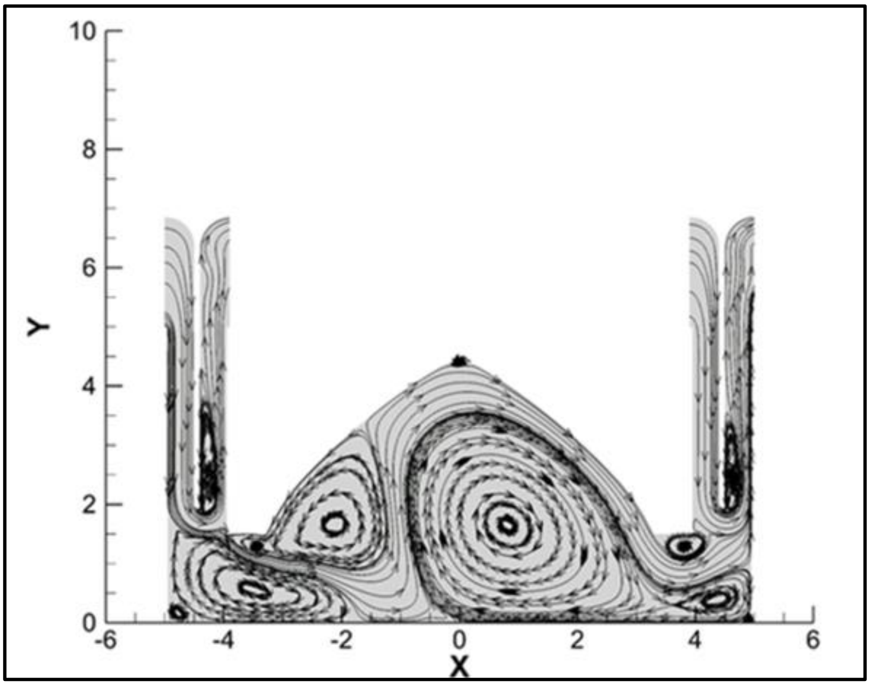
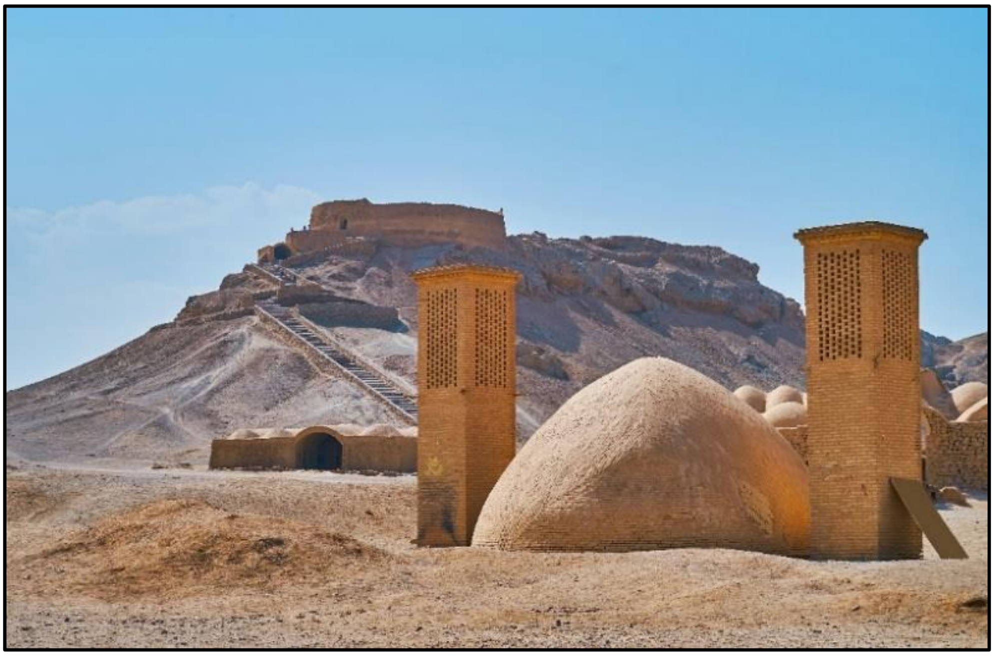


Figure 12: Pattern of air flow inside an establishment with a dome and wind-catchers (Yousefi and Nocera 2021)

5.4. Integrated energy system of geothermal, wind, and hydrothermic thermal energy storage

The integration of a *Badgir* with an *Ab-Anbar* (Figure 13) involves placing one to six wind towers around the perimeter of the water reservoir. This configuration harnesses the cooling capacity of the relatively frigid water by moving warm air across the water's surface, triggering evaporative cooling. In the evaporative cooling process, water evaporates into an airstream, transitioning from a liquid to a gas state. This phase change requires energy, which is absorbed from the surrounding air as heat. Consequently, this absorption of heat cools down the airstream, effectively lowering the air temperature. However, this process does reduce the water supply as evaporation occurs. The cooled air is circulated throughout the building via external shafts and wind towers, while the heated air is expelled through openings at the top of the *Badgir* (Figure 14). When combining the *Badgir*, *Ab-Anbar*, and *Qanat*, air enters the wind-catcher through inlet openings, circulates within the *Ab-Anbar* that is fed by the *Qanat* (Figure 15), and then exits through the wind-catcher's outlet, effectively ventilating the space (Sangin, 2023).



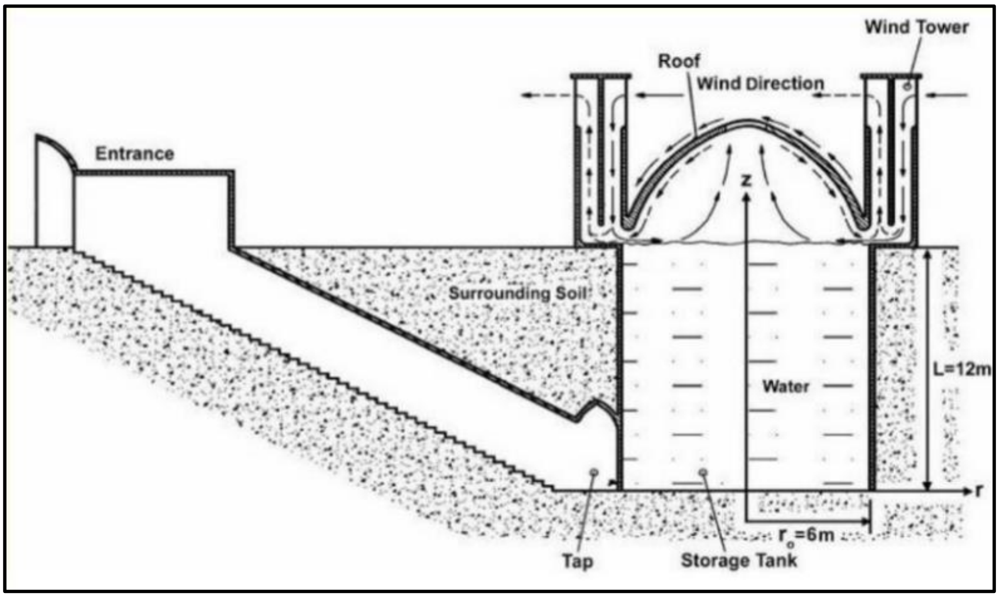


Figure 13 (Top): The view on an *Ab-Anbar* with two *Badgir*s Towers in Yazd, Iran (eFesenko 2017)

Figure 14 (Bottom): Vertical section of an *Ab-Anbar* equipped with *Badgir* (Shiri, Didehban and Taban 2022)

The first documented use of *Badgirs* and *Ab-Anbars* together in a single structure in Iran dates back to the 4th and 5th centuries A.H. (10th century A.D.), approximately 1,022 years ago. The oldest surviving buildings that showcase this combination of architectural features originate from the Timurid Empire era, around 550 years ago in the 9th century A.H. (15th century A.D.). During this period, *Badgirs* began to be incorporated into residences in Yazd-Ardakan, marking the advancement of this innovative technology (Aboui, Mozafar, and Ameli, 2012).

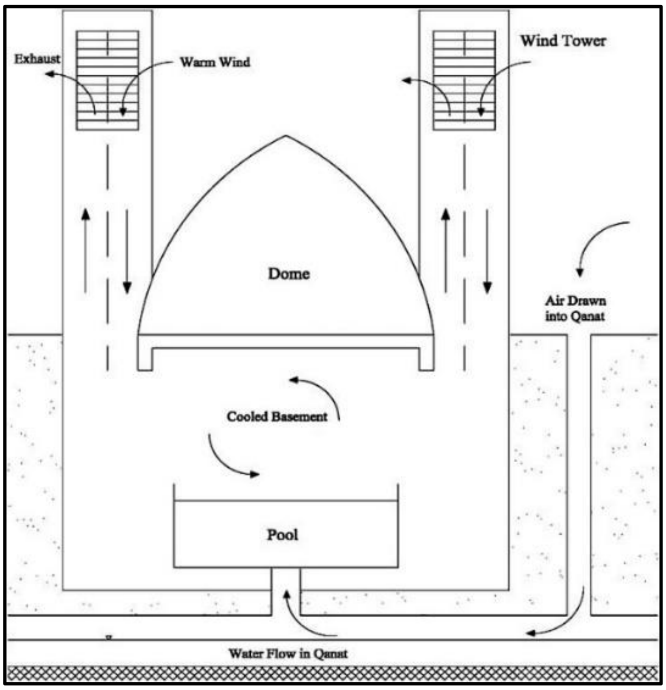
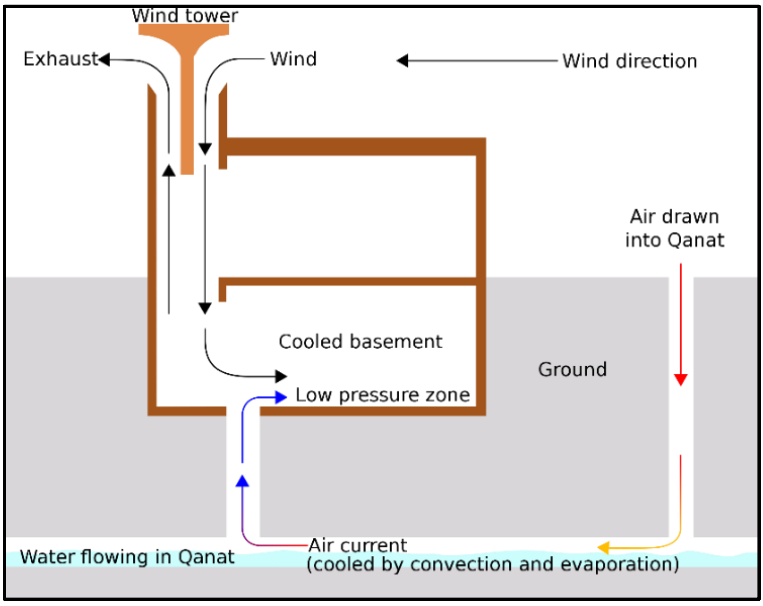


Figure 15: Vertical section of a cooling system that integrates a wind tower with an *Ab-Anbar* and a *Qanat* (Gholikandi, Sadrzadeh and Jamshidi 2013)

Badgirs are not always used in conjunction with *Ab-Anbars* that depend on cool *Qanat* water for their operation. In some instances, cooling is achieved through an integrated system using only *Badgirs* and *Qanats* (Figure 16). For example, traditional houses in the bazaar area of Yazd have multiple basements, accessible by stairs from the courtyard to the *Payab*, the water level of the *Qanat*. Well shafts are constructed from kitchens to reach the *Qanat* water, allowing water to be drawn up with winding wheels. Additionally, shafts lead from the summer living rooms in basements to the *Qanat* channels, channeling the cool, humid mountain air into these spaces (Roaf, 2009).

The tunnel temperature remains between 10°C and 13.5°C year-round, with minimal variation between the water temperature at the mother well and where it surfaces. Figure 17 illustrates a *Badgir-Qanat* system that effectively lowers the temperature in basements by approximately 5°C (Hartl, 1989).



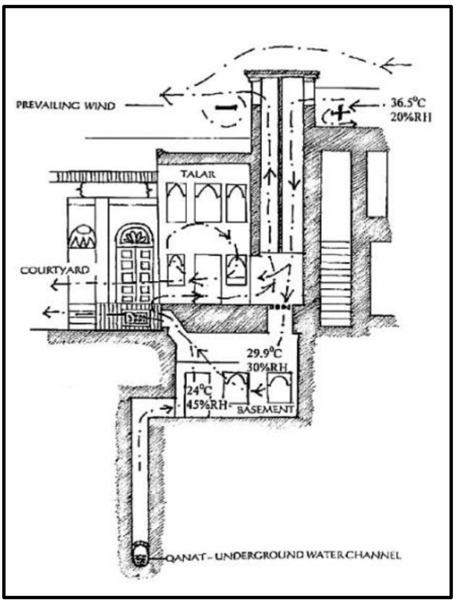


Figure 16 (Left): Schematic diagram of a cooling system that integrates a wind tower with a *Qanat* (Bahadori 1978)

Figure 17 (Right): Vertical section of a traditional house with multiple *Badgir*s, of which one is linked to the water level of the *Qanat* by a well (Roaf 2009)

There is no exact documentation pinpointing the initial instance of integrating *Badgirs* with *Qanats* in ancient Persia. However, it is probable that this combination emerged during the first millennium BCE, when both wind towers (*Badgirs*) for cooling and underground water channels (*Qanats*) for irrigation and temperature regulation were already well-established. The synergy between these two systems would have enabled the use of cool underground water to enhance the efficiency of *Badgirs*, providing an effective means to cool homes and public spaces (Sangin 2023).

6. SOLUTIONS TO ACCELARATE THE UTILIZATION OF SHALLOW GETHERMAL COOLING

As climate change intensifies and urban areas face increasingly frequent heatwaves, finding practical, scalable solutions to expand the use of shallow geothermal cooling has become essential. Shallow geothermal systems offer a sustainable alternative to conventional air conditioning, reducing greenhouse gas emissions and mitigating urban heat island effects. However, the architectural and infrastructural limitations of existing buildings, along with a lack of centralized cooling data, pose significant challenges to widespread adoption.

The following solutions address these challenges by introducing retrofitting options, hybrid cooling approaches, and advanced data collection methods, all tailored to enhance the feasibility and appeal of shallow geothermal cooling. These measures provide a framework for integrating geothermal systems into existing urban settings, while also encouraging innovation in new building designs and supporting policies that incentivize sustainable cooling. Together, these solutions lay the groundwork for a resilient, climate-adaptive approach to urban cooling.

6.1. Retrofitting Existing Buildings and District Cooling Solutions

- The retrofitting of buildings to accommodate shallow geothermal systems is crucial for expanding their use, especially in existing structures not originally designed for centralized cooling. Community-based cooling approaches offer a scalable solution, especially in densely populated urban areas where individual retrofits may be cost-prohibitive.
- Customized Retrofitting Solutions: Implementing shallow geothermal cooling without a complete infrastructure overhaul is possible with targeted retrofitting. Modifying HVAC systems or integrating smaller, modular geothermal units can enable shallow geothermal installation within current architectural layouts.
- Shared Duct Systems: For buildings lacking central cooling, a shared or centralized ductwork system can be introduced, particularly in multi-unit residential or commercial buildings. This approach provides a cost-effective means of distributing geothermal cooling.
- Community-Based Cooling Systems: Implementing district-wide geothermal cooling infrastructure serves multiple buildings through shared systems, making it viable in high-density residential and commercial areas. This collective approach leverages economies of scale, reducing costs for individual properties.
- Localized Cooling Hubs: Small cooling plants, strategically located within urban zones, can distribute cooled air or water to neighboring buildings, minimizing the need for extensive individual retrofitting.

6.2. Comprehensive Data Collection, Alternative Methods for Estimating Cooling Demand, and Enhanced Simulation Tools

Accurate cooling demand data and predictive tools are essential for planning and optimizing geothermal systems effectively in buildings that lack existing cooling infrastructure. Improving cooling demand estimation methods is crucial for precise system sizing and effective shallow geothermal implementation. To support this, creating a detailed cooling demand map or atlas for Europe and Germany would provide a valuable tool for assessing regional and localized cooling needs, guiding geothermal system design and urban planning.

- Enhanced Simulation Software: Utilizing advanced simulation software enables the estimation of cooling loads and geothermal potential, even in the absence of comprehensive cooling data. Data modeling based on climate, building orientation, and occupancy patterns provides a more accurate assessment of a building’s cooling requirements.
- Smart Building Technologies: Deploying smart meters and data collection devices for real-time temperature and energy monitoring helps establish a reliable cooling demand baseline. This information aids in designing tailored shallow geothermal systems that align with the building’s specific cooling needs.

- Temperature Differential Modeling: Estimating cooling demand based on the difference between indoor and outdoor temperatures while accounting for building materials and insulation provides a refined approach to understanding real-world variables. By integrating simulation tools to validate these temperature-based models against actual consumption data, this method enhances accuracy, enabling shallow geothermal installations to be more precisely tailored to meet actual cooling needs.
- Cooling Demand Map: Developing a comprehensive cooling demand map for Europe and Germany would enable targeted planning and resource allocation for shallow geothermal cooling projects. This map would detail regional cooling demand patterns based on climate projections, building types, and occupancy trends, assisting in identifying high-demand areas and guiding infrastructure investment.

6.3. Inspirations from the Past, Integration of Passive Cooling Methods, and Architectural Design Adaptations

Combining passive cooling methods with geothermal systems can optimize energy efficiency and ease the retrofitting process in older buildings. Future building designs should accommodate geothermal cooling systems and draw on traditional methods for more sustainable construction.

- Integrating Passive and Active Cooling: Enhanced insulation, along with passive cooling features like strategic shading, wind catchers, and thicker walls, can effectively complement shallow geothermal systems. This approach supports cost-efficient retrofitting, lowers overall energy demand, and reduces reliance on active cooling solutions.
- Learning from the Past: Incorporating historical design techniques, inspired by traditional architecture such as ancient Persian designs, can enhance modern shallow geothermal systems by integrating low-carbon construction elements that harness natural forces for cooling. Features like wind catchers and underground channels provide environmentally friendly methods to amplify cooling, reducing dependency on artificial systems and minimizing additional energy consumption.
- Future-Ready Building Design: Architects can design new structures that readily accommodate shallow geothermal cooling systems. By incorporating low-carbon construction elements that utilize natural forces for cooling, buildings can be designed with reduced reliance on artificial systems. These methods create a more sustainable approach, optimizing energy efficiency and lowering the overall environmental impact of cooling.

6.4. Learning from Hotter Climates

As Europe prepares for hotter summers, lessons can be drawn from regions that currently experience extreme summer temperatures.

- Monitoring and Simulation in Regions with High Cooling Demand: Conducting monitoring and simulation tests in buildings with centralized cooling in the Middle East and North Africa (MENA) can provide valuable insights for Europe. While shallow geothermal cooling is not widely used in these areas, testing its potential in buildings with air conditioning could inform Europe’s future needs, helping establish a district-level cooling demand database.
- Data Analysis of Cooling Demand: Examining cooling demand data from air-conditioned buildings in the MENA region can aid in projecting cooling needs for Europe’s future summers. These projections will guide district-level planning and enhance geothermal cooling design for European urban centers.

6.5. Policy and Incentive Adjustments

To create a climate-resilient future, European policymakers must prioritize sustainable cooling solutions and promote building renovations suited to rising temperatures. Supportive policies and financial incentives are essential to make shallow geothermal systems and retrofitting projects more accessible and attractive.

- Enhanced Renovation Policies: Renovation efforts should focus on adapting existing buildings to withstand hotter summers. Increased funding and incentives for energy-efficient upgrades will make sustainable cooling options, like shallow geothermal systems, more appealing and practical.
- Financial Incentives for Retrofitting: Subsidies, tax credits, and low-interest loans for homeowners and property managers can help offset the initial costs of geothermal installations, encouraging the retrofitting of existing buildings with sustainable cooling systems.
- Updated Building Codes: Working with policymakers to revise building codes can encourage architectural designs that facilitate future geothermal retrofitting. For instance, codes could require ductwork or geothermal-compatible piping in new construction, making it simpler to integrate geothermal systems later.
- Clear Regulatory Support for Sustainable Cooling: Regulations and incentives that promote sustainable cooling upgrades can guide architectural practices toward designs that accommodate shallow geothermal technology and passive cooling, making energy-efficient cooling solutions more feasible for developers and property owners.

6. CONCLUSION

Shallow geothermal cooling presents a viable pathway toward sustainable urban cooling, addressing both the rising energy demands and environmental impact associated with conventional cooling methods. However, significant architectural and infrastructural challenges stand in the way of its widespread adoption, particularly within Europe’s historical and non-centralized building structures. The solutions outlined in this paper, including adaptable retrofitting strategies, district cooling networks, and supportive policy frameworks, offer practical avenues to expand SGE integration. Furthermore, leveraging passive cooling techniques from historical designs can enhance system efficiency, aligning SGE with the broader climate resilience goals of European cities. Embracing these strategies positions Europe to mitigate urban heat effectively and reduce emissions, paving the way for a more climate-resilient future.

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