

Exploring the Legacy of Ancient Iran: Is Iran the Birthplace of Geothermal Energy Utilization for Refrigeration through an Integrated Energy System of Geothermal, Wind, and Hydrothermic Energy Storage?

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Keywords: Iran, Ancient, Geothermal, Cooling, Badgir, Qanat, Ab-Anbar

ABSTRACT

Geothermal energy utilization can be traced back to the Paleolithic era, an impressive 14,000 years ago. Although the majority of ancient societies predominantly relied on surface geothermal activities to extract heat and minerals, the remarkable Persian civilization ingeniously constructed a geothermal system that integrated wells, water channels, heat exchangers, and heat storage systems. The ancient Persian cooling methods were primarily centered around the *Badgirs*, which are windcatchers, and their amalgamation with *Qanat*, the underground water channels, and *Ab-Anbar*, the underground water storage cisterns. In a meticulously-designed integrated energy system comprising geothermal, wind, and hydrothermic thermal energy storage, the *Qanat* embodies the geothermal section, the *Badgir* represents the wind section, and the *Ab-Anbar* represents the hydrothermic thermal energy storage system.

This paper aims to examine the historical legacy of ancient Iran in the development of geothermal energy utilization for refrigeration. In addition, the paper seeks to verify whether Iran's cooling systems were the first geothermal cooling systems in history. By exploring the historical roots and unique features of this innovative energy system, the paper intends to shed light on how ancient civilizations utilized geothermal energy for cooling purposes and how this knowledge can be leveraged to develop sustainable and efficient cooling technologies in the modern world.

1. INTRODUCTION

Human civilization's use of geothermal energy can be traced back to the Paleolithic era, approximately 14,000 years ago (United Nations University, n.d.). During this period, humankind discovered the benefits of hydrothermal springs, such as thermal bathing, cooking, and balneotherapy. Archaeological evidence shows that thermal water use was widespread worldwide, with examples in China, Japan, and the Roman Empire (Fridleifsson 2000). In Japan, for example, traces of Japanese culture dating back to the pre-pottery period before 11,000 BCE have been unearthed near the Yuda hot spring in the Iwate Prefecture (Sekioka 1999). In addition, reconstructed pictures from 12000 years old wall paintings of the Çatal Hüyük cave in Turkey (Özgüler und Kasap 1999) show volcanic eruptions, water outflows, and steam emanations.

The Bronze Age saw the development of a civilization in central Italy with settlements and cities neighboring springs, geothermal manifestations, and creations of hydrothermal activity (Cataldi and Chiellini 1999). The Etruscans were most active in recovering, processing, and using geothermal products such as alum, borate, kaolin, iron oxides, sulfur, silica, travertines, and thermo-mineral muds, which were mainly used for the production of pottery, enamel, paints, dyeing glass, wool, cloth, ointments, and other medicines (Kępińska 2004). North America's first human use of geothermal resources occurred more than 10,000 years ago, with Paleo-Indians settling at hot springs for warmth and cleansing and their minerals serving as healers. The Americas were also home to many other geothermal phenomena considered sacred by indigenous cultures. For example, geothermal springs were holy sites believed to be places where spirits resided (Kępińska 2004).

While most of the ancient geothermal energy utilization involved exploiting the heat and minerals of natural geothermal activities appearing at the surface, one civilization, the Persians, developed a geothermal system made of wells, water channels, heat exchangers, and heat storage systems (Kępińska 2004). The Persians integrated that system with the energy of the wind and used it for cooling purposes. The ancient Persians were the only civilization in history to use the subsurface as a ground-coupled heat exchanger to exploit geothermal energy for refrigeration. Other ancient civilizations, such as Egypt, Greece, China, and Rome, also developed innovative cooling systems utilizing the principles of shading, ventilation, and underground ducts. For example, the ancient Egyptians used evaporative cooling systems, such as wind catchers and underground ducts, as early as 2500 BCE. The ancient Greeks utilized similar techniques, including wind towers, courtyards, and fountains, to cool their homes and public spaces, tracing back to the 8th century BCE. Ancient Chinese used yin-yang roofs, underground ducts, wind catchers, and courtyards as cooling systems as early as the 5th century BCE. The ancient Romans employed the hypocaust, a system of underfloor heating that also helped regulate temperature, and shading devices such as awnings and ventilation principles to cool their homes and public spaces. The focus of this paper is to explore the legacy of ancient Iran in the development of geothermal energy utilization for refrigeration through an integrated energy system of geothermal, wind, and hydrothermic thermal energy storage. We will delve into this innovative energy system's historical roots, unique features, and benefits.

2. GEOTHERMAL SYSTEMS FOR COOLING

Geothermal energy systems, particularly those of the underground hydrothermal subgroup, have traditionally been linked to heating applications. However, they also possess significant potential for cooling purposes, making them an underappreciated and sustainable means of cooling buildings and establishments (as depicted in Figure 1). Geothermal cooling involves utilizing the subsurface's relatively stable and lower temperature to transfer heat via a fluid, typically water, thereby employing the subsurface as a heat sink. The cooled water is subsequently recirculated to moderate the higher ambient temperature.

To enable geothermal cooling, a geothermal heat pump system is utilized, which involves a closed loop of pipes buried underground to extract heat and divert it away from the building. The heat is then dissipated into the cooler ground, where it is absorbed and dispersed. This approach exploits the natural temperature disparity between indoor and outdoor settings, relying on the fundamental principle of heat transfer from hotter to cooler regions. Aquifer thermal energy cooling, a subtype of geothermal cooling, employs the cooler and relatively stable groundwater temperature to provide cooling to a building. This sustainable and environmentally friendly cooling method employs a well or wells drilled into the ground, linked to a heat pump and a network of piping that circulates water between the building and the aquifer.

Geothermal cooling (Figure 1) has several substantial benefits, including sustainability, environmental friendliness, and consistency. Its consistent and reliable cooling source is due to the fact that the temperature of the subsurface remains stable throughout the year, even during temperature fluctuations above ground. This aspect makes geothermal cooling a dependable cooling source in hot and humid areas where traditional air conditioning systems may not be as effective. In addition to its environmental benefits, geothermal cooling is also energy-efficient, with potential energy savings of up to 50% compared to conventional air conditioning systems. However, it should be noted that most geothermal cooling systems require a heat pump, which operates on electricity, and, therefore, still entails a carbon footprint linked to its production and use. Although geothermal cooling systems require a heat pump that operates on electricity, they remain a greener and more sustainable option compared to conventional air conditioning systems.

It is worth noting that ancient Persian cooling systems were also renewable, green, and sustainable energy systems that did not rely on electricity, utilizing only the forces of nature thousands of years ago. As concerns over climate change continue to grow, geothermal cooling systems like these are becoming an increasingly popular and viable option for building owners and managers seeking energy-efficient and sustainable cooling solutions. The cooling methods utilized in ancient Persia were primarily based on the use of *Badgir* (windcatchers), their combination with *Qanat* (underground water channels), and *Ab-Anbar* (underground water storage cisterns). In an Integrated Energy System structure incorporating Geothermal, Wind, and Hydrothermal Thermal Energy Storage, the *Qanat* represents the geothermal section, the *Badgir* represents the wind section, and the *Ab-Anbar* represents the Hydrothermal energy system.

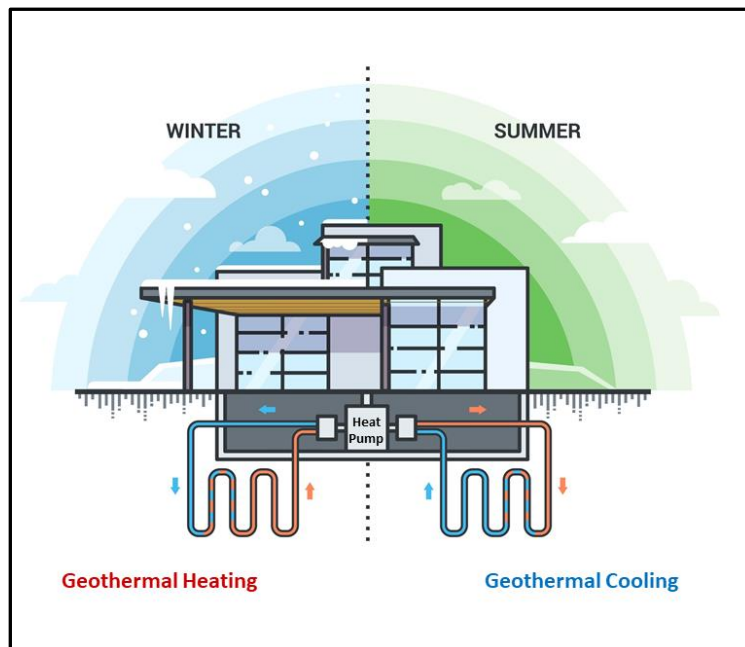


Figure 1: Geothermal cooling and heating (Sasha 2023)

3. QANAT SYSTEMS, THE GEOTHERMAL ASPECT

The Persian *Qanat* system (Figure 2 and Figure 3) is an ancient source of water management that has been utilized throughout much of the Middle East, such as Iraq, Afghanistan, and Central Asia. It has also been employed in various parts of North Africa, Spain, and South Asia. Today, *Qanats* are still used in many parts of the world, especially in arid regions with limited access to water. *Qanats* have played a crucial role in water supply management in Iran for many years in an arguably sustainable manner (Manuel, Lightfoot and Fattahi 2018). The system involves gently sloping subterranean canals tap an aquifer at a higher elevation than tilled land. The canals are interconnected by almost horizontal tunnels and withhold a series of vertical wells in an elevated field. The first shaft, known as the mother well, is dug to a level below the groundwater of an alluvial fan aquifer. At the same time, the rest of the wells are excavated at intervals of 20 to 200 meters in a 300-meter to 65-kilometer line between the groundwater recharge zone and the irrigated land (Figures 4 and Figure 5).

The *Qanat* system is built by hand and works only with the force of gravity, making it an eco-friendly method of water management that leaves zero carbon footprint. Moreover, the system drains out groundwater overflow and does not throw the aquifer inflow-outflow off balance (ICOMOS 2016). The *Qanat* system was highly valued in ancient Persia and was considered a technological marvel. It allowed for the sustained growth of crops and the creation of prosperous cities and civilizations in arid regions. In addition, the cool water (10 to 15 degrees Celsius) from the *Qanats*, together with underground ducts or wind towers (*Badgirs*), was used to cool homes and public spaces, making it an essential system for temperature regulation and cooling.

The location and date of the first built *Qanat* system are not well documented. However, *Qanats* are believed to have originated in Persia, present-day Iran, in the early 1st millennium BCE. The traces of the *Qanat* can be seen throughout the history of Iran, from the Elamites and Assyrians (1400-550 BCE) to the Achaemenian Empire (550-330 BCE), Seleucidian Era (312-250 BCE), Parthian (250 BCE-150 CE), Sassanid (226-650 CE) and the Islamic period from 621 CE (Lightfoot 2000). Thus, they were rediscovered, built, maintained, destroyed, and rebuilt in each succeeding civilization. Outside Iran, *Qanats* or their similar systems have been discovered in Afghanistan, Azerbaijan, Iraq, Oman, Pakistan, China, Algeria, Morocco, Spain, and Italy. Among these, five *Qanats* in Oman were submitted to the World Heritage List in 2006 as "The *Aflaj* (*Qanat*) Irrigation systems of Oman" (ICOMOS 2016). However, Wilkinson (1977) argued that the *Aflaj* of Oman were all constructed during the Persian occupation of Oman in the Achaemenid (550-331 B.C.) and Sasanide (till the mid of the 7th century A.D. before the advent of Islam) eras (Al-Ghafri, Inoue and Nagasawa 2003).

Regardless of exactly how it began, the system has spread widely in Iran (Figure 6). In 2014, 37000 active *Qanats* ran all over Iran, discharging about 7 billion cubic meters of groundwater annually.



Figure 2 (Left): Inside of a *Qanat* in Shahdad, Iran (Marshall 2016)

Figure 3 (Right): Outside of a *Qanat* in Ramsheh, Iran (Geo 2018)

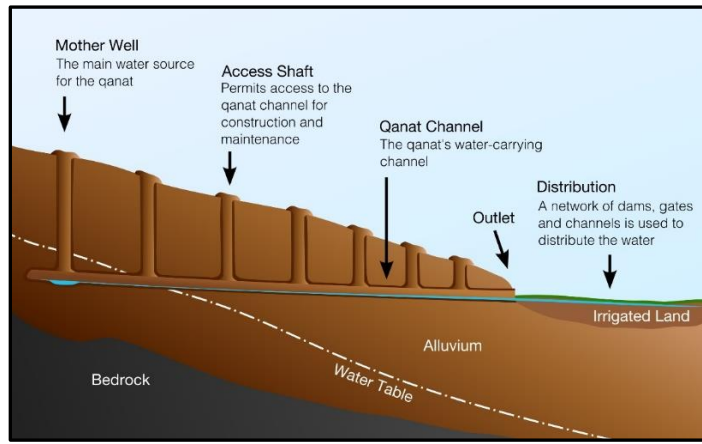


Figure 4: A cross section of the *Qanat* system (Bailey 2009)



Figure 5: An aerial view of the *Qanat* system (Rashedi 2014)

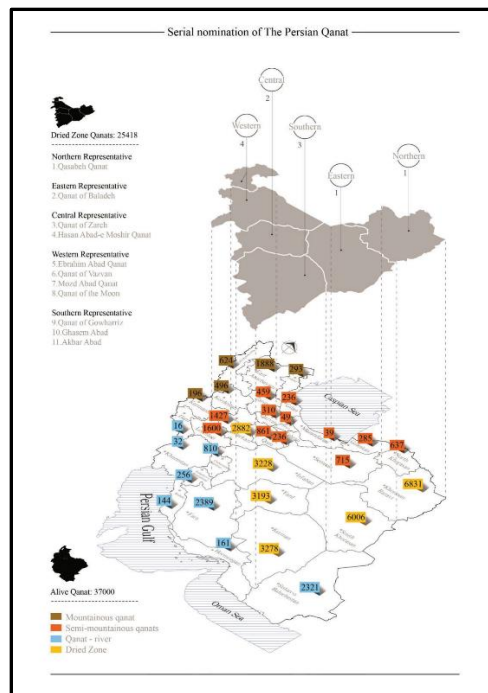


Figure 6: The spread of *Qanats* in Iran (ICOMOS 2016)

4. AB-ANBAR, THE HYDROTHERMIC ENERGY STORAGE ASPECT

The *Ab-Anbar* (Figure 7 and Figure 8) is a subterranean water storage cistern widely used in various settings, including cities, villages, forts, caravan routes, and mountainous regions in Iran (Yousefi and Nocera 2021) (Yousefi et al., 2021). The *Ab-Anbar* is constructed underground with a dome-like roof and possibly several ducts as *Badgirs*. Water is typically collected from *Qanats* and stored at depths of 10 to 20 meters, maintaining a cool temperature during the warm summer months (Saeidian 2013). However, rainwater is also stored. The architectural design of *Ab-Anbars* leverages the seasonal temperature changes and isolated nature of the ground to promote evaporation from the upper layer of water, which exits through the dome-like roof with the aid of an air trap (Yousefi and Nocera 2021).

The origin of *Ab-Anbars* can be traced back to the early civilizations of Iran, including the Elamite city of Duravantash and the Achaemenid rule, with remnants still evident in the area of Takht-e Jamshid (Le Strange 2011). The *Ab-Anbar* not only played a crucial role in the people's daily life but also held a vital place in their culture and beliefs, being considered sacred in some cases.

The diverse construction features of *Ab-Anbars*, reflect the climatic diversity across the country, showcasing the exceptional skill of Persian architecture and engineering (Memarian 2009). However, studies have shown that arched roofs absorb less heat than flat roofs through radiation (Bahadori and Haghighat 1986). The roof shape affects the average absorbed radiation heat and indoor air temperature (Gómez-Muñoz, Porta-Gándara and Heard 2003). In addition, studies have investigated the effect of shadow on the energy received by the domed roof compared to the flat roof (Figure 9). The findings suggested that the hemispherical dome receives nearly 35% less solar energy than a flat roof (Velayati and Yaghoubi 2004). Therefore, in hot and arid areas like Yazd, the higher the ratio of height to the span of the dome, the lower the internal heat, making the *Ab-Anbar* a practical solution for water storage (Yousefi and Nocera 2021) Overall, the *Ab-Anbar* is an exceptional example of the adaptive nature of Persian architectural and engineering practices.



Figure 7 (Left): Inside of the Klar *Ab-Anbar* in the Shah Abbasi Caravanserai, Meybod, Iran (MehmetO 2018)

Figure 8 (Right): Outside of the Klar *Ab-Anbar* in the Shah Abbasi Caravanserai, Meybod, Iran (Dealbert 2018)


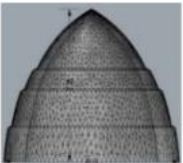
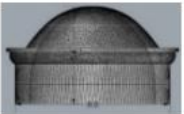
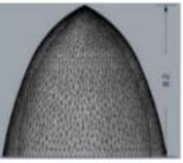

Shah vali Taft	Haj Ghazi	Barsuie Taft	Sahraie Dasti	Haj Nasir
				
185m ²	249m ²	281m ²	265m ²	196m ²

Figure 9: Different types of *Ab-Anbar* domes (Shiri, Didehban and Taban 2022)

5. BADGIR, THE WIND ASPECT

The *Badgir* (Figure 10), also known as the Persian wind catcher, is a quintessential feature of Iranian architecture in hot and humid regions. As a passive cooling system, it harnesses natural elements to establish a comfortable indoor atmosphere. The primary function of this architectural marvel is to regulate temperature by catching fresh air and channeling it into buildings, resulting in lower indoor temperatures. Figure 11 illustrates the flow of air as it enters through the inlet openings of the wind-catcher, rotates within the structure, and ventilates the interior space before exiting through the outlet (Aboui, Mozafar and Ameli 2012).

Apart from cooling, *Badgirs* also serve as effective ventilators, conveying pleasant air from the ground floor courtyards to the pinnacle of the wind tower (Hejazi and Hejazi 2014). For centuries, these structures have been utilized as a traditional ventilation and cooling system in various countries of the Middle East and Northern Africa, and their architectural and cooling characteristics have been the subject of intense research in recent decades (Hejazi and Hejazi 2014). The use of *Badgirs* dates back to 4000 BCE, as substantiated by excavations of Masouda in Shahrud, Northern Iran (Masouda 1974).

The *Badgir's* significance extends beyond cooling performance and ventilation. In regions with hot and arid climates, such as Kassar, Yazd, Kerman, and the northern coastlines of the Persian Gulf, they are viewed as a symbol of regional architecture (Yarshater 1989). In addition, the *Badgirs* is a tribute to the inventive and resourceful ancient Persians who used their knowledge of natural elements to develop a sustainable and comfortable living environment. They epitomize the convergence of architecture, culture, and climate.



Figure 10: Traditional house with the *Badgirs*, Aghazadeh, Abarkuh, Yazd Province, Iran (Morandi 2016)

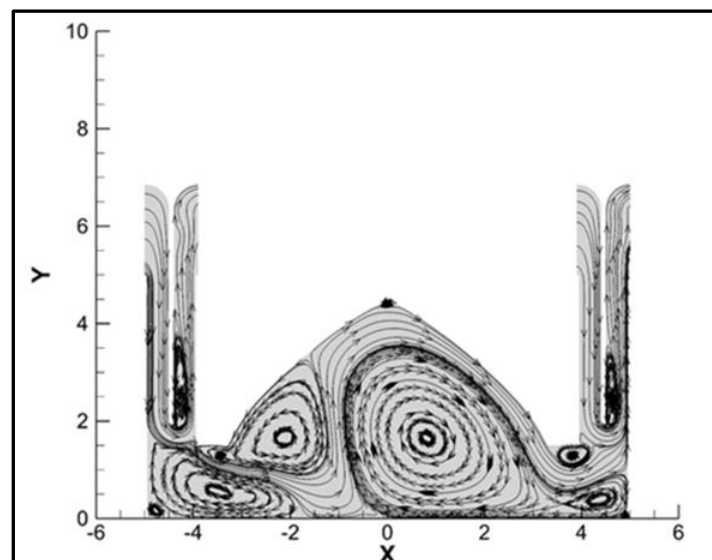


Figure 11: Pattern of air flow inside an establishment with a dome and wind-catchers (Yousefi and Nocera 2021)

6. INTEGRATED ENERGY SYSTEM OF GEOTHERMAL, WIND, AND HYDROTHERMIC THERMAL ENERGY STORAGE

The conflation of a *Badgir* and an *Ab-Anbar* (Figure 12) entails the application of one to six wind towers that encompass the periphery of the water reservoir. This mechanism capitalizes on the cooling potential of the relatively frigid water by instigating the movement of warm air across the water's surface, causing evaporative cooling. It is worth noting, however, that the quantity of evaporated water corresponds to a concomitant decrease in the available water supply. The ameliorated warm air is expelled via outer shafts and wind towers, thereby promoting the circulation of cooled air throughout the premises while venting heated air through the apertures situated in the pinnacle of the *Badgir* (Figure 13). When combining *Badgir*, *Ab-Anbar*, and *Qanat*, the airflow enters the wind-catcher through its inlet openings. After circulating within the *Ab-Anbar*, which is nourished by the *Qanat* (as shown in Figure 14), the airflow ventilates the interior space before exiting through the windcatchers outlet.

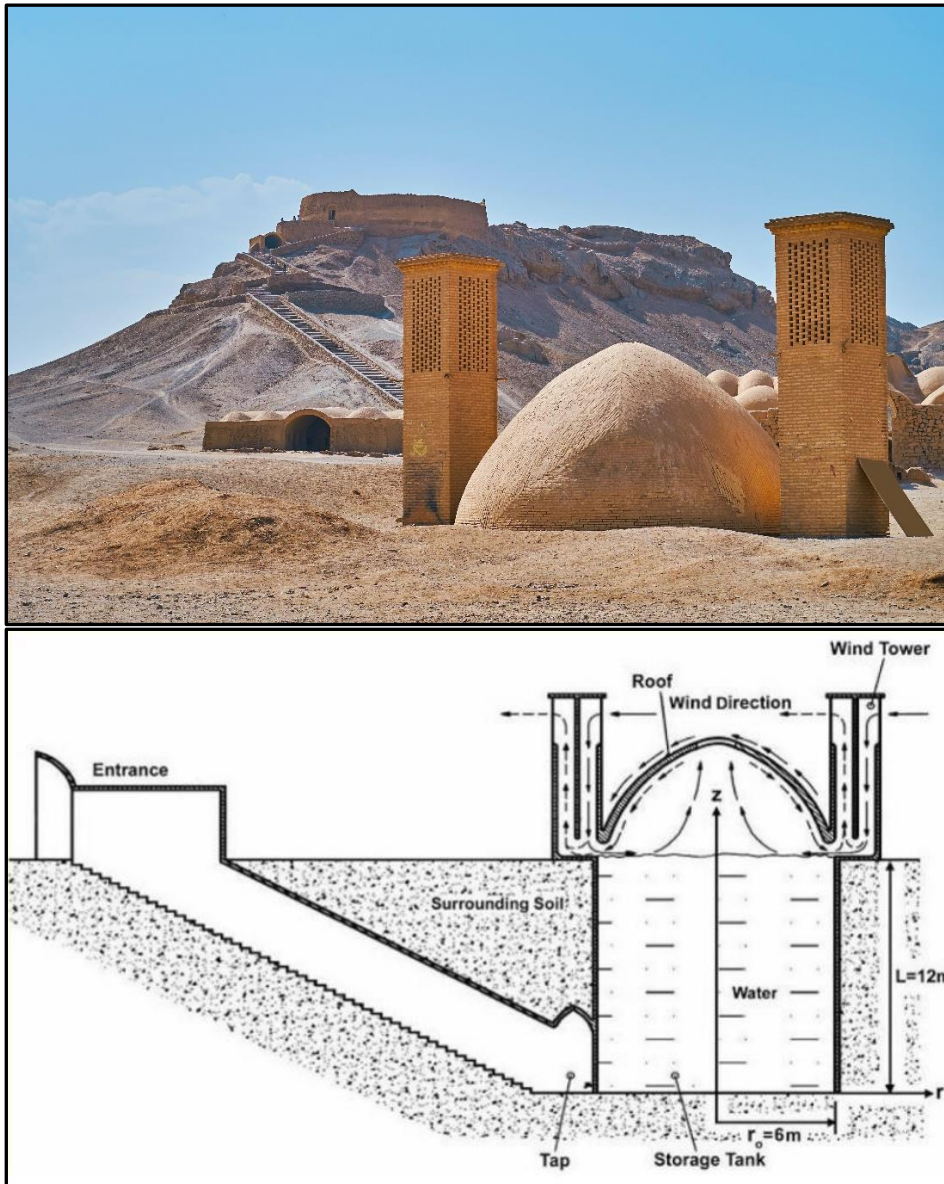


Figure 12 (Top): The view on an *Ab-Anbar* with two *Badgir* Towers in Yazd, Iran (eFesenko 2017)

Figure 13 (Bottom): Vertical section of an *Ab-Anbar* equipped with *Badgir* (Shiri, Didehban and Taban 2022)

The earliest documented evidence of the simultaneous implementation of *Badgirs* and *Ab-Anbars* in a singular structure within Iran can be traced back to the 4th and 5th centuries A.H. (10 A.D.), roughly 1022 years ago. The oldest standing edifices that manifest this fusion of architectural elements date back to the Timurid Empire's era, approximately 550 years ago, in the 9th century A.H. (15 A.D.). During this time, *Badgirs* began to appear in the residences of Yazd-Ardakan, marking the emergence of technology (Aboui, Mozafar and Ameli 2012).

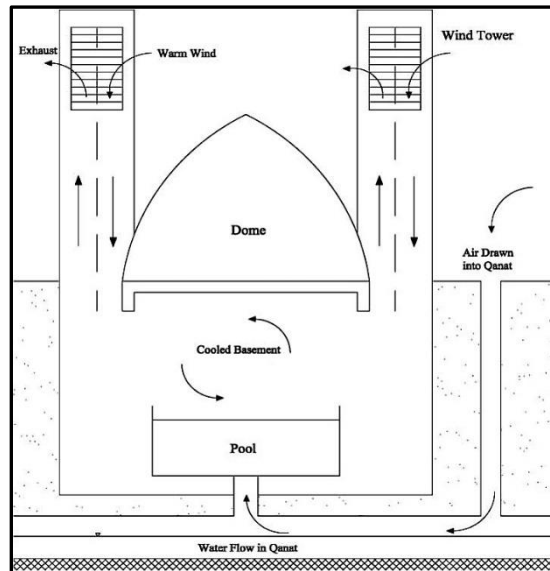


Figure 14: Vertical section of a cooling system that integrates a wind tower with an *Ab-Anbar* and a *Qanat* (Gholikandi, Sadrzadeh and Jamshidi 2013)

Badgirs are not always accompanied by *Ab-Anbars* that rely on cool *Qanat* water for their functioning. In some cases, an establishment is cooled using an integrated system of *Badgirs* and *Qanats* only (Figure 15). For example, the traditional old houses in the bazaar quarter of Yazd have many lower basements, which are accessible through a flight of stairs from the courtyard to the *Payab*, *Qanat's* water level. Well shafts are constructed from the kitchens to the *Qanat* water, where water is drawn up via winding wheels. Additionally, well shafts are constructed from the summertime living room in the basements into the *Qanat* water channels to direct the cool, humid mountain air into the basement (Roaf 2009).

The temperature inside the tunnel ranges from 10 degrees Celsius to 13.5 degrees Celsius throughout the year, and there is little difference in temperature between the water at the mother well and the point where it emerges from the ground. Figure 16 shows a *Badgir-Qanat* system that reduces the basement's temperature by nearly 5 degrees Celsius (Hartl 1989).

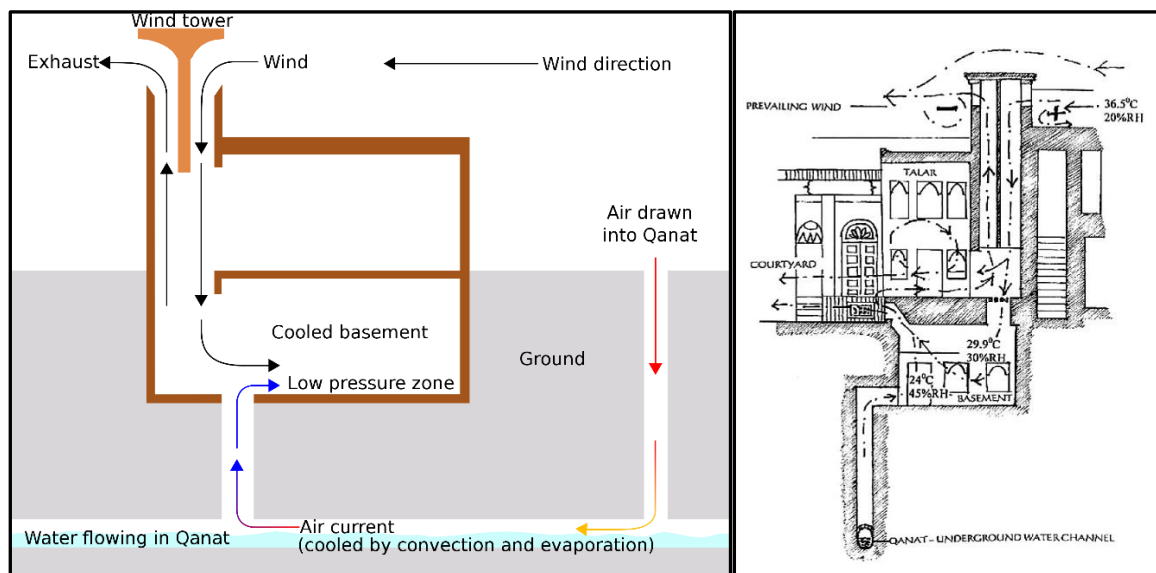


Figure 15 (Left): Schematic diagram of a cooling system that integrates a wind tower with a *Qanat* (Bahadori 1978)

Figure 16 (Right): Vertical section of a traditional house with multiple *Badgirs*, of which one is linked to the water level of the *Qanat* by a well (Roaf 2009)

There is no precise record indicating the date of the first instance where *Badgirs* were linked to *Qanats* in ancient Persia. However, it is likely that the combination of these technologies was used in the first millennium BCE when the use of wind towers (*Badgirs*) for cooling and underground water channels (*Qanats*) for irrigation and temperature regulation was already established in Persia. The connection between these two systems would have allowed for the utilization of cool underground water to increase the efficiency of the *Badgirs* in cooling homes and public spaces.

7. CONCLUSION

This investigation aimed to ascertain whether Iran's historical cooling systems were indeed the inaugural geothermal cooling systems. To attain this primary objective, it is pivotal to conclusively establish that the described cooling structure implemented in ancient Persia was indeed a geothermal system or, more accurately, a terrestrial hydrothermal energy system. In contemporary times, the principal constituents of a geothermal energy system in a building comprise a heat source, a heat sink, wells, a circulating fluid to either extract or dispense heat, a pump for circulating said fluid, and a mechanism to exchange and distribute the extracted heat or cold to the targeted premises. Upon reviewing figures 13 and 14, it is evident that the ancient Persian cooling system featured ambient air as the circulating fluid, the building's interior as the heat source, and the *Ab-Anbar* and *Qanat* as the terrestrial heat sink. It further comprised a production well attached to the dwelling for generating cold, an injection well located outside to inject the fluid into the terrestrial heat sink, and a wind catcher acting as the pump for circulating the air while transferring heat with the terrestrial heat sink, utilizing the subsurface as a ground-coupled heat exchanger. Thus, it is apparent that the ancient cooling systems in Iran qualify as geothermal cooling systems. Since the ancient Persian cooling system is the only known utilization of geothermal energy for cooling among ancient geothermal applications and is the sole ancient cooling system that employed geothermal energy for cooling, it is reasonably justifiable to posit that Iran represents the birthplace of Geothermal Energy Utilization for Refrigeration. This feat is achieved via an Integrated Energy System incorporating Geothermal, Wind, and Hydrothermic Energy Storage. Such an accomplishment is entirely sourced from the forces of nature, with zero carbon footprint and without electricity or fossil fuel consumption. The author contends that this archaic system can act as a source of inspiration for the modern world to design a similar system that is more environmentally sustainable, with significantly less carbon footprint, even compared to the existing cooling systems that operate on renewable energy.

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