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A survey in sustainable design of Iranian windmill technology in desert areas

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ABSTRACT

Considering the nature and utilizing its potential powers have got the long history in the eastern countries, so that the numerous examples of minimum energy consumption and *Renewable Energy* usage are recognizable in their historical past. Based on the studies on the local windmills known as *Asbads*, located in the eastern part of Iran (the southern part of *Khorasan* and *Sistan*), Wind power, known as *Renewable* or *Eco-friendly Energy* in the contemporary age, plays the pivotal role in the historical and cultural traditions of this country. The study mainly shows that *Asbads* as the traditional mechanical machines, used for the wind power transmission mechanism can be utilized again in the contemporary era, developing its overall mechanism or constructive materials. Such an action is considered as an innovative step toward overcoming the nature, but this time not to destroy it but to keep it for the following generations. Based on the research provided modeling, *Asbads* mechanism in transmission of wind kinetic energy to the energy needed for the agricultural activities such as gridding the wheat or barley can be simply applied in the contemporary era.

The present study is of descriptive-analytical type. Data gathering was done in library and fieldwork method. To this end, the *Lutak*, *Neshtifan*, and *Nehbandan* windmills, located in *Sistan* Province, were studied. Following the study of the windmill history of *Sistan* Province and southeast of Iran, the quotations from foreign travellers as well as the stand and the function of the mills in Iran's architecture were investigated. It is noteworthy that the functional elements of the mills are designed according to the aerodynamics rules. This fact suggests that the builders of these mills were cognizant of the capacity and behavior of the wind to satisfy the daily needs of people.

Introduction

The structures such as windmills, which are remained from past to add to the knowledge and understandings of the today and future generations, are also the indicators of creativity of our ancestors and ancient people. Windmills, dating back to 2,800 years ago, are among the oldest examples of using the power of nature by human beings. Some believe that the art of windmill building has been transferred from Iran to the European countries during the Crusade. Because of blowing a type of wind called 120-day wind in Iran, people of Sistan Province made several attempts to exploit the power of this wind. As a result, they invented the Windmills, which are considered as one of the most important inventions of human, to both control and take advantage of the wind power.

The word *Asyab*, which has its root in Pahlavi variety of Persian language, is composed of two parts, as and ab. *Asyab* means an as which turns around with the power of ab. *As*, in Persian, means crushing the grain into powder under a millstone (Nakhjavani1967), and *ab* is a Persian word, which means water. In Amid Dictionary, as is defined as two rounded and flat stones on each other through which a metal shaft passes. The above stone turns around by the power of men's hands, water, wind, or water steam and, as a result, the grains are ground.

A long time ago, Persian people took a step to exploit the power of nature, by building watermills and milling the grains. Before building watermills, man had to place reliance on his own hands or cattle power to mill the wheat. Thus, the first source of power to mill was the power of hand. After that, man started to use his livestock to do the act of milling. In some parts of Iran, the term *Kharas* was coined, which was composed of two parts. The first part, *khar*, means donkey, and the second part, as, means milling. This term was used to show the usage of donkey, camel, cow, or horse to rotate the millstone (Khosravi1994). Until recently, these kinds of mills were used to extract oil from the seeds [the term extractor or extractor horse is related to this action]. In Yazd City, these kinds of mills were operated with camel to rub henna, and were called Mazari.

The first time that wind power was recognizedas a source of energy is not clear. According to the domestic and foreign documents, Persian people were the first to use wind power to run windmills and the mill wheels (Bennert and Werner1991).It is generally admitted that after succeeding in benefitting from the technology of using one-directional movement of water to rotate the millstone, Iranian started to use wind power to rotate the millstones and draw well water from underground. There is no doubt that the first mills were built in a region in Sistan or Sagastan] Province to Ghuhestan [or Kuhestan], thousands years ago (Molly 1990). However, the realm of windmill construction in Iran is from North to South and between Khaf with 35 degrees and 16 minutes longitude as well as 59 degrees and 13 minutes latitude in North and Zabol with 31 degrees and 1 minute longitude as well as 16 degrees and 29 minutes latitude

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in South [Figure 1] where maximum temperature in the summer is 36 centigrade and minimum is 2.5 centigrade; annual fall is 115.2 millimeters, maximum relative humidity in winter is 72%, and minimum relative humidity in summer is 43%. This land is plane with no mountain. The main application of the windmills was to mill the wheat and grains. Today, by the reason of their slow operation, these mills are not used anymore.

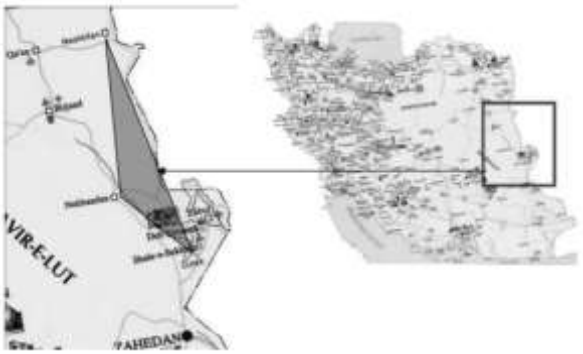


Figure 1. If Neshtifan, Lutak, and Nehbandan cities are imagined as the angles of a triangle, most of the Iran's windmills are positioned inside this imaginary triangle.
Source: author.

History and origin of windmills

There is no evidence on the exact point in time of the invention of the windmills. Most of the travellers and historians, who throughout the centuries traveled to Pars lands, considered the root of this invention to be in the years before the invasion of Muslim to Iran (Mortti 1984). However, it is reasoned that the origin of the windmills should date back to one thousand years before the creation of ship sailcloth, as the function of both, windmill and sailcloth, is the same. That is, both create a type of movement by wind power (Mortti 1984).

Some evidences on the construction of windmills have been found in the literature remained from the emergence of Islam. Masoudi, famous historian, says:

"… Omar did not permit anyone from Ajaman to enter Madina. Moghayar Ibn-e-Shaei wrote a letter to Omar and said: I have a servant who is painter, carpenter, and metal worker and is useful for people of Madina. Moghayar continued to say that if Omar allows him, he would send the servant to Madina. Omar permitted him to do that. Moghayar took two dirhams a day from the servant. The servant's name was Abdullah. He was a Magian from Nahavand town. So, he lived in Madina for a while. Abdullah went to Omar's mansion and started to complain about the tax, which he should pay to Moghayar. Omar responded: what can you do? The man said: painting, carpentry, and metal working. Omar said: The tax that you pay is not more than what you do. Abdullah murmured and exited the mansion. Another day, Abdullah passed the place in which Omar sat. Omar said: I heard that you can build a mill which works with the wind. Abdullah bounced back: I would build a mill for you that all people keep speaking about it. When Abdullah went, Omar said: This man is threatening me."(Masoudi 1962, 667).

The author of "history of Sistan" wrote:

"…and they rotate the windmills to mill the wheat. They ground the wheat with windmill or watermill. They have made such mills to draw well water from underground or to water the farms … they make many uses from winds…"(Masoudi1962, 204).

In addition, Sven Hedin (19 February 1865-26 November 1952), who had a journey to Iran deserts, late at 19th century, points to the existence of windmills (Hedin 1977). He encountered an array of windmills in Nehbandan. He compared these mills with those of Meigun. Khosravi, a historian and geographer who has recently visited the windmills, stated:"In the downstream of Khaf and Zouzan, windmills have eminent value, above the doors and walls, in the design of the building. They demonstrate appraised and fruitful gains of the past" (Khosravi, 1994, 83). Masoudi(1962, 204) explains more about the windmills by saying:"Sistan is the land of the winds and gravel. In there, wind moves the mills and the mills draw well water. In no area in the world, people may take advantage of the wind as much as Sistan people do". Estakhri reports:"In there, the wind blows strongly in a way that the mills are moved by the power of this wind. Among the regions in which the remaining windmills can be found, Hozdar is named. Hozdar is 800 meters far from Ghale Mochi [Mochi castle] and is located in the southwest of Zabol city. The leftover decoration of the walls is the indicator of the historical identity and nobility of the structure"(Estakhri, 1969, 191).

Researchers and historians, all, agree on the originality of Sistan for the windmills. Masoudi asserts:"Now that is 302 Hegira, landed estates, palm trees, and malls in mountains of Sistan are near a river, called Bostan River. Sistan is the land of wind and gravel. Sistan is the land on which the wind rotates the mills and the mills' sails and draws well water. The water satiates the thirsty gardens. Nowhere in the world benefits from the wind as this city does. God knows…"(Masoudi1962). Moghadasi, in Ahsan al-Taghvim fi Marefate Aghalim [the best book to know the lands] book in 375 Hegira penned about the wonderful land of Sistan:"… Sagastan windmills and its sand dunes are wonderful" (Moghadasi1953, p. 8).Baghdady, also, has written about Sistan as: "In Sistan, powerful winds blow and, for this reason, the windmills were built to crush the wheat into powder"(Baghdady1967, 210). Estakhri, in his Masalek va Mamalek [religions and regions] book, states:"Sistan is a tropical city. It has date trees. It has no mountain. In winter, no snow falls. Powerful winds continuously blow. The mills are built for the winds" (Estakhri 1969). In Asar al-Belad va Akhbar al- Eelad [Ages and news of the lands] book written by Ghazvini, it is mentioned that the whole land was sandy and lutaceous. No rest, the wind took. The rotation of the mills was rather by the winds than water (Ghazvini 1943).

According to Piccoloskian, most of the Iran's towns or cities had mills in Parthian Empire (from BC 227 to AD 334) and Sasanid dynasty (from AD 224 to AD 651). They had strict rules for using these mills, payment of the millers, and the goods (Piccoloskian 1987). Jan points to a kind of windmill that was used in China to draw well water and is still used in some cities [Figure 2]. This type of windmill, though had vertical axis, was completely different from those of Persian lands in structure. This was because the sails were situated in an open area and a wind-directing system was not mounted on the sails (Afshar Sistani1989). Ali Balad Kabashi in *Great Encyclopedia of the great Islam* book has cited from Ghazvini and habibi's book of *The history of Afghanistan after Islam* that Khorasan Province was on par with Sistan in using and constructing mills (*The Great Encyclopedia of the great Islam*1989). But the point is that, in most of quotations from historians, windmills are recounted as the unique feature of Sistan Province. This fact simply indicates that there were other mills in other lands, but they were not considered as the typical characteristic of that land. In the records of a traveller in Ghajarid dynasty(from 1875 to 1925) about the eastern part of Iran, the names of the cities

and towns that had windmills is successively mentioned, but the exact number of these cities is not clear. This means that the travellers reacted to the windmills at the first time they saw them and wrote about them in their registers. Then, they attached an image or a picture of the windmill to their registers. Sven Hedin, Colonel Mc Gregure (1988), Sir Persy Sikes (1965), and Colonel Charlse Pitt (1967) as well as others who traveled to the eastern borders of Iran reported more than one or two towns with windmills.

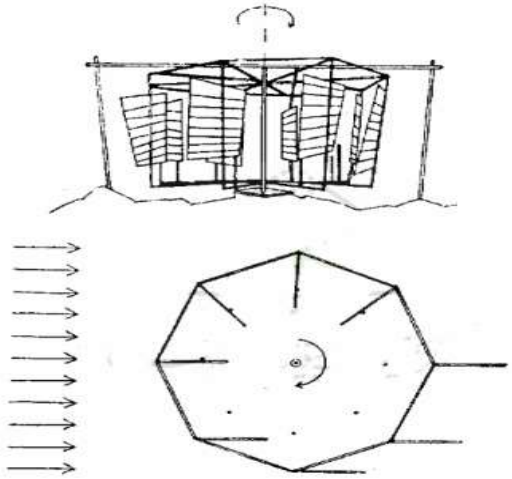


Figure 2. Chinese windmill with vertical axis.
Source: Naar, Jan. 1981. *The New Wind Power*, New York: Penguin Books.

The original model of windmill

Ansari Dameshghi(1925) had drawn the oldest image of the structure of a windmill in Sistan. In his book, Dameshghi had drawn many pictures of the interesting and wonderful places of Sistan. Hence, the major changes made on the original model can be found. The picture [Figure 3] that Dameshghi provided is different from what we see as today's windmills. In that time, the windmill's sails were positioned at the bottom with the millstone on them. It was, in fact, another model of watermill which benefitted from wind rather than water.

Ansari Dameshghi(1925, p. 108) points to the picture saying:

"…What you see is a picture of a windmill and the above as well as the below rooms. It is like a khamas, as it has two rooms above and four openings for the beneath room, like ayoogh which has four rooms. The structure of the openings is in the form that their smaller sideis toward wind path and the bigger side is positioned toward the forge. From the two openings that are located toward forge, one with tighter opening is toward the forge mouth and the other toward inside the forge. In this way, from whatever direction that may come, wind enters the rooms very powerfully. When the wind enters the room, it strikes the column or mast, which is similar to spindle. The mast has six to twelve sails, which are covered by skin. The skin coverings are put on the sails in a way that every sail [blade] has skin and cane coverings, from which the air passes and pushes the sails forward. Then, the air goes to the next sail".

This is probably the oldest complete description of the windmills. Even, Masoudi(1962)in Moravej al-Zahab, which is mostly relied on by the foreigner researchers, did not offer such a complete description. By reading the records of Ansari Dameshghi, we conclude that:

• In past, at least until the time that Ansari had lived, the structure of the windmills was as described above (Hedin1977).
• The openings of the windmills are indicators of the knowledge of the builders of aerodynamics.
• As opposed to Ansari's claim, these types of windmills were constructed only for the using monsoon winds which blow in a specific direction.
• Most probably, the difficulty in carrying the millstone as well as flour and grain packs to the above room and outside of the mills caused making changes in the structure of these mills.

Figure 3. Original model of the windmills
Source: Ansari Dameshghi. 1925. *Nokhbat Al Dahr Fi Ajaieb Al Bahr Va Al Bar* , Tehran: Rooz co.

Sustainable architecture of the windmills

Windmills are made of two stories. On the top or house of as[the tool that mills the grains], lateral curved walls direct the wind to the sails, which are fixed on the windmill. There are more than 1000 windmills in Khorasan and Sistan Provinces which are on the way to be completely destroyed.

The body and walls of this structure are, like a tower, situated in the middle of the building. They move three sails of eight sails of the polygonal structure of the windmill. The rest of the sails, which are not in the wind direction, do not inhibit the circular movement of the sails. The sails are mounted on a vertical mast. In the sails, the mast rotates in the hole of a horizontal lumber and the end of the mast, which is inside the mill, moves the runner stone on the bed stone. The above room, depending on the direction of the wind, has two walls toward north and south. The entrance of the room is located on the north side of the top room and occupies a half of the north side. The entrance is located at the place that the wind blows to the sails. The exit is located in the south, in which the distance between east and west is completely open. The above room has no roof and the opening is funnel-form. Thus, two sides of the opening of the wall are diagonally located toward the wind direction and, as a result, the wind strikes the sails powerfully. Ground floor of the system is a place where the wheat, flour, and other tools are collected. One of the prominent characteristics of windmills is that the sails, though being light and built by rustic building materials, are covered by canes to avert the structure destruction by the termites.

The season of using windmills

In Sistan land and Khaf planes, located in Zouzan plane, a type of wind, called 120-day wind blows. This fact made the people of the area invent a tool to benefit from the wind. The advantage of this wind is that it blows very regularly and with steady speed. It blows from northwest, west, and southwest, about 4 months a year, May, June, July, and August (Mortti1984).

In summer, a low pressure center with 775 millimeters pressure is extended from the center of Asia continent to Siberia. This stream covers the eastern of part of India, Middle East, Arabia Island, and north of Africa. At the same time, In Indian Ocean, there is a high pressure center with 765millimeters pressure which causes the creation of the air streams, developed from Indian Ocean to Asia, and monsoon winds. In summer, two high pressure centers are developed near Atlantic Ocean, one with 757millimeters pressure near Iceland and Greenland and the other with 765millimeters pressure near Asour Island. The second one is of less importance. Part of the stream, which is developed in this region, is extended to east. It is directed to north on Caspian Sea and along the borders and Shouni Mountains and then to Sarakhs town, in which this wind is called *Chahchahe* (Saadat 1979).This wind moves from Khorasan to Gonbadad and Ghaenat, in which it is called *Farah baad* or *Baad-e-Gheis*. After that, it moves toward Sistan, in which it is called *Levar*. Next, it moves to Zahedan city, in which it is called *Baade-e-Nashi* (Nadery1988).A branch of this stream moves from Caspian Sea toward Turkmenistan and thence to the east borders of Iran. In summer, this wind blows strongly from east borders of Iran and is called 120-day wind. In Ghaenat and Gonbad towns, this wind is called *Baad-e-Rast* [Right Wind]. According to the official reports, the speed of this wind is about 36 kilometers per hour and sometimes is about 70 or 90. This wind, because of its high speed and power, is used in the mills. According to Sven and other historians, the basis for designing the windmills was this powerful wind (Hedin, 1977).

Windmill functions

According to the historical documents related to Sistan, indigenous people gained advantage of wind power in different aspects of their life, including grinding the wheat (Masoudi 1962) and drawing well water (Yent 1984). The mills were also used to ventilate house air. That is, they had a function similar to that of the wind catchers in the central cities of Iran. However, it is not clear whether the wind catchers are as old as windmills or not.

According to Ghazvini (1943), Ansari (1925), and Baghdady (1967), wind power was used to carry sand and to deposit the garbage. Following the study of historian books on the way of using wind power in Sistan, we conclude that the people of Sistan were familiar with the basic principles of aerodynamics. They called these rule geometrics. Baghdady, in Sovarat al-Arz [The pictures of the earth] writes that people of Sistan preserve their land against the danger of sand tornados, by using the experience of their antecedents (Baghdady1967).

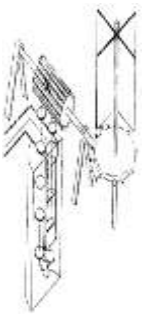
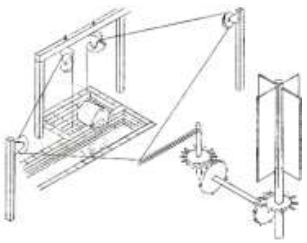
Windmills, like the wind catchers, air conditioned the house

Yent (1984), by considering the structure and location of the windmills near the houses, reasoned that the windmills were used to ventilate the house. He also added some information about the windmills of Palangi ruined buildings by saying that in the northwestern part of Iran or so, the walls were in front of and along with the house fences and were extended along an angle to not only keep the sails but also to direct the wind toward the house. This point suggests that the windmills were used for two purposes: firstly, to crush the wheat into flour and secondly to ventilate the rooms and keep the rooms cool"(Yent 1984).

Drawingwell water

In Hodud al-Alam men Mahsregheela al Maghreb [boarders of the world from east to west] book, it is mentioned that there was a region in Sistan, which was called Zarang by the native speakers and was tropical (Tehrani 1936). In this region, no snow fell and, thus, many mills were built in the path of wind (ibid). People built sails on the mills and the wind rotated these sails. Other mills had sails which were rotated by wind or man's hand to draw well water and cultivate the farms. Where the amount water was not enough, people made use of winds (Razavi1991).The tools which, by the windmills, drawn the well water were chain pump, *gavgard*, and the well wheel. [Table 1] shows the way that well water is drawn with the chain pump (Hill 1981).

Table 1. **Sample of the windmills which were used to draw well water**

An imaginary picture of a combination windmill and chain wheel	An imaginary picture of a combination of windmill and *gavgard*	An imaginary picture of a combination of windmills and two-buckets
		

Source: DR. Hill. 1981. Mechanical Engineering in Medieval Near East. *Scientific American*, 3(1):102, 104.

Windmills "today"

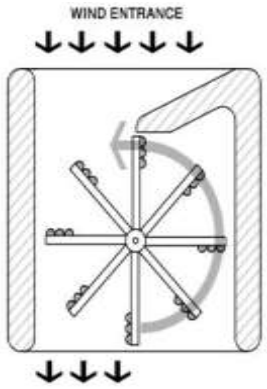
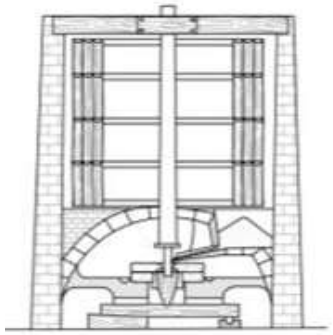
The original windmills had vertical sails and, according to the reports, were built around seventeenth century. They had about six to twelve sails, which were covered by the leaves of the date trees. Their function was milling the grains or drying them (Notebaarl1972). Following Ansari [who traveled to Sistan in 727 Hegira], Sven Hedin, a Swedish scientist in 1328 Hegira, wrote about what he saw in Iran; the barren regions, windmills of Meigun, Nehbandan, and Tabas, and he attached some illustrations of his observations to his register, when passing from Iran in his way to India. Hedin, in his book about Iranian desert, described Meigun town as: "Meigun has a ruined castle and, in the rural area, there are two windmills with special appearance. In the middle of June, northeaster blows and lasts for two months. The blow of the wind is stronger at night. The wind, like a tower, passes through the columns and walls of the mills, which are made of stone and clay brick. The wind moves three of eight sails of the mill. The rest of the sails which are not in the wind direction stand still, but do not inhibit the movement of other sails. The sails are mounted on a mast, which is placed in a vertical position. On the top, the mast rotates in the hole of a horizontal piece of wood. At the bottom, the mast moves the runner stone on the beneath one. The whole system is simple but sensible. Such system can only be used wherever the wind is constantly blowing" (Hedin 1977, 66).

According to Hedin, in 1328 Hegira, the structure of the mills was very similar to those of Falarag, Neshtifan, etc. Most of the mills were built on the top of the hills and few on the plane. The above room had two walls toward north and south. On the north side, opening was located. The side walls of some of the mills were paralleled and in some other they were curved

so that they were harmonized with the direction of the sails. The openings were located in the north wall. The north wall occupied half of the north side of the room and its opening was structured in a way that the wind struck the sails, when it entered the mill. In the southern part of the mill, an outlet was designed. In most of the mills from Khaf to Nehbandan, the distance between east and west sails is open and has no roof. To prevent too much stress from occurring on the sail and to protect the sails against excessive pressure of the wind on the opening, some lumbers were mounted on the wall. The lumbers could decrease the wind pressure, when necessary. The opening width of the mills in Khaf was 1 meter. In windmill, the beginning of the opening is funnel-form. Thus, one side of the opening is diagonally positioned in the wind direction and directs the wind into the opening. As a result, the wind hits the sail with more pressure. But the windmill of Nehbandan, Shousef, and Khaf, had simple openings, without any diagonal wall to direct the wind. Also, the outlet of the Neshtifan mills is 4.1 meters wide. The difference of width of opening and that of the outlet caused the creation of a vacant part at the back of the sails.

The difference between the old mills and the current ones is that the old mills had the millstone on the top of the wind wheel, but the current ones have the millstone below the sails [Table 2].

Table 2. Today's model of the windmills

Schematic plan of windmill	Schematic view of windmill
	

Source: ChereMisinoff, N. P. 1975. Fundamental of Wind Energy. *Ann Arbor Science, 12*(2):16.

Method of configureuration

Notebaarl, the famous researcher of Netherland who has conducted various researches on the windmills, says: The method of constructing Sistan windmills is as follows: First, a tall tower, like a minaret, is built. The structure of windmill has two parts. In the below part of the windmill, there are some millstones which, as a result of the rotation of the bed stone, grind the wheat. In its above section, there is a wheel, which is moved by the wind. When this two-floor structure was built, people of Sistan created four gaps in the walls of the structure. These gaps act like the battlements in tower and castles. The gaps are smaller toward inside of the structure. The wind passes through these gaps with pressure, like the air which exits the forge (Badihi1992).

Dameshghi, Syrian geographer, explained the method of constructing the mils, by the aid of some pictures. He wrote: When people of Sistan decided to build a windmill, they built a tall building, like a minaret, on a high hill or a palace steeple. They build one structure on the other structure. The above structure plays the role of a mill, which rotates the millstones. In the beneath structure, a wheel rotates in the restricted walls. With the blow of the wind, the mills rotate, though only one of the stones moves. When building both structures was finished, as it is shown in the picture [Figure 4] , three or four clefts [gaps] are created in the wall. In the ordinary mills, the wider part of the clefts is toward the inside and the less wide part toward outside, but in these mills the opposite is true. They act like channels for the entrance of air which, like a forge, enters the structure. Since the wider part is in the opening and narrower part is toward outside, the gap is its suitable form for the wind from whatever direction that it blows. If the wind enters from the situated opening, it would find its way, like a weaver who weaves the threads. This machine has twelve sails, which can be decreased to six. On the sails, a mesh such as matting texture is put like a lantern. This is the only case that the matting texture is distributed on the sails.

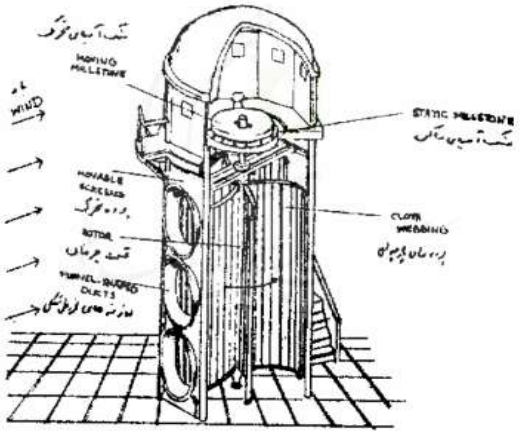


Figure 4. Scheme of the primary structure of the windmills
Source: Ansari Dameshghi. 1925. *Nokhbat Al Dahr Fi Ajaieb Al Bahr Va Al Bar* , Tehran: Rooz co.

This mesh has holes to keep the air in and push it forward. Then, the air fills in the next sail and pushes it forward, too. Next, the third sail rotates the steel axis. The rotation of the steel axis moves the millstone and crushes the corns. This type of mill can be found on the high hills or in the areas which water is scarce but blow of the wind is strong and continuous (Maurice1984).

Mechanics, elements, and parts of windmills

With regard to the structure, windmills are very simple. That is, the design of their details is straight forward and they are connected to each other with no complex technique. Windmills are composed of integrated elements, whose failure of each causes the failure of the whole system. Iranian, in Sistan, chose a name for each part of the windmill. Each of these parts is built to do a specific function in the integrated system of the windmill [Figure 5]. These parts are as follows:

1. Bridge is defined as the pieces of three logs, which their leaves are removed and has lost their tree façade and turned into lumbers.
2. *Sarpol* or *kharpol* is defined as a log with 45 centimeters width, 4 meters length, and 30 centimeters thickness. It is a unified and smooth lumber, which restson the wall by its two ends. From its middle, *sarpol* is attached, by a wooden axis, to the windmill. Its function is to prevent the lateral movement of *tirpol*.
3. *Tirpol* is defined as a rounded log with 8 meters length, 35centimeters thickness. The diagonal of *tirpol* at both top and bottom is identical. As finding a tree with such size is impossible, *tirpol* is built in three parts which are locked together. Then, a connector is passed through it, so that it

prevents the lateral movement and, probably, dislocation caused by the wind. *Tirpol* is made of pine timber, which indigenous people call *Naju*.

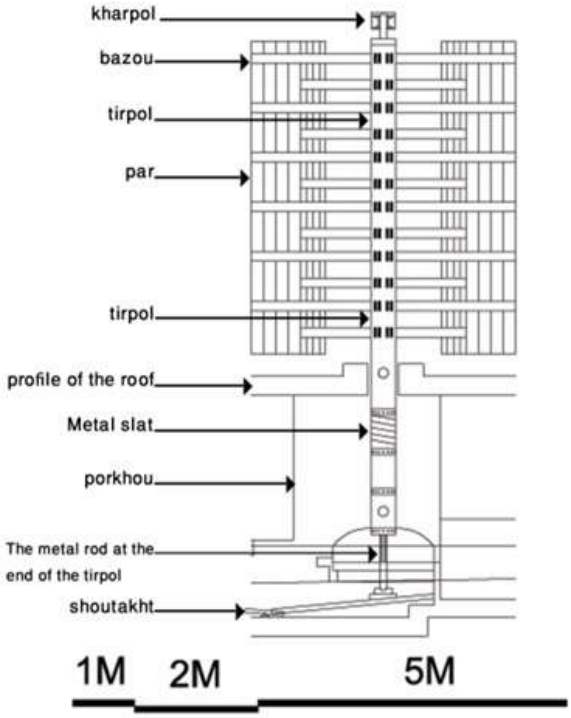


Figure 5. A profile of the wind wheel to show the way the elements are joined to each other.

Source: Author

4. Arm [also called *Bazu* or *Bahou* by native people] is defined as a series of lumbers with 175 centimeters length and diameter as well as 7 centimeters width.

From one end, it is connected to the sail and from the other end to the end of *tirpol*. Each arm is the connector between *tirpol* and the sails and transmits the forces, made by the rotation of the sails, to the *tirpol* and, in this way, causes the *tirpol* to rotate. Each sail has 6 to 7 arms and the arms are mounted on the joints of the *tirpol* in a way that prevent the bridge from breaking. Arms also make the *tirpol* stronger and firmer.

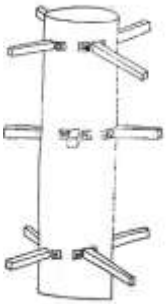
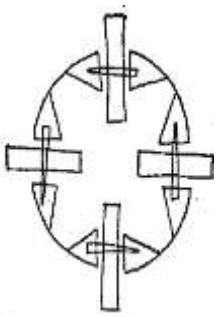
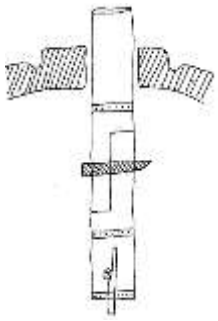
5. Sail is defined as a piece of lumber with 14 centimeters width and 1 centimeter thickness. The reason for selecting thin planks was to lighten the weight of the sails, in order for the sails to be rotated by the summer wind.

The approximate length of each sail is 6 meters. There are four or five cut-out windows in the each sail. The width of the sail is identical to that of the opening.

6. Support [also called *poshtiban* by the native people] is defined as a set of lumbers with 74 centimeters length, 6 meters width, and 1 centimeter thickness, which are pinned to the sails by nail. The aim of using this set was to strengthen the connection of the arms to the sails in order to prevent them from unhooking from the sails.

7. Two-folded lumber is a type of lumber with 140 height and 7 to 10 centimeters which its ends are two folded. This lumber starts to function when the mill is to stop moving [Table 3].

Table 3.The elements and main parts of the windmills

The connection of *bahou* [arm] to *tirpol*	The bottom of *tirpol*	*Tirpol*, which is composed of three parts
		

Source: Author.

8. Cane of wind [also called *nei* bad by the native people] is defined as a series of canes, which are woven together. They are used to stop the mill.

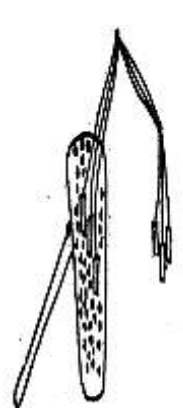
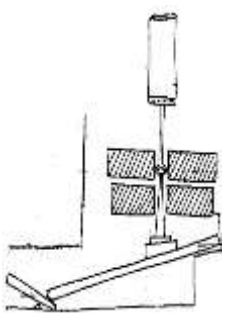
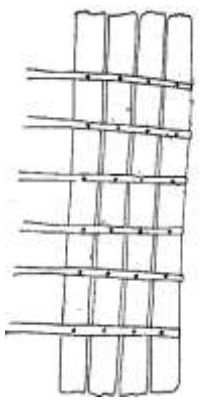
9. Port is defined as the distance between the sails. The distance is 62 centimeters. To prevent the sails from falling down, they are connected together by wire or rope.

10. *Porkhogandom*[or *porkhonamak*] is located inside the mill and near the millstone and is composed of two parts; the above part is a container for the wheat and the below part is the place for pouring salt, which by passing from an opening to the duct enters a passage to millstone.

11. *Toure*is a piece of metal, like swallow tail or bow tie with 36 to 50 centimeters length. *Toure* in its narrowest part, which is its middle part, is 10 to 12 centimeters wide. It is also 2 centimeters thick in its thinnest part and 12 centimeters thick in its thickest part. A thick metal slat is amounted on one end of the *tirpol* whose end is two-folded and is located in the middle of *toure*. With the rotation of *tirpol* and its end slat, the *toure* and then the runner stone rotate.

12. Duct is a lumber, 12 to 15 meters in diameter and 60 to 70 meters in length. However, the length of the duct is not of crucial importance because, by mounting *porkhonamak* [or *porkhogandom*] and with pushing it backward or forward, it can be increased or decreased. Inside the duct a hole is dug in a way that one end of it is open to the *porkhonamak* and the other end of it is built diagonally so that it directs the wheat or salt to the passage of the mill [Table 4] (Nadery1967).

Table 4.The elements and main parts of the windmills

Kajerekub	millstone	sails
		

Source: Author.

Millstone

The millstones of Khaf town were supplied from a rocky area near Neshtifan Castle, which is 18 kilometers far from south of Khaf. Some experts lived in this region whose only job was to supply the millstones. In fact, the millstones were change when their thickness reached 10 to 15 centimeters. The normal thickness of the millstone is 30 to 45 centimeters. The bed stone, in comparison with the runner stone, because of having less movement has less erosion and, as a result, longer lifetime. The millstone was replaced depending on its function and the amount of wearing. However, they normally were changed every 5 to 10 months of working [Figure 6].

Figure 6. An example of a windmill millstone, which is on its way to destruction

Source: author.

To supply the millstone, a man whose job was building millstone selected a part of a rock which was smooth and glossy. He measured the thickness of the rock and circled a line around a 30 to 40 centimeters area of the rock surface. Then, with special tool, round the circle was dug. After that, with the aid of other skillful men and a crowbar, or maybe some other tools, that piece of stone was removed out of the rock. When the stone was removed, they were carried to their mills. As the stones were not yet ready to mill the wheat, the mill was operated with new millstone and some gravel were put into the mill to make the beneath surface smooth. To make the beneath surface smoother, the mill was operated to mill some grist and then millet. When the mill milled the grist and millet for a few times, it became ready to mill the wheat (Ravandi1976).

The Operation of Windmill

A giant system with 48 arms, 32 sails, and 8 ports operated on a higher place. The whole body was held by a *kharpol* [Figure 7]. The wind passed through wind catcher gate and reached the corners of the eight-folded port, and moved the wheels and sails. This was because the end of mast was attached to the runner stone. As a result, the millstone was rotated with the rotation of the mast. When the runner stone was rotated, it shook a small piece of wood called *laklaki*. The movement of *laklaki* shook the *dulbareh* of the mill. *Dulbareh*, by horizontal movement, directed the wheat from the *porkho* to the middle hole of the stones. Remember that the higher the speed of the wind, the higher the speed of rotation of millstone and, as a result, the more wheat the *laklaki* and *dulbareh* can carry out to the stone.

By removing the stones, the flour, which was the outcome of wheat crushing, poured out around the millstones and became prepared to be collected. In the hole underneath the stones, a very old system was situated, which could stop the stones by the operation of the lever. A tool called *takhtomoushete* from inside of the windmill slowed down the movement of the stones. Immediately after that, the wheels and sails were stopped by another lever and the whole work stopped (MC Donald 1967).

Figure 7. The wind, passing the wind catcher gate, reached the corners of eight-folded ports and moved the wheel and sails.

Source: author.

Typology of windmills

It is evident that the regions such as Falarag, Laj, Barabad, Tizab, Shangan, Neshtifan, Lutak, and many other regions of Khaf town and Sistan province had various windmills whose number was rather high. But now, they became obsolete by the pass of time. These windmills are divided into two groups typologically, including single and grouped windmills [Figure 8]. Each type has its own typical characteristics.In this section, single and grouped windmills and their characteristics are introduced. Moreover, Lutak, Neshtifan, and Nehbandan windmills, as the examples of the single and grouped windmills are presented. Then, their history, architecture, and specific features of are offered.

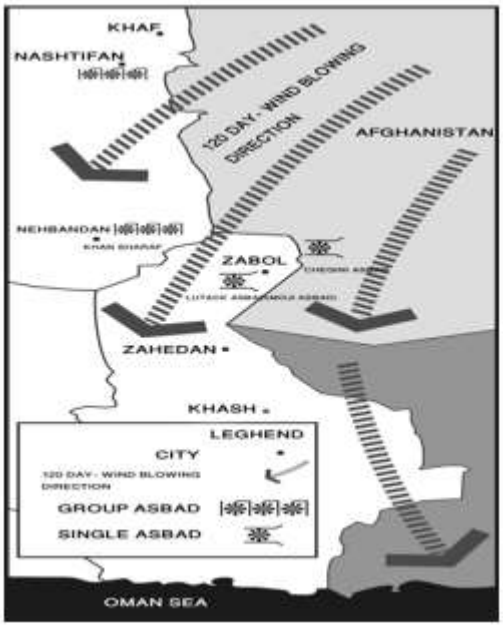


Figure 8. The locations and distribution of the windmills in the western parts of Iran

Source: author.

Single (Corridor Windmill)

The main characteristic of this type of windmill is the use of dome, vault, and vacant walls, made of brick, thatch, gypsum, and a combination of mud and gypsum. The body and structure of this type of windmill is, because of applying the technique of dome and vault constructing, very resistant against 120-day winds and the imposed load from the wind wheel. The walls are made of brick and some thatch is used in between the bricks to

stick the bricks together. In this way, the walls are resistant against the weight and expected movements of the *kharpol*. Building vacant walls beneath the wind wheel (or millstone room) was a thoughtful technique to increase the tolerance of walls against the transferred load of the wind wheel and to transfer the mentioned load to the foundation [Figure 14]. Since the walls are built far from each other and the entrance is big, domes and vaults are used to cover the entrances and brick, gypsum mortar and mud and gypsum were applied as their composed materials. To prevent the rain drops from penetrating into the structure, a rainproof made of thatch was used. This rainproof was composed of the same thatch materials that were used in the roof and outer body of the structure. It is noteworthy that using dome and vault technique in Iran is of long history. Because Iran is on earthquake belt and Iranian had the memory of takht-e-Jamishid destruction by fire in their minds, Iranian architectures built domes and vaults, which are more stable and secure, instead of wood covered roofs.

The most developed and beautiful type of windmill is the one which has been constructed considerably larger than the coupled type with bricks. It is a two-floor building in which the lower floor is the place of millstone and the upper floor is the place of *bazou* (arm). Like other types of *bazou*, this *bazou* consists of a central axis with 8 to 12 blades attached to it. The upper part of this axis is connected to the windmill sidewalls by a staff. The wind trench has been turned to an unroofed corridor with a large span and the side *pars* which gather the blowing winds. Then, the wind passes through two or three crannies to the interior, embedded in the span wall where there are some *par*s. Moji is a good example of this type of windmill.

Lutak windmills (or the same as moji windmill)

Lutak windmills were found 62 kilometers far from the southeast of Zabol city, in other words, 5 kilometers to the north of archeology base of Shahr-e-Sukhte [The Burnt City].The emergence of this type of windmill dates back to Sasanid period [Figure 9].

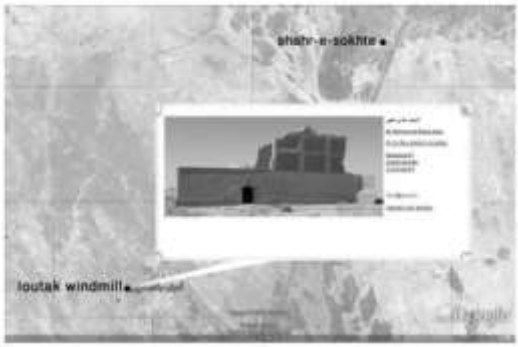


Figure 9. The plan of Lutak (or Moji) windmill in 61 degrees and 11 minutes of east and 30 degrees and 32 minutes of north.

Source : www.google.com

According to the windmills plan, this structure was made of two floors. The ground floor had three rooms, one of which was milling house. Milling house consists of water container and a place to put the millstone as well as two other rooms, which are store or service room. On the first floor, only wind wheel existed [Figure 10]. The building materials of this structure were brick and thatch. The thick walls of the structure signal the structure old history [Figure 11].

The structure and building of the windmills are, like a tower, situated inside the mill and move three sails of the eight sails of the windmill. The rest of the sails, which are not at the wind direction, do not prevent others to move. The sails are, vertically, put on a mast. Depending on the wind direction, the above room is built in north to south direction and in the northern side of the room, the opening is built. The opening is placed where the wind, when entering the room, hit the sails. In the southern part, there was an outlet to keep the distance between eastern and western walls open. The above room lacks roof. The opening of the mill is funnel-form and its two sides are diagonally positioned in the wind direction. In this way, the wind is directed into the entrance and, as a result, strikes the sails with more pressure. A typical characteristic of Sistan windmills was that their sails were covered by canes. This allowed the mills to stay light and, at the same time, impregnable against wear and tear as well as termite [Figure 13]. The decoration of the structure includes its decoration of eastern and western walls. These walls are beautifully decorated with set-backs and juts, which are made with adobe brick [Figure 12].

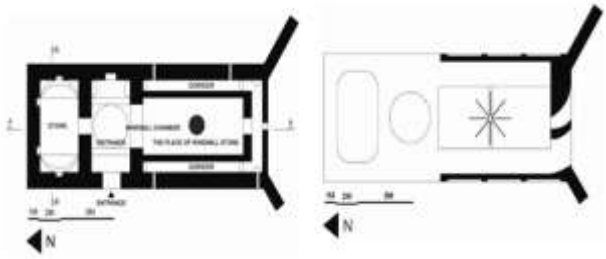


Figure 10.The plans of watermill's ground and first floors

Source: author.

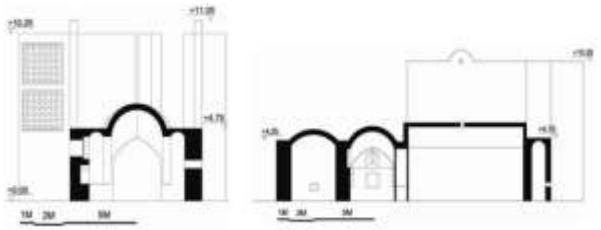


Figure 11. The profile of the windmills [Note that the thick walls sign the oldness of the structure].

Source: author.

Figure 12. Set-backs and juts of east and west wall, which add to the beauty of the structure

Source: author.

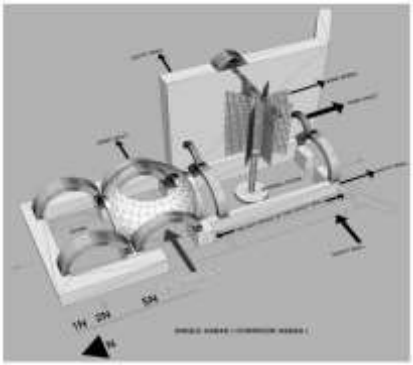


Figure 13. The dome load, by the ogee vault, is transferred to the . The elements of single windmills and their relation in

the windmills' stories. Vacant wall, bearing wall and non-bearing wall, vault, and dome are the main elements of single windmills.

Source: author.

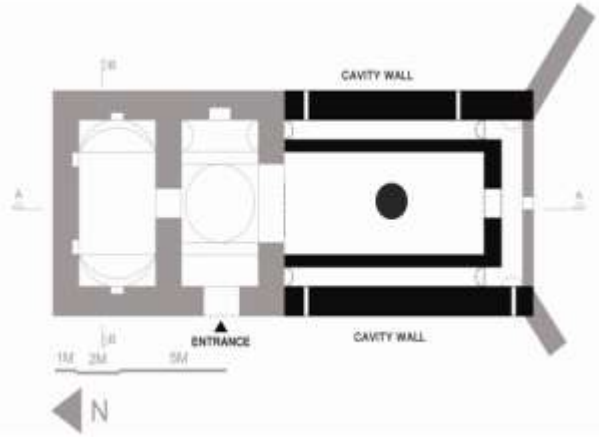


Figure 14. The position of the vacant wall, which to tolerate the weight of wind wheel and to transfer wind wheel load to the foundation is located beneath the wind wheel.

Source: author.

Grouped (simple windmills and cylindrical windmills)

This type of windmill is smaller than the single windmills and most of the time some of these mills are arranged near each other on the high hills. Because of their entrances being small, only vault and bearing walls are used in their structures. The point is that they are grouped together so that their resistance against 120 day winds and the imposed load from the wind wheel is increased.

That is, each of the windmills in the group enjoys the same amount of wind power. Vacant wall and dome structures, which were used in single windmills, are not built in this type of windmill.

Grouped windmills, in accordance to the materials used in their structure, their dimensions, and geometry, are divided into two types. The two types are called simple windmill and cylindrical windmill, which are described in details as follows.

Simple windmill: Simple windmill is a two-floor adobe building with a simple square plan that the upper floor is the place of stone mill and the lower floor is the place of *bazou*. *Bazou* consists of a central axis with 8 to 12 blades attached to it and the upper part of this axis is connected to the windmill side walls by a staff.

The local simple windmills have been built in the most altitude part of the village in two adjacent rows, so that there is no building before them to a large distance. To take the most of the wind power in the regions with the maximum wind speed, all the village simple windmills have been constructed side by side with the same length, width, height and form [Figure 15].

Although the functional potentiality of such mills is relatively limited, they could be built and utilized widely by all the farmers.

This was because of their simple construction material and structure. Thus, such windmills were considered as the private property of the farmers, used for the purpose of producing wheat flour.

Figure 15. Simple windmills with the identical length, width, height and form, creation an indicate horizontal line

Source: author.

Cylindrical windmills: this kind of windmills is more developed than simple windmill known as Village Windmill, regarding its constructive structure and material. Its construction material is brick and the plan of upper floor has been designed in a semi-cylindrical form to prevent the possible wind resistance in the windmill's interior and the surrounding space. The height of this type of windmills is considerably more than the Village type. Such windmills are consisted of two high columns, in addition to a large wooden axis in the center of each column. The axis transfers the force from the upper part of windmill to its lower part. There is no wall in the southern part of upper floor and the form of side walls have been designed in accordance with the wind effect on them. Hence, the most significant difference of cylindrical windmills with simple type is limited to their constructive material and the plan of upper floor [Figure 16].

Figure 16. A cylindrical windmill and a simple windmill after restoration

Source: author.

Neshtifan windmill

Neshtifan with 60 degrees and 10 minutes longitude as well as 24 degrees and 26 minutes latitude is located 20 kilometers far from Khaf town, in the margin of flat grounds ended in desert. It is in a gentle slope of one of the alluvia of Kalshour River. It is ended to Bakhzar Mountain in north, Abasabad, Mohammadabad, and Behdadian towns in south, Barabad and Sungan towns in east, and Kalateha lands in west. Neshtifan had 40 windmills, most of which are ruined now [Figure 17]. The development of windmill in Neshtifan in Khorasan Province dates back to Safavid dynasty (from1501 to 1736). Neshtifan town was developed from northwest to southeast and falls plum on the direction of 120-day wind [Figure 18].

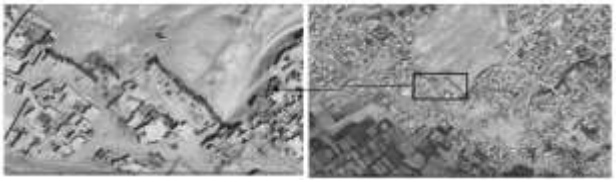


Figure 17.The plan of Neshtifan windmill location, which is located in 60 degrees and 10 minutes of east and 34 degrees and 25 minutes of north.

Source : www.google.com

The building stuff of these windmills is clay brick which is filled in with thatch. Each windmill in Neshtifan consists of two parts, lower and upper. Lower part, which is in the roof of the structure, includes the wheel and sail. The height, width, and the diameter of the windmill wheel are 5, 1.5, and 3.5 respectively. This wheel is mounted on a heavy and firm *kharpol*. The *kharpol* is located on an adobe wall, with 5.5 meters length and 2.3 meters width. The firm mast of *kharpol* is situated on a hole, called *kalosi*, which is in the middle of *kharpol* [Figure 19]. Lower part of the windmill a room is built with 12*4.5 meters dimensions, which has a type of cross-sectional covering and is mounted on the windmill horizontal wall in a semi-circle form. This part includes a millstone, which has two lower and upper stories [Figure 20], *porkhor* or the wheat container and *dulbareh*, which directs the wheat from the container to the middle hole of the millstone (Nori 2004).

On the facade of Neshtifan windmills, no decoration can be seen. In other words, the only aim of building such structure was to crush the wheat and grains. The view of the giant wheel and sails is aesthetically pleasing.

Figure 18. The Neshtifan windmills are built in a multi-storied form to exploit the wind.

Source: author.

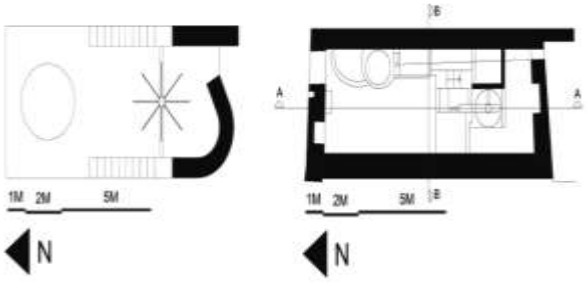


Figure 19. The plan of ground and first floors

Source: author.

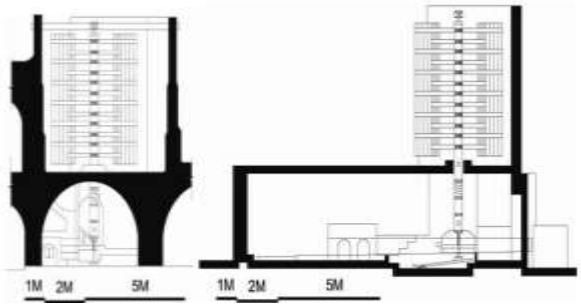


Figure 20. A profile of the windmill, in which the giant wheel and sails can be seen

Source: author.

Nehbandan Windmills

Nehbandan, as a town which is located in the furthest south of Khorasan, is in 60 degrees and 20 minutes longitude as well as 31 degrees and 31 minutes latitude and is 1195 meters above the free sea level. Nehbandan is located in plane with small width. In its northern part, Bahran mountains, in its east, Garm mountain are located and its west Chashme mountains, Shahkour, Hamri. The south of this land ended in the Estand Mountain slopes. The Nehbandan windmills rotate with the wind power. With regard to their structural and appearance, Nehbandan windmills belong to Ghajarid dynasty [Figure 21].

Two parallel walls with 10 meters height and 4 meters distance in between composed the main structure of the building. In the northern part of these walls, there are some giant sails which rotate with the wind power. The plan of Nehbandan windmills is adopted from Sistan windmill and they are very similar. The windmills are made of two parts:

a. The upper part: it is the part in which the big moveable elements are located [Figure 22]. This part has three walls, which are vertical and toward north and west and have sloped edge. A half of the wall is connected to the east wall so that it is extended to the west and its open side is toward 120-day wind. For this reason, the wall is built in a curved form toward the wind direction. The wall edge on the south view has a stairway for the individuals to have access to the elements of the windmill structure [Figure 23]. The axis of the windmill is in the form of a fix mast, with 4.5 to 5 meters length, on whose surface rectangular-form slots are made for the arms to be placed in. The arms have parallel pieces of lumber, which keeps the mast on its vertical position against the 120-day winds and then transfer the wind power to the arms and masts. The fixed mast of windmills includes a wooden lumber, with 4.5 to 5 meters length, usually made of buttonwood log. Without this element, the other elements of the windmills cannot be fastened together. The windmill axis, which is like the fix mast of the windmills, is attached to a wooden nail by two pieces of a wood or one piece of a thin wood.

b. The lower part: it is the part of the windmill with a limited space, which is a place to store the wheat and flour and has a stairway to the upper floor and platform. The roof of the floor is covered by adobe in a cross-sectional and semi-circle form. The ground floor, at the time that the windmill did not work and there was no flour and wheat, was a place to keep the arms and sails. The main building materials of the windmills were adobe, stone, clay, and wood. The connection between ground floor and the upper floor was made possible by a stairway outside the structure.

Nehbandan windmills are all apparently similar. However, if we look at the interior space of the windmills carefully, we find that they are very different from each other with respect to their interior space. This point indicates the active state of the windmills. Changing to the interior spaces, adding to the storehouses of the wheat, using small or big platforms are among the differences that can be observed. The other point is the use of some stones among the piles of the adobe, which is done carefully and has added to the stability of the structure (Khosravi 2003).

Regarding the fact that the function of the windmills was mainly to satisfy the major needs of the people of the town, making a different space with various applications were considered to be crucial and no attention was paid to the decorative aspects. Thus, Nehbandan windmills were mostly left without any decoration and ornamental elements. Different kinds of windmills are compared in figure 24 and the way the wind enters into their entrances is shown. The arrangement of the windmills near each other is also illustrated [Figure 24].

Figure 21.The edges of the walls have stairways on the south view so that the millers can access different elements and parts of the windmills.

Source: author.

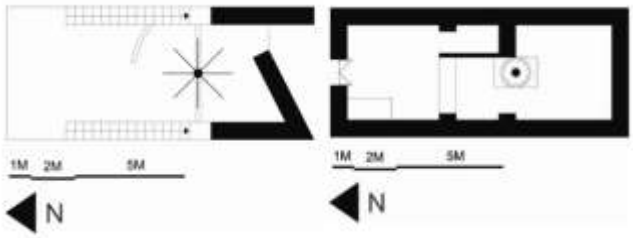


Figure 22. The plans of ground and first floor

Source: author.

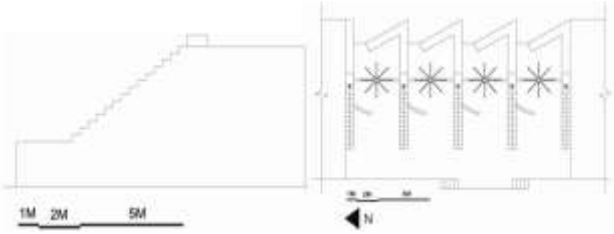


Figure 23. The south view of the structure which shows the stair ways on the walls and is considered as a very delicate architectural and technical point

Source: author.

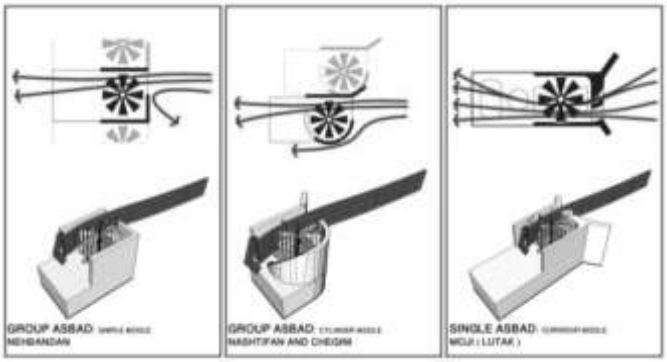


Figure 24. The comparison of different types of windmills

Source: author.

Conclusion

Khaf town, which is in the path of 120-day winds, has a lot of windmills. The windmills have wooden sails which are moved by the above mentioned winds. In this way, the rotation of the sails produces energy. The produced energy is conveyed to the millstones and the millstones crush the wheat into powder. The indigenous people consider the start of the blow of the winds to be from the beginning of spring to the beginning of the fall. This wind blows with the utmost power all the time during the day and night. It is the only type of wind which can rotate the sails of the mills with a very high speed. All the mills of each area were located close to each other, with the same length, width, height, and Figure, on the highest points of the land.

The main reason for using the windmills by the residents of Sangan, Neshtifan, Khargard, and Khaf was that the north winds blow throughout the whole year. In fall and winter, all the provinces in Iran are in the path of the winds. In spring and winter, at least in the eastern part of Iran, from Sistan to Ghuhestan, the wind blows. In Taybad and Khaf, 120-day winds blow from the middle of April to July, with a very high speed. The other reason for using the mills was the shortage of water, which made the people to use wind energy to mill the wheat. In Khaf and Zouzan, the mills are considered as the vital element of the buildings. They, more important than the doors and walls of the building, display the special and noble values of that time. Windmills are not built separated from each other. In other words, they are put near each other to prevent the strong winds from destroying them. Consequently, the mills form a set in a wide area in order to increase their resistance against the winds. Also, they provide a center for the farmers to be together and have a chance to trade the wheat, after the harvest.

Preserving such valuable historic monuments is an aid to attract Iran and glob travellers and the people who are interested to know about them. The cultural and historical heritages are the manifestations of the cultural and artistic development of our civilization which can boost the creativity of the people living in the current era and in future. In fact, it teaches us how to benefit from nature. Capitalizing on the continental conditions of Sistan Province leads to take economical steps to make a steady progress in the form of using modern technologies. As a result, constructing windmills in this province can play a pivotal role in providing the electricity or sustainable energy of the land.

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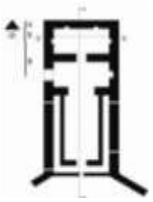
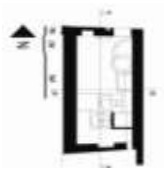
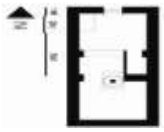
Table 5. A comparison of Lutak, Nahbandan, and Neshtifan windmills

Name of the structure	location	Number of the floors	Direction of the walls toward the wind	The opening for the entrance of the wind	Height of the structure	The plan of the ground floor	The plan of the upper floor
	Function of the windmill	The ground floor	Number of the wind wheel and the covering of the sails	The outlet of the wind	Length of the structure [in [meter		
	View of the structure	Year of construction	First floor	Building material	View of the structure		
Lutak Windmills	Sistan province, South east of Zabol city, Lutak town	2 floors	North-South	North side	10.25		
	Sistan province, South east of Zabol city, Lutak town	2 floors	North-South	North side	10.25		
	Windmill, to mill the wheat and grains	3 rooms: Container, the wheel and water, store or service rooms	8 Cane covering	South side	25.40		
Neshtifan Windmills	Sasanid and Savafid dynasties	Wind wheel	Adobe, thatch, and wooden coverings	East and west walls are decorated with adobe	9.30		
	Khorasan province, Khaf town, Neshtifan region	2 floors	Northeast-Southwest	Northeast	10		
	Windmill, to mill the wheat and grains	2 rooms: Container, wheel and water, store rooms	6 to 12 Pieces of cloth or the leaves of date tree coverings	Southwest	15		
Nehbandan Windmills	Savafid dynasty	Wind wheel	Adobe, thatch, and wooden coverings	No decoration	6		
	Khorasan province, Nehbandan town	2 floors	North-South	North side	10		
	Windmill, to mill the wheat and grains	2 rooms: container, wheel and water, and store rooms	10 Cane and sedge covering	South side	14		