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Assessment of Renewable Energy Resources in Iran; with a Focus on Wave and Tidal Energy

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Abstract

A growing world population and socio-economic development are at the root of an ever-increasing energy demand throughout the world. Much of this demand is met by means of fossil fuels, leading to greenhouse gas emissions and climate change – hence the need for increasing the share of renewable energy sources in the global energy mix. Marine energy is a reliable, high-density source of energy with limited environmental impacts. Iran, with its long coastline, growing population, increasing energy demands and extreme air pollution, has a great potential for the

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development of marine energy. However, this potential has not received sufficient legislative or entrepreneurial attention so far. This review covers renewable energy resources in Iran in general – including solar, hydropower, wind, biomass and geothermal energy – with a focus on marine resources – wave and tidal energy. On the basis of the review, it can be stated that there are many energy hotspots with a high potential for marine energy development in the Caspian Sea, the Persian Gulf and the Gulf of Oman.

Keywords: Renewable energies, Wave and tidal energy, Iran, Caspian Sea, Persian Gulf, Gulf of Oman.

1. Introduction

Fossil fuels (e.g. coal, petroleum oil and natural gas) contributed to unprecedented economic growth in the past two centuries, and the global economy still relies heavily on them. However, ever-increasing concerns have emerged over air pollution, greenhouse-gas emissions and climate change caused by such fuels in domestic, transportation and industrial applications [1-3]. Additionally, fossil resources are limited and expected to be depleted in the near future [4]. These issues are the primary motivation for a paradigm shift towards renewable energy sources with minimal environmental impacts. Solar, wind, ocean, hydropower and geothermal energy are poised to provide an ever greater share of the energy mix, in a gradual transition towards a carbon-free world.

The ocean is an abundant, sustainable repository of power, which can be harnessed from waves, tides, thermal gradients and marine currents [5]. Among ocean energies, wave energy is considered most promising given its energy density (the highest among renewables), good predictability and low visual and environmental impacts [6]. The universal offshore wave energy potential has been estimated at between 1 and 10 TW, which is substantial for the global power demand [7]. Tidal energy also presents a great potential, albeit restricted to certain areas, and its nearly perfect predictability is worth mentioning. In order to exploit the massive energy of water currents created by the rise and fall of the tides, tidal barrage systems, tidal fences and tidal turbines are employed [5]. The theoretical potential for wave and tidal energy conversion is considerable in parts of the world with long oceanic coastlines [1].

The economy of Iran is heavily dependent on crude oil and natural gas. It holds the fourth rank in crude oil reserves (Fig. 1 [8]) and the second rank in natural gas reserves in the world [9]. There are many reasons why Iran should employ renewable and sustainable energy resources, among which its growing population, increasing energy demands, great potential of renewable resources, extreme air pollution, and proven reliability and benefits of renewable energies [10-12]. Iran has 1259 km of coastline on the Persian Gulf and 784 km on the Gulf of Oman, both to the south of the country. On the north side it has 657 km of coastline on the Caspian Sea [13]. The current share of renewable energies is a mere 0.17pc of the total energy production in Iran – an insufficient value. Figures 2 and 3 indicate the energy production since 1971 to 2013 and the share of total primary energy supply in 2013 for Iran, respectively [14].

Below, a brief review of renewable energy resources in Iran in general is presented, including solar, hydropower, wind, biomass and geothermal energy. So far energy systems based on fossil fuels have been at the forefront, and not enough attention has been devoted to the marine energy potential. The main focus of this study is to comprehensively review the literature on wave and tidal energy in Iran. It is predicted that the share of global electricity supply from renewable energy sources, including wind, biomass, solar, geothermal and marine, will increase more than five-fold, from 3pc in 2008 to 16pc by 2035, while the shares of hydro and nuclear stay flat at 16pc and 14pc, respectively [15]. Figure 4 indicates the world electricity generation in 2008, 2020 and 2035. As is clear from the figure, global electricity generation grows by 75pc over the outlook period, rising from 20183 TWh in 2008 to 27400 TWh in 2020, and to 35300 TWh in 2035. Coal continues to be the main source of electricity production, despite its share of the world mix declining from 41pc in 2008 to 32pc by 2035 [15].

2. Renewable energy potential in Iran

2.1. Solar energy

Solar energy is the energy released from nuclear fusion within the sun [3]. The amount of solar energy received by a given point on earth is dependent on its latitude and climate.

Covered by many deserts and unoccupied land, Iran has plenty of suitable areas for solar energy deployments. The annual average of solar radiation for Iran is 20 to 30 MJ/m^2 per day. The sunny hours during the four seasons are 700 h during spring, 1050 h during summer, 830 h during autumn and 500 h during winter [16]. Nowadays, there are solar sites for electricity production in operation in Iran, and 77000 m^2 of solar energy collectors were mounted during the third and fourth plan of national development. The major cities with collectors of solar energy are Tehran, Yazd, Semnan and Shiraz. Figure 5 [17] illustrates the latest map of Iran solar radiation potential. The capacity of Iran’s solar power plants is also represented in Table 1 [18].

2.2. Hydropower

Iran has many rivers with ideal conditions to house small, medium and large scale hydropower plants. Hydropower has been used in Iran since 70 years ago, and in 2013 there were 42 active hydropower stations with a total capacity of 10266 MW [19]. In addition, many other projects are currently under development to construct hydropower stations in Iran. Table 2 shows the nominal capacity of hydropower stations from 2007 to 2013. The comparison between the capacities of power generation of hydropower stations for 2007 and 2013 indicates a 38pc increase.

2.3. Wind energy

Subjected to strong winds, Iran enjoys a moderate supply of wind power [20] with excellent potentials to be harnessed in the future [21]. The spatial distribution of wind speed at 60 m above the ground level is presented in Fig. 6. As shown in Fig. 7, the wind energy density at 80 m above ground level is higher than 150 W/m^2. According to these figures, which are based on the latest available maps, it is obvious that there are several locations in Iran which have considerable potential for capturing wind energy for power supply. Starting from 2004, Iran has experienced significant annual growth in its installed capacity for harvesting wind energy. By the end of 2014, the installed capacity (151 MW) had increased six-fold relative to the 2004 figure [22]. This level of development is, however, far from the expectations of the 5th National Development Plan of Iran (2010-2015), indicating that the installed capacity of renewable power plants would reach a total of 5000 MW by the year 2015, of which 4,500 MW on wind farms [18].

Table 3 represents the wind energy data for 2007 through 2013, demonstrating an increase in the installed capacity of wind energy over recent years.

The first and the largest wind farm of Iran is located in Manjil – a northern town known for its strong winds - with a total capacity of about 100 MW [23]. Located in Khorasan-e Razavi province, the Binalood wind farm is the next largest wind farm in Iran, with 43 turbines and a total installed capacity of 28.3 MW. Since its foundation, this power plant has assisted the economy of the surrounding areas, especially the agriculture sector. This is because a large number of water wells supply the agricultural needs of the region, and the electricity produced by the Binalood wind farm has been instrumental in replacing local diesel generators by less expensive and cleaner wind power [24], revealing the importance of wind energy as a renewable energy. The research work carried out on wind energy in Iran is quite abundant [25-33].

2.4. Biomass

Biomass here refers to material derived from growing plants or animal manure [34]. The combustion of biomass emits less pollutants than fossil fuels and also reduces landfill waste in industries such as forestry and lumber plants, and food processing [18]. There are different types of biomass energy resources including forest and agricultural wastes. Feedstock is the principal contributor to the biomass waste produced in Iran, and about 19.4×10^6 tonnes of residues are produced from main harvests [35]. The contributions of the different types of biomass resources in Iran are: 59pc from agricultural solid waste, 28pc from animal waste and 11pc from effective composting materials [36]. Figure 8 illustrates the maximum electricity generation potential from different types of biomass power plants in Iran. Figure 9 shows the latest technical potential of methane, energy and electricity generation of sewage in different provinces of the country. It is clear from these figures that the provinces of Tehran, Isfahan, East Azerbaijan and Khorasan-e Razavi are capable of utilizing biomass energy more than other provinces.

2.5. Geothermal energy

The word "geothermal" has a Greek etymology, and consists of geo (referring to earth) and thermal (related to heat). In fact, the planet earth is a huge source of thermal energy. Recently, global geothermal energy output has increased from 65 TWh to about 280 TWh, and installed capacity has increased from 11 GW to over 40 GW, mainly in the United States, Indonesia and south-east Asia [15].

Iran is located on the seismic belt, and the young seismic activities create a proper condition for formation of geothermal fields, as evidenced by the hot water springs in the country [18]. The geothermal energy sector of Iran is entirely run by the government [37]. Hence, there is a need for private industries to be linked to the government for a rapid development of the geothermal energy sector. Figure 10 indicates the geothermal potential of Iran and ten areas suggested by Renewable Energy Organization of Iran (SUNA) for geothermal power installations, numbered in order of priority from 1 to 10. According to this figure, the hottest known regions are around Sabalan and Sahand. Recently, a geothermal power plant, the first one in Middle East, with a capacity of 55 MW is approved to be installed in Meshkinshahar, hillside of Sabalan which is an inactive stratovolcano.

3. Wave and tidal energy potential

The regular rise and fall of the surface of the ocean due to the gravitational force of the moon and the sun and the centrifugal force produced by the rotation of the earth and moon about each other is called a tide [4]. For their part, waves are produced by winds acting on the water surface. Wave and tidal energy contain the highest energy density among clean energy resources [38] and are among the most promising forms of renewable energy, providing a persistent, environmentally friendly source of power [38-42]. Wave power is proportional to the square of the amplitude and to the period of the motion. Therefore, long period and large amplitude waves have great energy fluxes, offering up to 70 kW per meter width of oncoming wave [43]. On these grounds, the world's attention has naturally been drawn to the exploitation of marine energy resources. According to the International Energy Agency (IEA) statistics, wave energy technologies are still in their infancy, requiring much further research and development. It is predicted that by 2035 marine energy output will have increased to some 60 TWh and installed capacity to 17 GW.

Assessing the wave energy of an area is of essential importance for deploying wave farms, i.e. arrays of Wave Energy Converters (WECs), in proper locations. The substantial spatial variability of the wave resource nearshore, with great differences over relative short distances, means that selecting the nearshore hotspots is crucial to the successful exploitation of wave energy. There are several studies in the literature which have surveyed the marine energy potential in different regions of the world. Some of these concern the world energy potential [44, 45], Europe [46], UK [47], Spain [48-50], US [51-54], Portugal [55, 56], Australia [57], Turkey [58], Sweden [59, 60], Italy [61, 62], Colombia [63], Indian Ocean [64], Baltic Sea coast [65] and Southeast Asia [66]. In this section, a thorough study is done to review the literature on wave and tidal energy potential in Iran, which can be useful in determining the optimum sites for marine energy exploitation.

Regarding tidal energy, it is as such a form of hydropower that converts the energy obtained from horizontal motion of seas and oceans to useful form of energy. Over the last decade, The National Cartographic Center (NCC) of Iran has established some permanent tidal stations along the coasts of Persian Gulf and Oman Sea. The Center has also established temporary tidal sites primarily for data collection to serve research projects. Most Iranian ports also monitor the tides and sea-level variations. Hourly tide-gauge data collected since are available [67].

3.1. Caspian Sea

The Caspian Sea is the largest enclosed inland body of water on earth by area and is classified as the world's largest lake. With a negligible tide, only waves are relevant in terms of energy. It is located between the latitudes of 36.341ºN and 47.131ºN and the longitudes of 46.431ºE and 54.511ºE [68]. It has the surface area of 390000 km^2, water volume of 78700 km^3 and coastal length of 7000 km, with average and maximum depth of 208 and 1025 m, respectively [69]. The Caspian Sea can be divided into three parts: the northern part, with an average depth of 5-6 m, which covers about 80000 km^2; the central part, with an average depth of 190 m, which covers about 138000 km^2; and the southern part, with a maximum depth of 1025 m, which covers about 168400 km^2 [70]. The mentioned bathymetry of the Caspian Sea is shown in Fig. 11 [71]. The changes in water level have always affected the lives of nearby inhabitants. It is also suggested that 45pc of the change in the water level is due to an increase in river flow, 16pc to an increase in surface precipitation and 25pc to a decrease in evaporation rates [72].

With average and maximum wave power of 14 kW/m and 30 kW/m, respectively, the Caspian Sea is an area with great wave energy potential. Only limited research has been conducted on this potential. Alamian et al. [73] evaluated the existing systems for converting wave energy into electricity and their application in the Caspian Sea. The availability of WECs was analyzed based on the conditions of the Caspian Sea – wave heights and periods, bathymetry, and seabed and shore conditions, and a benchmark table was presented with a wide range of parameters to determine the most suitable WEC for the Caspian Sea. The parameters of installation, access to manufacturing technology, output power, availability of the electrical system, construction of the generators, generator efficiency and security of the installation site were considered in their investigation. Finally, the ratings and total scores of each WEC were tabulated, as shown in Fig. 12. According to this figure, the point absorber system has the highest score among available converting systems. This choice is reasonable given the wave conditions in the area and the advantage of a relatively easy transport onshore if necessary.

Rusu and Onea [74] assessed the wind and wave energy resources along the Caspian Sea. For this purpose, the remotely sensed data and results provided by numerical models were considered, reporting that the central part of Caspian Sea has a maximum significant wave height of 3 m and wave power of 20 kW/m in the case of the average energy conditions. In high energy conditions, corresponding to the winter season, the maximum values of significant wave height and wave power are 6 m and 100 kW/m, respectively. Based on the findings, the Caspian Sea will be an important source of conventional energy in the near future. Also, Iran is to develop many renewable projects in the Caspian Sea due to its characteristics [20, 75]. Golshani et al. [76] presented a wave simulation in the Caspian Sea to obtain the wave climate atlas of this basin. Their results showed that the southern basin has a high wave height, with a high energy potential. Tavana [77] examined possible examples of wave power installations in Tonekabon, in the southern part of the Caspian Sea. According to his studies, the mean wave power in further offshore areas is about 9 kW/m. He also suggested to focus on this region as an appropriate location for wave energy conversion with several advantages compared to other conventional renewable sources.

Fadaee-Nejad et al. [78] studied the potential of wave energy on the southern coast of the Caspian Sea, indicating that wave power along the Mazandaran province seashore can reach up to 18 kW/m or higher – a considerable value. In addition, Babolsar city is recognized as having the highest potential for wave power in the area. Faiz and Ebrahimi-salari [79] studied the potential of the seas in Iran for wave energy conversion using linear permanent magnet generators, determining that wave heights can reach up to 12 m. On this basis, the Caspian Sea is suggested as an area with potential for the development of wave energy, especially by applying converting systems with direct-driven linear permanent magnet generator.

Hadadpour et al. [80] described the existence and variability of wave energy in the southern part of the Caspian Sea. Furthermore, the monthly average and seasonal variations of wave energy were determined at the port of Anzali (Fig. 13) [81], revealing that the maximum efficiency of the converting system to be deployed should be in the range of less than 2 m in terms of significant wave height and between 4 and 7 s in terms of peak period, which should be taken into account for selecting proper WECs. Moreover, it was noted that waves with the highest energy occur during winter, followed by spring. The months of January and February were identified as the most energetic in the study area. The easternmost area was also found to be the most appropriate for wave energy extraction. The contribution of the different sea states to the total annual energy for one hotspot at Anzali is illustrated is Fig. 14. According to this figure, wave energy is centralized for peak periods between 4.5 s and 6.5 s and for significant wave height less than 1.5 m.

Khojasteh et al. [82, 83] introduced Babolsar as a wave energy hotspot by analyzing the performance of various heaving point absorbers at this location. The authors have realized that the cone-cylinder and the hemisphere-cylinder heaving point absorbers are among the best types of WECs to be deployed on the coast of Babolsar. Kamranzad et al. [84] assessed the feasibility of wave energy harvesting in the southern Caspian Sea to locate the most appropriate stations. The spatio-temporal variations of the wave energy were investigated and found that the wave condition is relatively stable at all stations. The central Caspian was found to be the most appropriate part for wave energy extraction due to its higher exploitable storages of wave energy. The research on the wave energy potential and its exploitation in the Caspian Sea is summarized in Table 4.

3.2. Persian Gulf and Gulf of Oman

The Persian Gulf is an important semi-enclosed water body with a long marine boundary with southern Iran. It is an important area due to its rich resources of gas and oil, and for maritime transport. Located between the latitudes of 24ºN and 30ºN and the longitudes of 48ºE and 57ºE [85], the Persian Gulf is connected to the Gulf of Oman through the narrow Strait of Hormuz. It has a length of 990 km and covers an area of 226000 km^2, with an average depth of about 35 m and a maximum depth of approximately 107 m [86]. The average wave energy potential is about 6.1 kW/m. However, there is considerable potential in the Persian Gulf islands, with maximum and average values of 16.6 kW/m and 19 kW/m, respectively [87].

The Gulf of Oman is located in the Middle East between Iran, Oman and the United Arab Emirates. This Gulf is the entrance to the Persian Gulf and the Indian Ocean. Therefore, it is a strategic area, especially for adjacent oil producing countries. The Gulf of Oman has a length of 545 km and its width varies between 56 km and 370 km [7]. Its average wave power has been estimated at 12.6 kW/m [87].

In this section, we have provided a comprehensive review of the wave and tidal energy potential of Persian Gulf and Gulf of Oman. Kamranzad et al. [88] investigated the spatial distribution of wave power in two coastal stations (Boushehr and Assalouyeh ports) in the central part of the Persian Gulf. It was noted that there is a negligible variation in the future annual average wave power. The wave power distribution in Boushehr and Assalouyeh is shown in Fig. 15. As is obvious from the figure, the highest wave energy can be obtained from significant wave heights of 1 to 1.25 m and peak periods of 5.5 to 6 s for Boushehr, and significant wave heights of 1.5 to 2 m and peak periods of 5.5 to 6 s for Assalouyeh.

Akhyani et al. [89] studied the circulation in the Persian Gulf and the Gulf of Oman to assess the power density of ocean currents. Their results indicated that the energy of the current increases during monsoon periods. Furthermore, the marine current energy of these Gulfs is non-negligible; however, its harnessing will have to be postponed until more efficient power conversion systems become available in the near future.

Saket and Etemad-Shahidi [7] probed wave power along the northern coasts of the Gulf of Oman. It was suggested Chabahar port (southeastern coast of Iran) as the best site for the installation of a wave farm due its considerable wave resource. The monthly average wave power for a site near to Chabahar port is illustrated in Fig. 16. This figure indicates that the monthly averaged wave power varies between 0.97 kW/m and 5.16 kW/m, and the highest average energy occurs during July and August, and the lowest are associated with autumn in October and November.

Soleimani et al. [90] evaluated the best locations for tidal and wave energy conversion in the Iranian seas. In the case of tidal potential energy, it was found Khowr-e Doragh in the Persian Gulf to be suitable, with a tidal range of 3.75 m and an average 15.8 MW of electricity that can be extracted by constructing a tidal barrage in this area. In addition, Faroor and Assalouyeh, also in the Persian Gulf, were proposed as appropriate locations to harness wave energy, especially by means of bottom-fixed heave-buoy WECs.

Zabihian and Fung [87] reviewed the state of the art in the harnessing of marine energy and studied Iran from an energy point of view and the possibility of using these energy resources. The wave power per meter of several coastlines in Persian Gulf and Gulf of Oman was presented, with the result that Chabahar port is the best site in terms of wave energy potential. This is because Chabahar is located in the Gulf of Oman, linked to the Indian Ocean, with an average wave power between 10 and 15 kW/m [91]. The wave power potential for different hotspots of these two Gulfs is indicated in Table 5.

Etemad-Shahidi et al. [92] determined the hotspots of wave energy in the Persian Gulf. According to their results, the average values of wave power are higher in the middle part of Persian Gulf due to the long fetch of this Gulf in the NW-SE direction, which is also the dominant wind direction. Kamranzad and Chegini [93] studied spatial, seasonal and monthly wave energy distributions in the entire Persian Gulf and, in particular, at nine coastal stations. Lava Island for its high average wave power and Ra's-e-Motaf for its high maximum wave energy were highlighted.

Kamranzad et al. [94] presented the wave energy extracted from three points in the western, central and eastern parts of the Persian Gulf. It was noted that there are both seasonal and decadal variations in the wave energy trends at all the sites considered due to climate variability. The study area, selected sites (W, M and E) and seasonal variation of wave power for these sites are presented in Fig. 17. It may readily be seen that there is a reduction in wave power from the year 1990 to 2000 in comparison to the previous and following years.

Rashid and Hasanzadeh [95] analyzed the possible examples of offshore wave power installations in the Chabahar area of the Gulf of Oman. It was declared that the technical potential of the area for a large scale roll-out should be recognized. Based on their results, it is noted that by applying a single Pelamis WEC (750 kW), an average energy production of 0.32 GWh can be achieved. This value is 4.9 GWh for a 1500 kW single Pelamis and 2 GWh for a single point absorber. However, a recent study investigated the spatio-temporal variations in the whole domain of Gulf of Oman and also in selected stations and indicated that the wave power increases from west to east and there is more wave power and more exploitable wave energy moving towards the east from Chabahar [96].

Abbaspour and Rahimi [97] provided an atlas of the Iranian offshore renewable energy resources to map out the wave and tidal resources at a national scale for the Persian Gulf and the Gulf of Oman.

Rashid [98] employed a statistical method for estimating the tidal current energy resource at Khowr-e Musa Bay, on the southwestern coast of Iran, where the peak tidal currents exceed 2 m/s. It is reported that this area should be considered for its technical potential to extract tidal current energy.

Khojasteh and Kamali [82, 99] investigated the performance of two geometries of point absorbers (cone-cylinder and hemisphere-cylinder) deployed at different energy hotspots in the Persian Gulf and the Gulf of Oman, with the aim of establishing the best location for these heaving absorbers. It was found that Khowr-e Musa in the Persian Gulf and Chabahar Bay in the Gulf of Oman are the best sites in view of their substantial wave resource. The comparison in terms of power capture between the cone-cylinder and hemisphere-cylinder point absorbers for Khowr-e Musa and Chabahar Bay is presented in Fig. 18. In this figure, P_{abs}, H_{s}, D, d, cc and hc are absorbed power, significant wave height, point absorber diameter, draft, cone-cylinder and hemisphere-cylinder, respectively. It can be deduced that a considerable amount of wave energy may be harnessed at these sites.

The numerical simulations for three potential tidal sites in the Persian Gulf and the Oman Sea: Khowran Strait, Hengam Island and Greater-Tunb Island were carried out by Radfar et al. [100]. According to these evaluations, Hengam and Greater-Tunb Islands showed more potentials for implementation of a commercial scale tidal turbine farm. For Khowran Starit, it had the most power density among them, but due to its low water depths, tidal energy converters cannot be placed in this site. Aslani et al. [101] studied Doragh estuary, a branch of Khowr-e Musa Estuary, in the Persian Gulf to estimate the potential of electricity generation by using two proposed barrages in the Doragh estuary. The results indicated that the total electricity generation were about the significant values of 150 MWh for the first barrage and 535.98 MWh for the second one over a typical mean spring tidal cycle. The research on wave and tidal energy potential in the Persian Gulf and Gulf of Oman is summarized in Table 6.

4. Conclusions

The current energy model in Iran, based on fossil fuels, is not sustainable owing to its environmental repercussions and the finite nature of the fuel reserves. The transition to a different, sustainable model requires the development of renewable energy sources. In this work, the potential of different forms of renewable energy in Iran was reviewed, with a focus on marine (wave and tidal) energy.

Regarding solar energy, Iran has extensive barren lands exposed to solar radiation of great intensity most days; therefore, many appropriate locations are available for the development of solar energy, including Tehran, Yazd, Semnan and Shiraz [18]. As for hydropower, it is already a well-established source of energy production in Iran, with a total installed capacity of 10266 MW [19]. By contrast, the level of wind energy development of the country is far from the expectations of 5th National Development Plan of Iran, in spite of the very substantial resource and the consequent abundance of suitable locations for wind farms; it may be concluded that wind energy development requires further attention [20, 21]. As for biomass, its commercial utilization should be accelerated by constructing biomass plants, not least in the provinces of Tehran, Isfahan, East Azerbaijan and Khorasan-e Razavi, with the double objective of contributing to the energy mix and treating urban waste. Regarding geothermal energy, Iran enjoys favorable conditions for the formation of geothermal fields, and the sector is seeing renewed activity with the approval of a 55 MW geothermal power plant in Meshkinshahar [18].

As regards wave energy, various investigations have reported the Caspian Sea as an area with a considerable wave energy potential and numerous wave energy hotspots, including Babolsar, Anzali and Tonekabon. In a general overview, the central part of the Caspian Sea was found to be the most appropriate zone for wave energy development, with point absorber WECs the most suitable devices [84, 99].

The Persian Gulf islands and the Gulf of Oman coastline, with 16.6 and 12.6 kW/m of average wave power, respectively, are suitable areas for harnessing marine energy to supply the energy demands of the people inhabiting these deprived, remote, inaccessible and dry rural areas [87]. Moreover, there are a number of wave energy hotspots in the Persian Gulf and Gulf of Oman, including Chabahar Port, Boushehr, Assalouyeh and Khowr-e Musa Bay. Based on the wave conditions of these hotspots, bottom-fixed heaving buoys, single point absorbers and attenuator systems (e.g. Pelamis) have been suggested as suitable WECs to capture the substantial wave resource of these areas [7, 95, 99].

As for tidal energy, the best area for a tidal barrage would be Khowr-e Doragh, in the Persian Gulf, where an average power of 15.8 MW could be generated [90]. Furthermore, the islands of Hengam and Greater Tunb are suitable sites for the construction of a commercial scale tidal farm [100].

In sum, this study has reviewed the potential for renewable energy development in Iran. A succinct review was presented on solar, hydropower, wind, biomass and geothermal energy, and a thorough review on marine (wave and tidal) energy. It has been found that considerable potential exists for the development of marine energy, in particular wave energy, in certain areas of Iranian seas.

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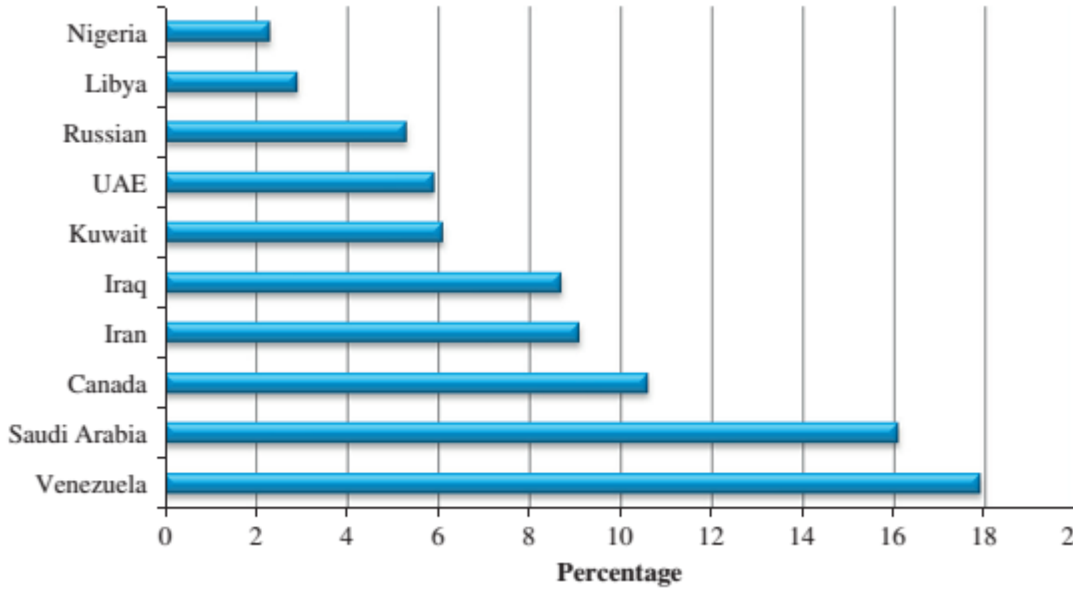


Fig. 1. Top 10 oil reservoir countries [8].

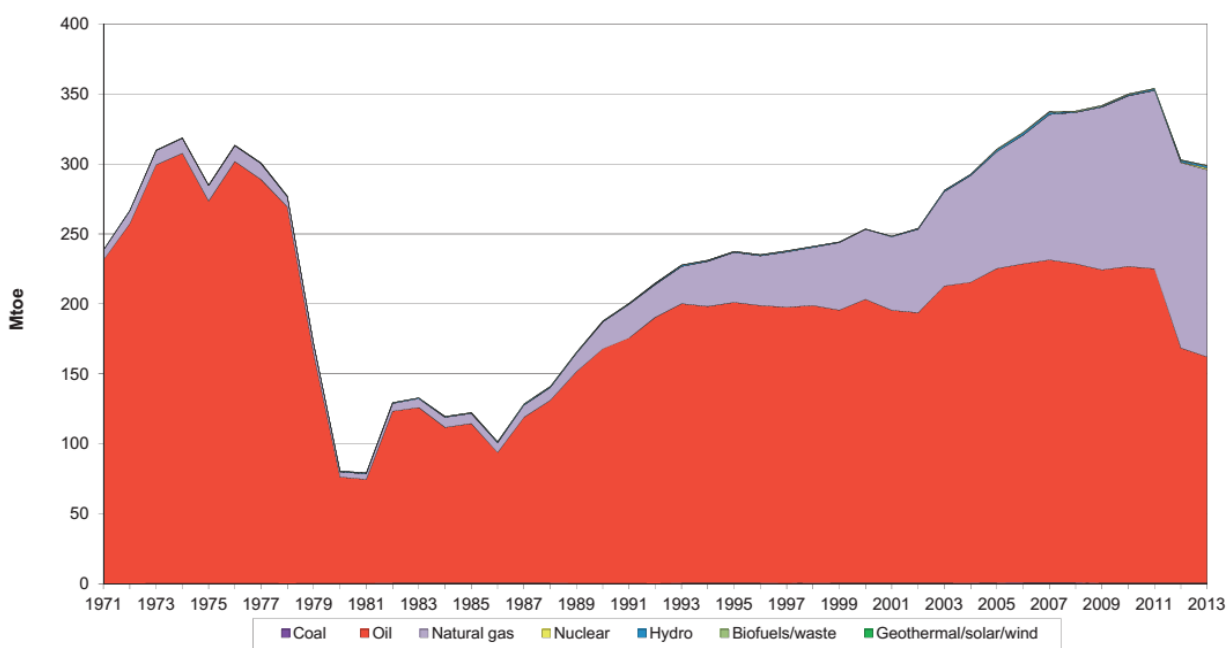


Fig. 2. Iran energy production [14].

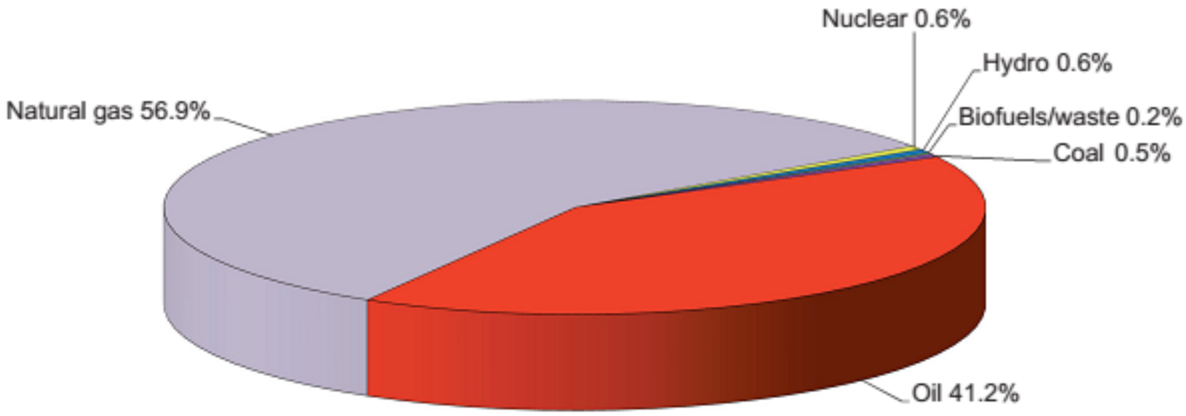


Fig. 3. Iran share of total primary energy supply in 2013 [14].

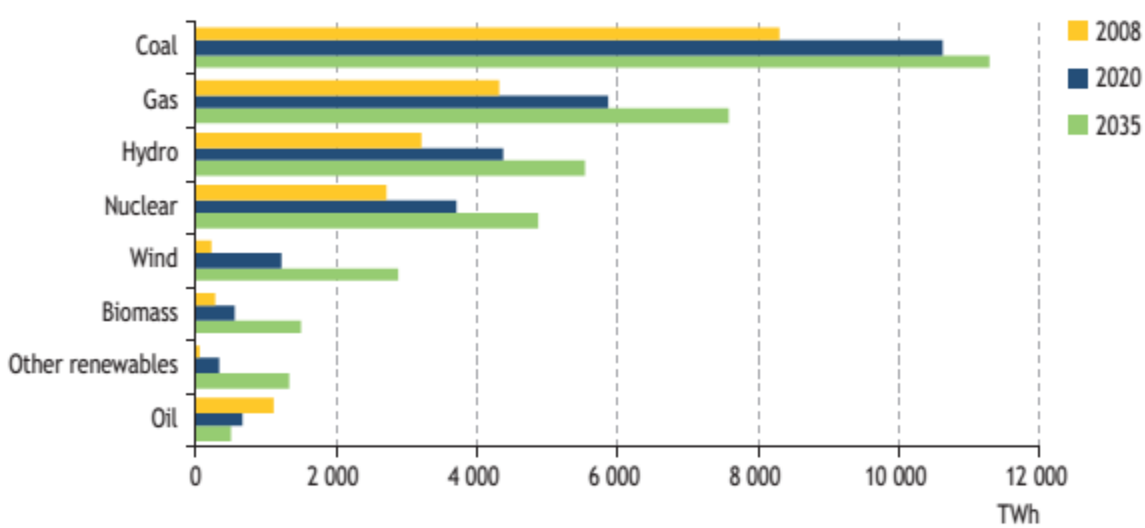


Fig. 4. World electricity generation by type [15].

Fig. 5. Iran solar radiation potential [17].

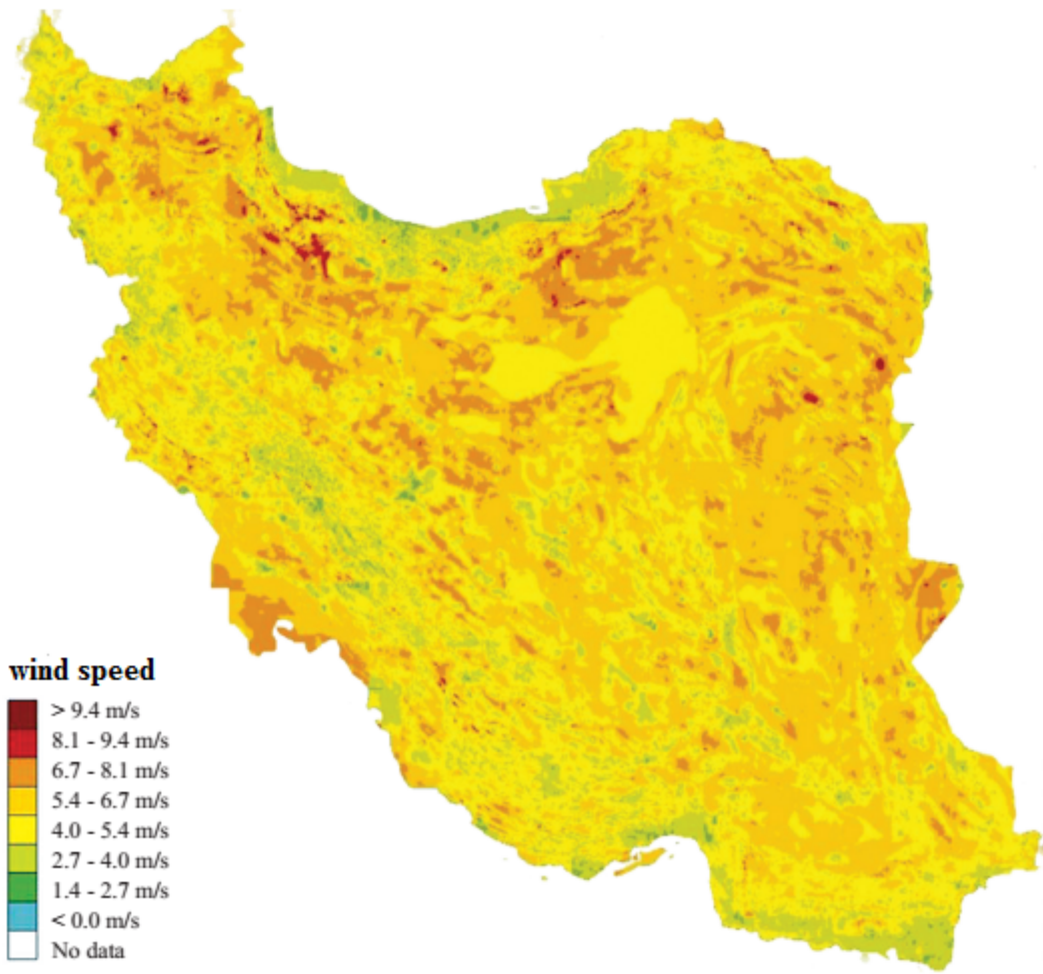


Fig. 6. Iran wind speed (m/s) at 60 m above the ground level [17].

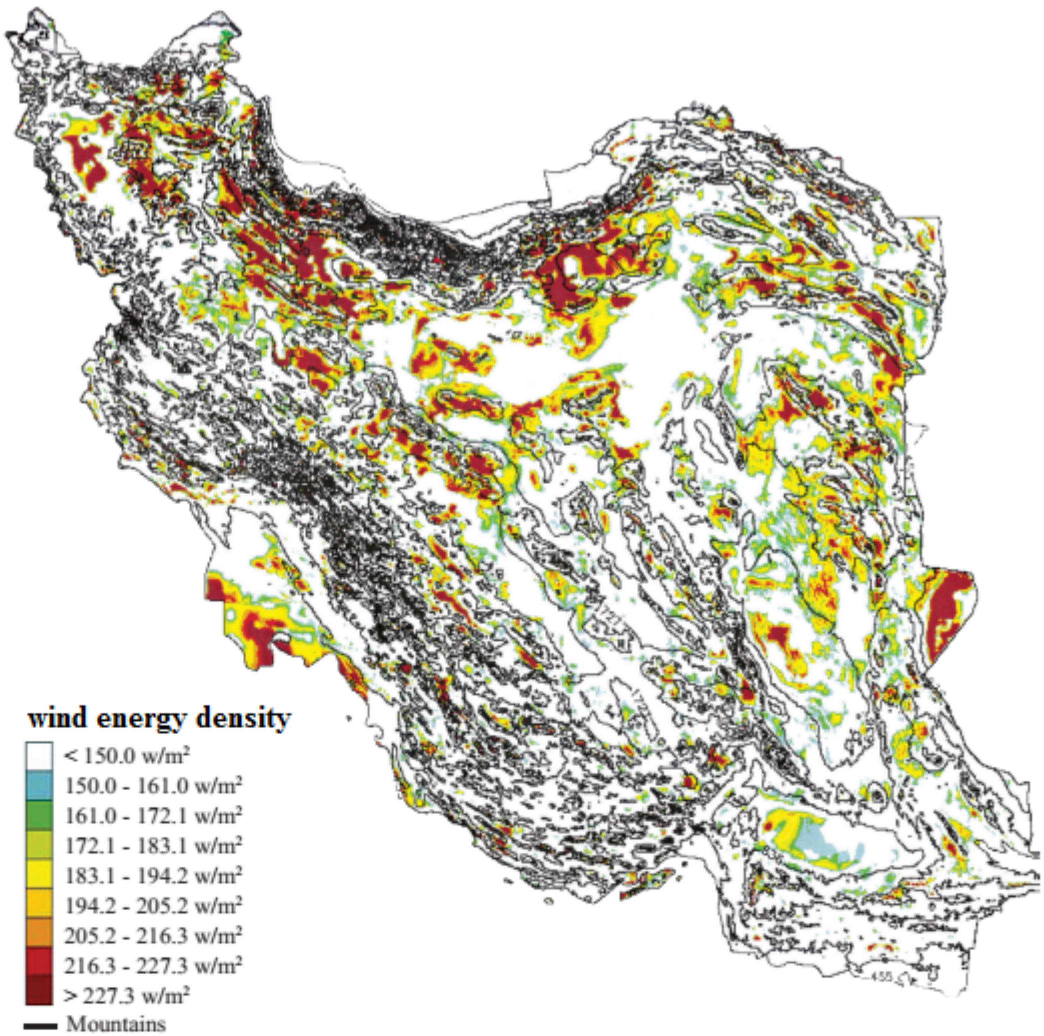


Fig. 7. Iran wind energy density at 80 m above ground level and higher than 150 W/m^2 [17].

Fig. 8. Maximum electricity generation potential (MW) from different types of biomass power plants in the cities over 250000 people in Iran [17].

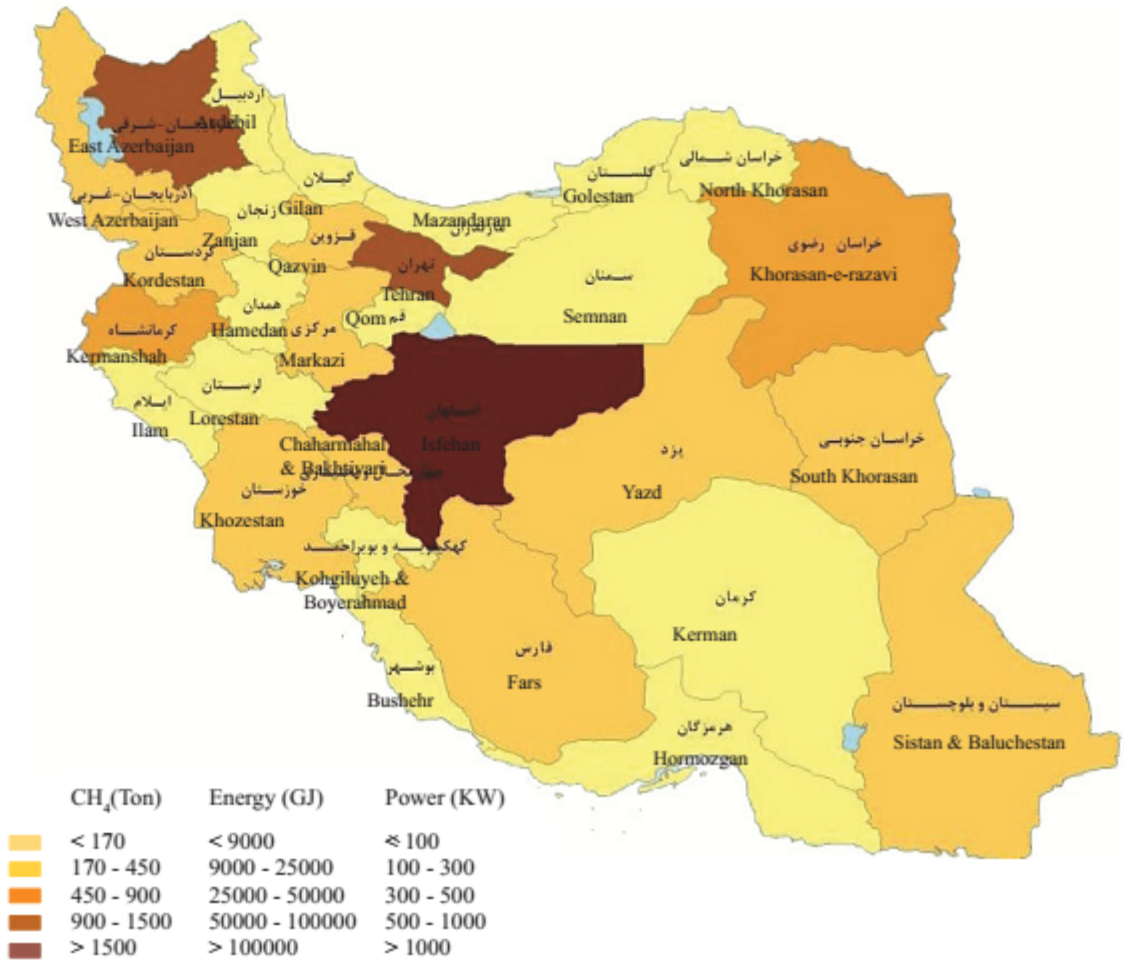


Fig. 9. Technical potential of methane, energy and electricity generation of sewage in different provinces of Iran [17].

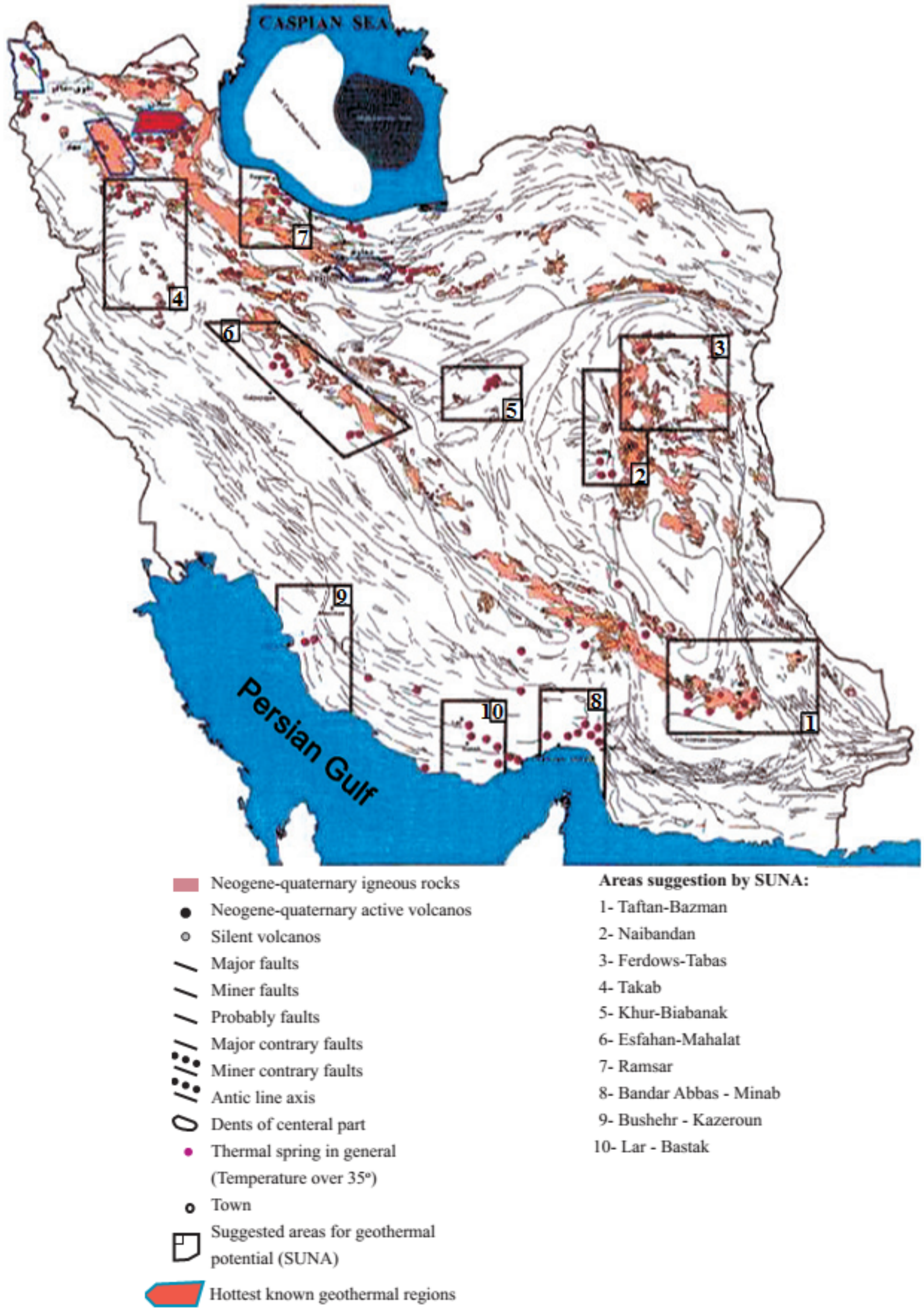


Fig. 10. Geothermal potential of Iran [18].

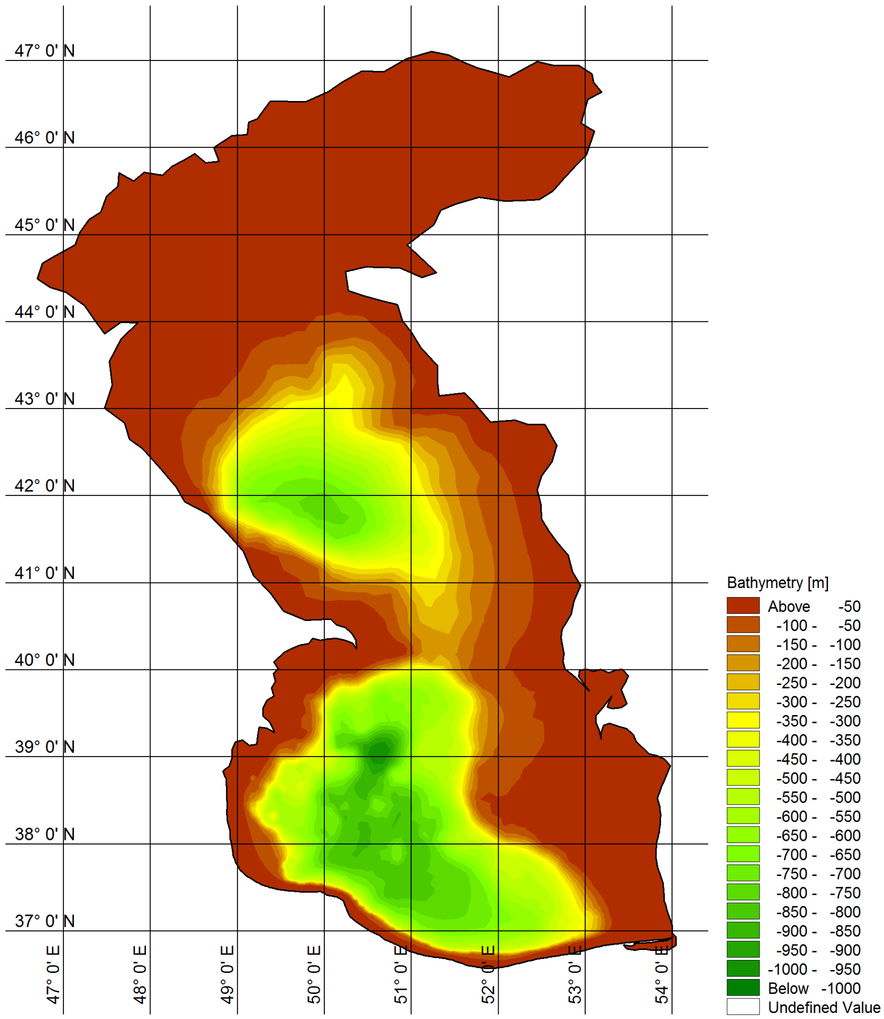


Fig. 11. Bathymetry of Caspian Sea [71].

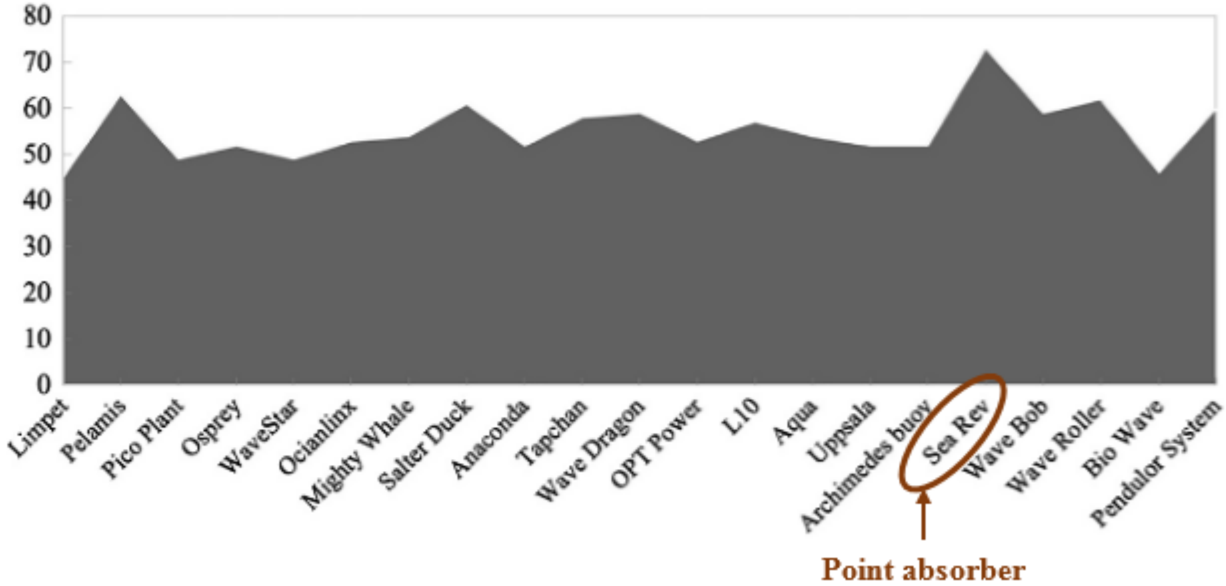


Fig. 12. The total score for the wave energy converters for use in Caspian Sea [73].

Fig. 13. Location of Anzali port [81].

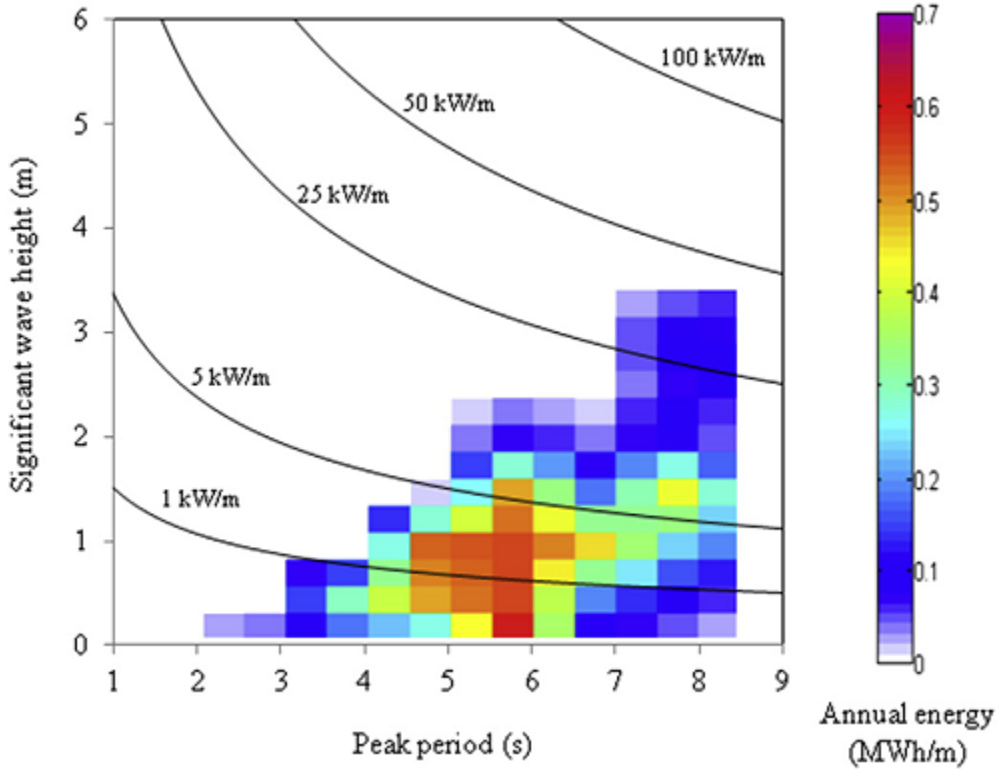
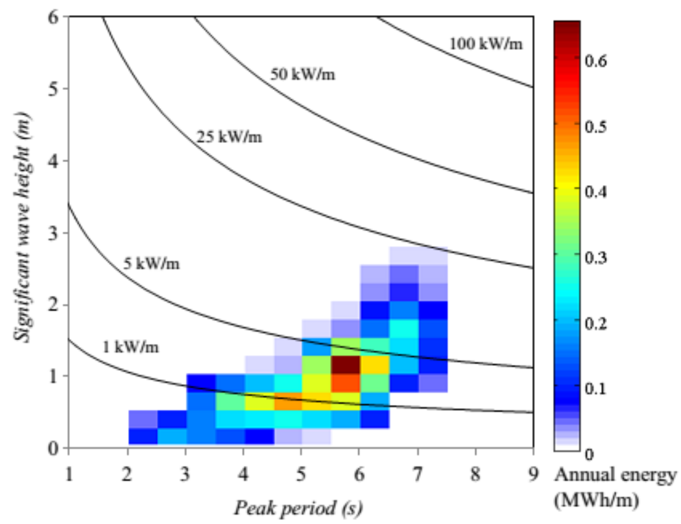


Fig. 14. Contribution to the total annual wave energy (MWh/m) of the different sea states for a wave energy hotspot in Anzali port [80].

a)



b)

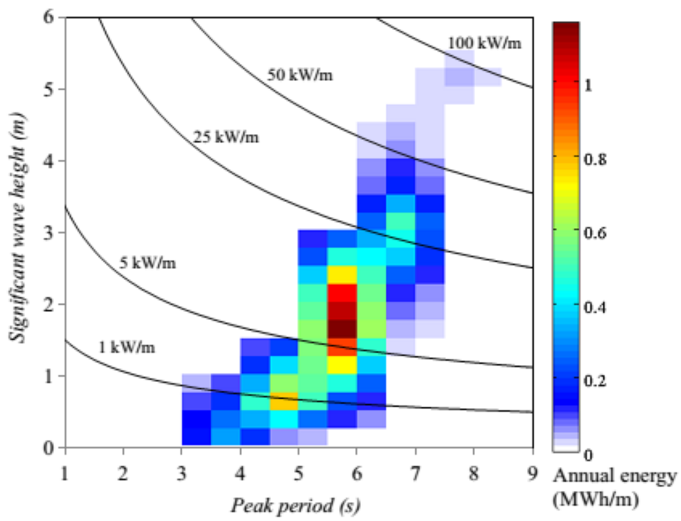


Fig. 15. Wave power distribution in: a) Boushehr, b) Assalouyeh [88].

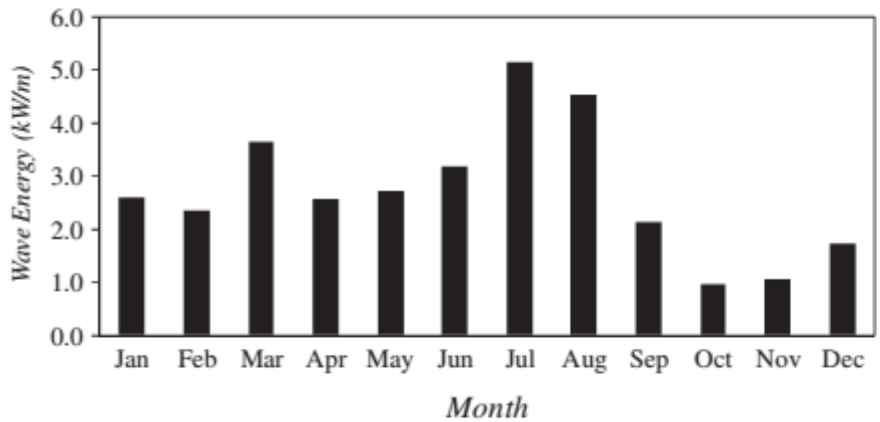


Fig. 16. Monthly average wave power (kW/m) for a site near Chabahar port [7].

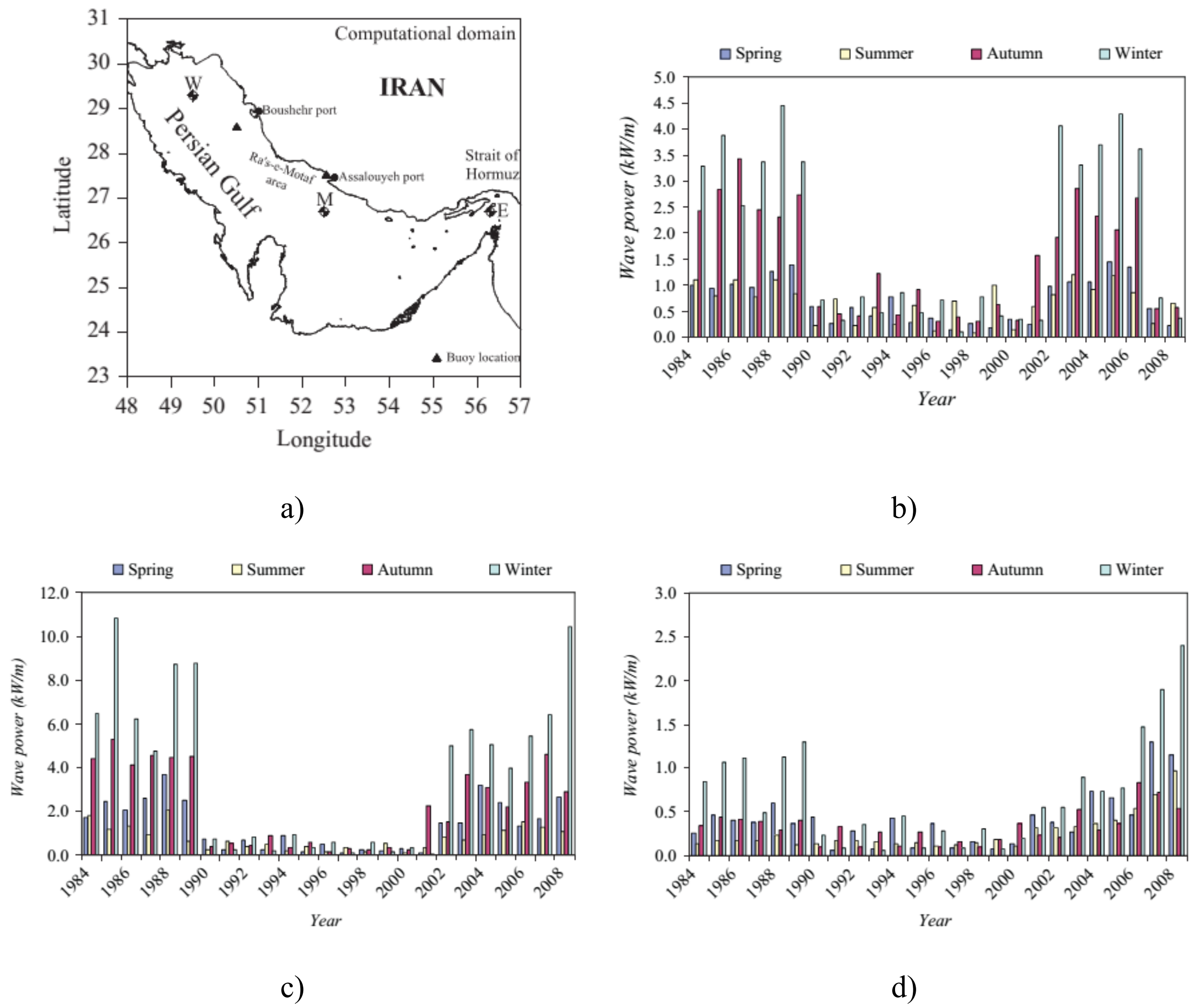


Fig. 17. Seasonal variation of wave power: a) locations of selected sites, b) site W, c) site M, d) site E [94].

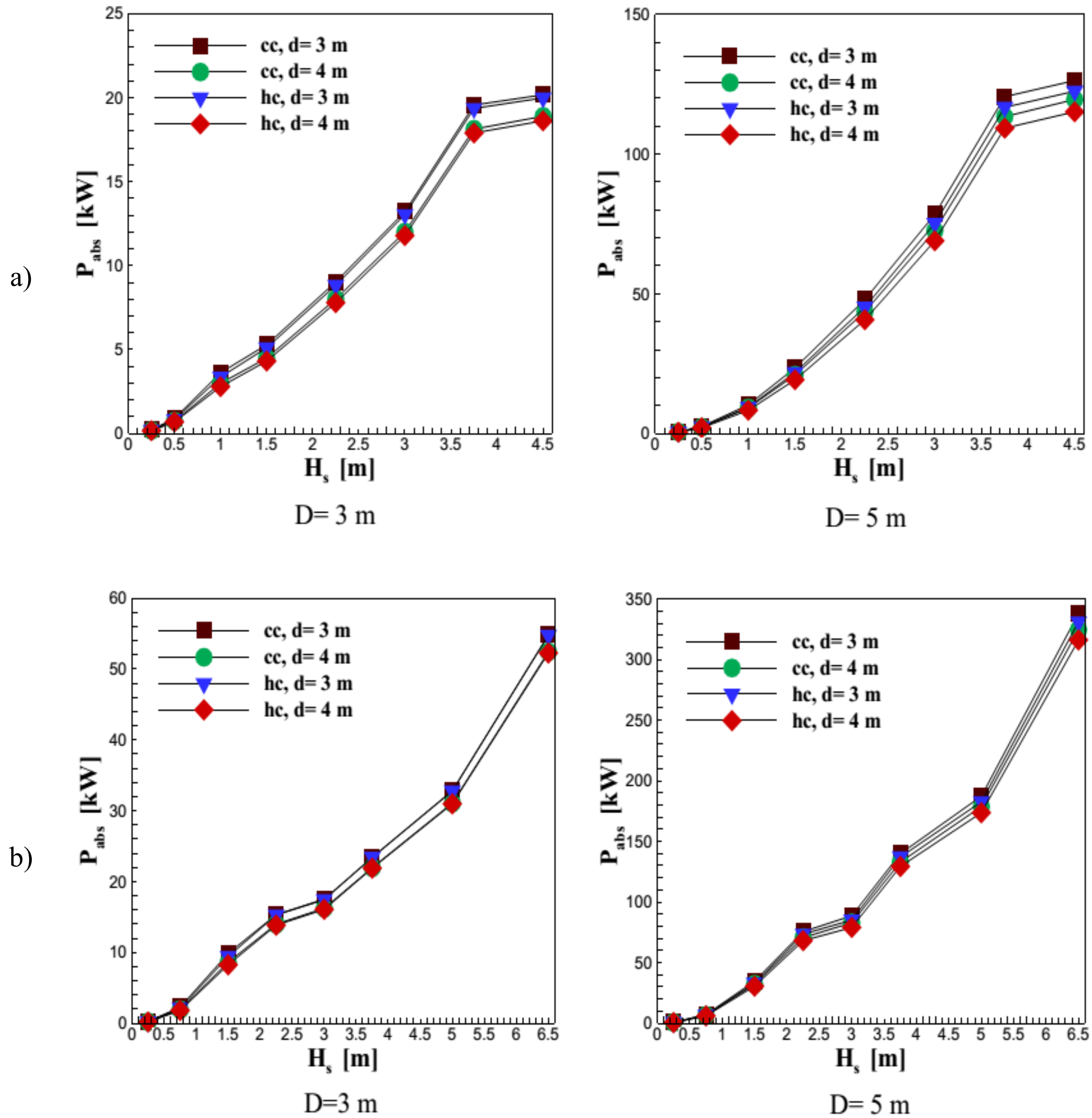


Fig. 18. Power absorption of cone-cylinder and hemisphere-cylinder heaving point absorbers at:

a) Khowr-e Musa, b) Chabahar Bay [99].

Table 1. Solar power plants in Iran [18].

Item	Installed capacity (kW)	Description
1	32105	Universities, Distributions and Regional Electricity companies, SUNA, Telecommunication systems, Rural Electrification and other state offices by 20.03.2014
2	7158	Installed capacity of photovoltaic systems from electricity levies from March 2013 to 21.06.2015
3	514	Capacity installed by private sector
39777		Totaled installed capacity (KW)

Table 2. Nominal capacity of hydropower stations of Iran [19].

year	2007	2008	2009	2010	2011	2012	2013
Capacity (MW)	7422.3	7672.5	7704.7	8487.8	8746.2	9746.1	10266

Table 3. Total capacity of wind power in Iran [19].

year	2007	2008	2009	2010	2011	2012	2013
Capacity (MW)	74	89.8	90.3	92.9	98.2	106.1	110.1

Table 4. Investigations on wave energy potential in Caspian Sea.

Investigators	Location	Important findings
Alamian et al. [73]	whole Caspian Sea	Introducing point absorber system as the best WEC according to Caspian Sea conditions
Rusu and Onea [74]	whole Caspian Sea	Presenting the Caspian Sea as an important source of conventional energy in the near future
Golshani et al. [76]	whole Caspian Sea	Recognizing southern basin of the Caspian Sea to have high wave height with high energy potential
Tavana [77]	Tonekabon city	The mean wave power in further offshore of this area is about 9 kW/m
Fadaee-Nejad et al. [78]	Mazandaran province	The mean wave power of this area can reach up to 18 kW/m which is a considerable value
Faiz and Ebrahimi-salari [79]	whole Caspian Sea	Suggesting the Caspian Sea as an area with high energy potential with high waves up to 12 m
Hadadpour et al. [80]	Anzali port	For maximum efficiency of WECs the significant wave height of 2 m and peak period between 4 and 7 s should be taken into account
Khojasteh et al. [82, 83]	Babolsar	The cone-cylinder and the hemisphere-cylinder heaving point absorbers are among the best types of WECs to be applied at this coast
Kamranzad et al. [84]	whole Caspian Sea	The central Caspian is the most appropriate part for wave energy extraction due to its higher exploitable storages of wave energy

Table 5. Wave power potential for different areas of Persian Gulf and Gulf of Oman [87].

Site name	Power per meter of coast (kW/m)	Coast length (km)	Total power (MW)
Siri	5.3	5	27
Mahshahr	1.7	223	380
Jask	3.2	289	925
Chabahar	5.8	265	1539
Boushehr	2.2	474	1045
Lenge	3.4	359	1222
Bandar Abbas	0.9	232	210
Abu-musa	5.1	5	26
Abadan	2.9	34	101

Table 6. Investigations on wave and tidal energy potential in Persian Gulf and Gulf of Oman.

Investigators	Location	Important findings
Kamranzad et al. [88]	Boushehr and Assalouyeh	There is a negligible variation in the future annual average wave power of these areas
Akhyani et al. [89]	Persian Gulf and Gulf of Oman	Marine current energy of these Gulfs are considerable, especially during monsoon periods
Saket and Etemad-Shahidi [7]	Chabahar port	Suggesting this area as the best site for the installation of a wave farm due its highest wave resource
Soleimani et al. [90]	Khowr-e Doragh	Presenting this location with a tidal range of 3.75 m and an average 15.8 MW of electricity to be extracted
Zabihian and Fung [87]	Persian Gulf and Gulf of Oman	Introduced Chabahar port as the best the best site in terms of wave energy potential and indicating various energy hotspots in these Gulfs
Etemad-Shahidi et al. [92]	Persian Gulf	average values of the wave power are higher in the middle part of the Persian Gulf due to the long fetch
Kamranzad and Chegini [93]	Persian Gulf	Recognizing Lava Island and Ra's-e-Motaf area with high wave power
Kamranzad et al. [94]	Persian Gulf	There are both seasonal and decadal variations in the wave energy trends in whole Persian Gulf
Kamranzad et al. [96]	Gulf of Oman	The wave power increases from west to east of this Gulf and there is more more exploitable wave energy moving towards the east from Chabahar
Rashid and Hasanzadeh [95]	Chabahar port	This area should be recognized as technical potential for a large scale energy extraction especially with Pelamis and single point absorbers
Abbaspour and Rahimi [97]	Persian Gulf and Gulf of Oman	Providing an atlas of marine energy for these Gulfs
Rashid [98]	Khowr-e Musa Bay	High amount of tidal current energy is available in this area
Khojasteh and Kamali [82, 99]	Persian Gulf and Gulf of Oman	Reporting Khowr-e Musa in the Persian Gulf and Chabahar Bay in the Gulf of Oman as the best sites for wave energy extraction
Radfar et al. [100]	Persian Gulf and Gulf of Oman	Suggesting Hengam and Greater-Tunb zones with high potentials for implementation of a commercial scale tidal turbine installations
Aslani et al. [101]	Persian Gulf	Offering Doragh estuary as a suitable area to generate electricity by constructing barrages