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Localization of solar-hydrogen power plants in the province of Kerman, Iran

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Abstract. This research presents an in-depth analysis of location planning of the solar-hydrogen power plants for electricity production in different cities situated in Kerman province of Iran. Ten cities were analyzed in order to select the most suitable location for the construction of a solar-hydrogen power plant utilizing photovoltaic panels. Data envelopment analysis (DEA) methodology was applied to prioritize cities for installing the solar-hydrogen power plant so that one candidate location was selected for each city. Different criteria including population, distance to main road, flood risk, wind speed, sunshine hours, air temperature, humidity, horizontal solar irradiation, dust, and land costare used for the analysis. From the analysis, it is found that among the candidates' cities, the site of Lalezar is ranked as the first priority for the solar-hydrogen system development. A measure of validity is obtained when results of the DEA method are compared with the results of the technique for ordering preference by similarity to ideal solution (TOPSIS). Applying TOPSIS model, it was found that city of Lalezar ranked first, and Rafsanjan gained last priority for installing the solar-hydrogen power plants. Cities of Baft, Sirjan, Kerman, Shahrbabak, Kahnouj, Shahdad, Bam, and Jiroft ranked second to ninth, respectively. The validity of the DEA model is compared with the results of TOPSIS and it is demonstrated that the two methods produced similar results. The solar-hydrogen power plant is considered for installation in the city of Lalezar. It is demonstrated that installation of the proposed solar-hydrogen system in Lalezar can lead to yearly yield of 129 ton-H2 which covers 4.3% of total annual energy demands of the city.

Keywords: data envelopment analysis (DEA); hydrogen production; location planning; solar energy

1. Introduction

Production and storage of hydrogen from different renewable energies are promising solution

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to suppress the stochastic behavior of renewable forms of energy (Aiche-Hamane *et al.* 2009).

Hydrogen is the most abundant substance in the universe. This gas is a good source for generating clean energy. However, this material is not widely used as a fuel (Ennetta *et al.* 2016). Hydrogen is mainly used in production of ammonia, oil refining and production of methanol (Ni 2013). Therefore, though hydrogen is one of the elements that are abundant in the earth's surface, this element does not exist in nature as pure state, but it can be achieved by several different methods from other elements (Kos and Once 2014). Today, hydrogen can be obtained from processes such as water electrolysis, natural gas reforming and partial oxidation of fossil fuels. Currently 98% of the total hydrogen produced in the world comes from fossil fuels (Marquez *et al.* 2014). Of course, there are also more appropriate, cheaper and more sustainable procedures both in the station and sporadically to produce hydrogen including using renewable energy (solar energy, wind energy). Renewable energy sources are environmentally friendly, since they do not have negative environmental impacts like fossil fuel (Khorasanizadeh *et al.* 2014). There have been numerous related works in renewable energy areas in different parts of Iran which have been studied by authors of this research work which all of them confirmed that implementing renewable sources especially solar and wind are feasible in most areas of Iran (Mostafaeipour and Abesi 2010, Mostafaeipour *et al.* 2014, Mostafaeipour *et al.* 2016b, Alavi *et al.* 2016b, Qolipour *et al.* 2016). Among different sources of renewable energies, solar energy is considered as the most reliable source of energy for the most parts of the world especially in Iran. Solar energy is an abundant renewable energy source that can fulfill required heat and electricity demands of cities without polluting the environment (Genwa and Sagar 2013, Demirhan *et al.* 2013). Iran is rich in number of oil fields, but low price of oil in recent years made government to urge for finding alternative and reliable source of clean and renewable energy. Iran receives an annual average solar irradiation of between 4500 and 5750 kWh/m^2/day. Abundant of sun in most parts of Iran has encouraged the government, policy makers and researchers to pay more attentions towards solar energy technologies. Thus, Iran has embraced solar energy investments. Solar energy can play a major role in achieving government objectives to provide required energy to off-grid and remote regions. To encourage people to use solar energy in order to reduce consumption of fossil fuel, the government pays subside to individuals who install solar equipment. In addition, the Iranian government encourages the development of off-grid solar PV systems and solar PV hybrid system, such as wind-solar. The utilization of solar energy is on the rise in Iran with recent increasing governmental investment and support.

1.1 Solar energy exploitation

Deokattey *et al.* (2013) investigated a study about hydrogen production using High Temperature Reactors. Many researchers are trying to find a strategy for optimizing the energy production (Alavi *et al.* 2016a, Mostafaeipour *et al.* 2016a). Bioenergyis a major source of renewable which refers as gas carrier energy (Kose and Oncel 2014). Márquez *et al.* (2014) studied hydrogen production using photocatalytic source of renewable energy. Kar and Gopakumar (2015) studies the wind-solar renewable energy sources which are the most abundant in the country. Mukhopadhyay and Ghosh (2016) also studied the use of solar tower combined cycle plant with thermal storage. Carnevale *et al.* (2016) investigated economic evaluation of wind and solar energy for electricity production. Ennetta *et al.* (2016) investigated feasibility of hydrogen enriched methane flames simulations. Optimization and modeling works related to solar collectors and biodiesel were performed by researchers for reducing greenhouse gas emissions (Ismail *et al.*

2016, Dhillon and Tan 2016).

Solar energy has not been exploited in many countries yet. Solar panels and solar collectors have extensively been employed for electricity and heat generation in the globe (Khorasanizadeh *et al.* 2014). Solar photovoltaic (PV), and concentrating solar power (CSP) are among major types of solar energy technologies. PVs convert solar energy into electricity directly by using cells made of the semiconductor material. But concentrating solar power systems absorb radiation from sun which convert it to heat at high temperature. Growth of photovoltaic varies by countries worldwide. Four major leading countries in this field were Germany, China, Japan, and USA in 2013. The global PV capacity was 139 GW which is sufficient to generate 160 TWh every year and is equivalent to almost 0.85 percent of the electricity demand in the world (Wikipedia, 6 June 2016). PV was the fastest-growing renewable energy from 2000 to 2011 globally. Solar PV cumulative installed capacity was 1.5 Gigawatt in 2000 while it reached 65 GW at the end of 2011. Germany and Italy had the highest shares, followed by Japan, Spain, the United States and China in 2011. Concentrated solar power market is popular in many countries. Almost 350 megawatts (MW) of commercial concentrated solar power plants were built in California in the 1980s. This technology started again in the United States and Spain seriously in 2006. These two countries have the highest rank of CSP capacity now, with 1 GW and 500 MW installed capacity, respectively. Also, there are more plants under construction or development in these two countries (http://www.iea.org/topics/solarpvandcsp/).

Fig. 1 illustrates the world map of horizontal global solar irradiation (Google 2017). Solar panels can generate power in locations far from power plants and without an electricity grid, but planners need to know where there is sufficient solar energy to operate the plant efficiently. As observed in Fig. 1, Iran has great potential to use its endowed renewable energy resources to power its economy with a sustainable energy supply. There are different methods like Tabu Search, Simulated Annealing, and Genetic Algorithm for location planning (localization) of different problems (Demirel *et al.* 2010). Also, Multi Attribute Decision Making (MADM), and Multi-Criteria Decision Making (MCDM) methods are extensively used for priority and location optimization too (Saaty 2000). Social Multi-Criteria Evaluation (SMCE) method can be considered to locate wind farms (Gamboa and Munda 2007).

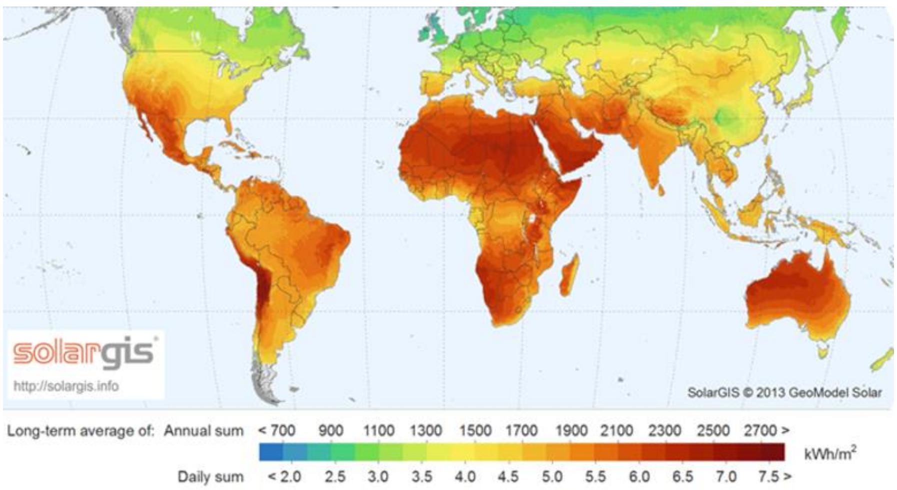

Fig. 1 World map of horizontal global solar irradiation (Google 2017)

There are extensive researches on the evaluation of hydrogen production from solar energy. Padin *et al.* (2000) proposed a novel hydrogen production system from a hybrid solar collector using the water electrolysis. They concluded that the introduced system results in 200% more hydrogen production in comparison with other conventional systems. Rzayeva *et al.* (2001) expanded a mathematical model for producing hydrogen from solar energy by using the electrolysis of water. They analyzed the hydrogen production under two various pressures and also assessed the volt-ampere characteristics of the examined electrolyzer. Gretz (1980) evaluated the feasibility of solar energy for converting to hydrogen and other fuels. He studied different water decomposition methods. Torres *et al.* (1998) performed a simulation on a system consisting of PVs, electrolyzer, fuel cell, battery and hydrogen storage. They selected some locations at Mexico as case studies. Balabel and Zaky (2011) investigated a hybrid solar-hydrogen system in Egypt. Also, they simulated this system in Matlab. The results illustrated that the performance of water electrolysis depends strongly on the input voltage and the distance between the electrodes. Other investigations have been conducted on different locations, such as Algeria (2013), China (2010), and Northwestern Europe (2014).

1.2 Solar to hydrogen literature

The idea of combining a renewable energy source with a hydrogen production system to reduce uncertainty has been originated from several researchers in the past. Solar to hydrogen energy is one of the newly considered exploitation from renewable energies (Momirlan and Veziroglu 2002, Bak *et al.* 2002, Sherif *et al.* 2005, Momirlan and Veziroglu 2005, Veziroglu 2008). Solar to hydrogen energy storage system is the challenging option to convert the electric power extracted from a photovoltaic solar system into an electrolyser to produce hydrogen gas which is then stored by a water separator system. Next, the stored hydrogen gas needs to be feed into a fuel cell element for storage to come into eclectic production when there are shortfalls of the electricity supply due to low or no sunlight (Winter 1987, Linkous 2001, Ghosh *et al.* 2003, Satyapal *et al.* 2007).

Several advanced concepts about hydrogen production from renewable energies have also been examined recently. Amongst these, a hybrid energy conversion system consisting a different number of wind turbines and solar panels so as to produce hydrogen by a water electrolyzer was presented in (Khalilnejad and Riahy 2014). The comparison of a hydrogen production system, including an alkaline electrolyzer in both grid-connected and stand-alone modes, was drawn in (Ferrari *et al.* 2016). The main aim of this study was to determine the optimal size of hydrogen plant when it is supplied by a photovoltaic panel instead of power grid. Dincer and Ratlamwala (2013) analyzed different hybrid hydrogen production systems which utilized solar thermal and also PV power plants in terms of efficiencies as well as the sustainability indices. The operation of a PV-based alkaline water electrolysis without considering maximum power point tracking (MPPT) techniques was carried out by (Ahmed and Shenawy 2006). Additionally, some other studies demonstrated alternative hydrogen production systems such as ammonium sulfite solution and GaN-based structured-systems for improving the performance and efficiency of these integrated energy systems (Huang 2013, Benton *et al.* 2013).

There is also vast amount of research on different parts of a solar-hydrogen system including the solar PV panel, electrolyser, hydrogen storage and fuel cell (Dicks 1996, Bak *et al.* 2002, Larminie *et al.* 2003). The PEM fuel cells were extensively examined by Shabani and Andrews (2011) to provide both heat and power into the solar hydrogen energy system called RAPS. Their economic study on using the fuel cell to heat up a LPG hot water system indicated that only 15 % of the total initial cost can be recovered using the solar hydrogen system in 30 years period. Dou & Andrews (2012) have designed a control unit for a solar-hydrogen system in a remote area in Australia. They demonstrated the system performance through simulations in MATLAB and also in real life situation. In the above literature, a large number of experimental and virtual solar-hydrogen systems can be found although there are challenges on economic aspects as well as the control unit of these systems. There are researches to increase the lifespan of the components, testing for splitting the Photovoltaic and electrolyser for certain operating conditions, ascertain high power transmission efficiency (Van de Krol *et al.* 2008).

In the present study, Data Envelopment Analysis (DEA) methodology was applied to optimize location of solar plant, and then Anderson-Peterson (AP) was used to prioritize 10 cities for installing solar farms. The results obtained by the DEA and AP models are verified and validated against the Technique for Ordering Preference by Similarity to Ideal Solution (TOPSIS), recognized as a well-known method for localization. Criteria used for analysis are population, distance to main road, flood risk, wind speed, sunshine hours, air temperature, humidity, horizontal solar radiation, dust, and land cost. There are many other factors such as water resources available for hydrogen production (9 liters H_2O/kgH_2), existence of electricity generation power plants and density of grid distribution network, local electricity consumption can also be considered. But, the addressed parameters in this study were important for local authorities to decide on development of the solar systems. For this study, Photovoltaic Solar Power Plants for 10 cities of Kerman Province in Iran is analyzed.

DEA is an MCDM powerful tool for solving many problems which has numerous advantages such as:

• It is able to consider multiple input output models.
• It is not required to assume a functional form related to inputs to outputs.
• Comparison of DMUs can be done against combination of peers or a peer.
• Different units can be used for input and outputs.

Limitations of DEA can be summarized as:

• DEA method works well for estimating “relative” efficiency of a DMU but it converges very slowly to “absolute” efficiency.
• DEA is a nonparametric method, therefore research works related to statistical hypothesis tests are difficult to solve.
• Large problems can be computationally hard to solve, because a standard formulation of DEA creates a separate linear program for each DMU.

The next section offers a discussion of geographic characteristics. An overview of the solar power plants in the world and Iran is presented in sections 3. Methodology is brought forward in section 4. Data description is illustrated in section 5. Analysis is discussed in section 6. Finally concluding remarks are presented in Section 7.

2. Geographic characteristics

Kerman province is located in the southeast of the central plateau in the area between 25°55$^{/}$ N and 32° N and also between 53°26$^{/}$ E and 59°29$^{/}$ E. Kerman provincewith an area of 180,726 km^2 ranks as the second largest province of Iran which occupies nearly 11 percent of the total land area of the country. The province has variable climate type across regions such that in the north, northwest, and central areas enjoy a dry and moderate climate while in the south and southeast it is warm and relatively humid. City of Kerman, the most important city in the southeast of Iran, is the capital and largest city of the province (Wikipedia, 14 May 2016). In this research work, 10 cities distributed in different parts of Kerman province have been nominated to identify the more appropriate location for developing the photovoltaic power plants. Fig. 2 illustrates map of Iran including 10 cities in Kerman province.

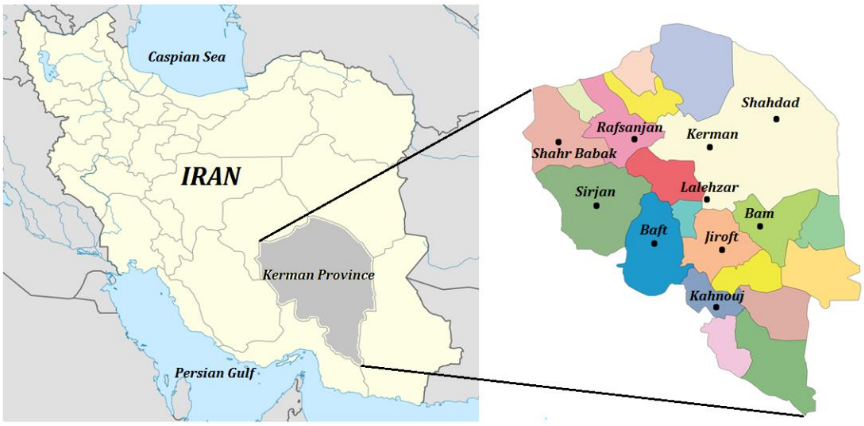

Fig. 2 Map of Iran including Kerman province and the cities within the province (Wikipedia, 14 May 2016)

Table 1 illustrates the geographical information of the nominated cities.

Table 1 Geographical location of the selected locations in Kerman province (Wikipedia, 14 May 2016)

No	City	Longitude (E)	Latitude (N)
1	Baft	56°33'52.69"E	29°14'48.44"N
2	Bam	58°22'47.12"E	29° 3'24.31"N
3	Kahnouj	57°44'50.97"E	28° 0'5.61"N
4	Kerman	57° 0'41.37"E	30°18'4.45"N
5	Lalezar	56°49'40.05"E	29°31'2.79"N
6	Jiroft	57°41'24.76"E	28°40'15.65"N
7	Rafsanjan	55°56'58.99"E	30°25'36.89"N
8	Shahdad	57°42'53.55"E	30°27'55.22"N
9	Shahrbabak	55° 9'20.00"E	30° 7'9.34"N
10	Sirjan	55°43'4.41"E	29°29'8.50"N

3. Solar power plants in the world

The installed capacity of solar power plants is growing in many countries as one of the major renewable energy sources. From the two types of technology of solar power plants, photovoltaic technology can be mounted on the ground (solar parks) or to be mounted on buildings to provide electrical energy. But solar thermal plants use concentrated solar energy into thermal energy for generating steam which then converts thermal energy into electricity using steam turbines (Wikipedia, 9 Aug. 2016). Silicon (Si) based solar panels are expensive which require high initial investment although useful life of the Silicon (Si) based solar panels are about 25 years. Numerous factors affect the life of a solar panel; thus, it is difficult to predict exactly how long it will operate. As a matter of fact, many of the panels made which were installed in the 1970s are still running at 80% of their original power capacity (Wikipedia, 6 May 2016).

Largest photovoltaic (PV) plants in the world were Agua Caliente Solar Project, in Arizona, USA with 250 MW, which increased to 290MW in 2014. Solar photovoltaicplant in California Valley Solar Ranch (CVSR) has capacity of 250 MW. Welspun Energy Neemuch plant in India has capacity of 150 MW. Mesquite Solar project in Arizona has capacity of 150 MW. Neuhardenberg Solar Park in Germany has capacity of 145 MW. Templin Solar Park in Germany has capacity of 128 MW. Toul-Rosières Solar Park in France has capacity of 115 MW, and Perovo Solar Park in Ukraine has capacity of 100 MW (Wikipedia, 9 Aug. 2016).Solar power development in different countries depends on national economic strength although incentives considered more important than initial installation costs (Wikipedia, 9 Aug. 2016). Table 2 illustrates operational photovoltaic power stations in the world. Charanka solar park in India with nominal power of 590 MW ranks first. Clearly, USA, China, and Germany have great share in photovoltaic power business (Civic Solar 2016).

Table 2 Operational photovoltaic power stations in the world (Civic Solar 2016)

Country	Nominal power (MW)	Photovoltaic power station
India	590	Charanka Solar Park
USA	500	Topaz Solar Farm
China	320	Longyangxia Dam Solar Park
USA	290	Agua Caliente Solar Project
USA	500	Desert Sunlight Solar Farm
USA	250	California Valley Solar Ranch
China	200	Huanghe Hydropower Golmud Solar Park
USA	206	Mount Signal Solar
USA	200	Imperial Valley Solar Project
USA	170	Centinela Solar Energy Project
Germany	166	SolarparkMeuro
USA	150	Copper Mountain Solar Facility
USA	150	Mesquite Solar project
Germany	145	Neuhardenberg Solar Park
USA	143	Catalina Solar Project
USA	139	Campo Verde Solar Project
USA	130	Imperial Solar Energy Center South
Germany	128.48	Templin Solar Park
USA	125	Arlington Valley Solar II
France	115	Toul-Rosières Solar Park

Table 2 Continued

Country	Nominal power (MW)	Photovoltaic power station
Ukraine	105.56	Perovo Solar Park
USA	100	Antelope Valley Solar Ranch
China	100	Xitieshan Solar Park
China	100	Gansu Jiayuguan Solar Park
China	100	Ningxia Qingyang Solar Park
Canada	97	Sarnia Photovoltaic Power Plant
Germany	91	Brandenburg-BriestSolarpark
Germany	84.7	SolarparkFinow Tower
Italy	84.2	Montalto di Castro Photovoltaic
Thailand	84	Lopburi Solar Farm
Germany	83.6	Eggebek Solar Park
Japan	82.02	Oita City Mega-Solar Power Plant
Germany	82	SenftenbergSolarpark
Germany	80.7	Finsterwalde Solar Park
Ukraine	80	Okhotnykovo Solar Park
China	80	Datong Solar Park
South Africa	75	Kalkbult Solar Park
South Africa	75	Lesedi Solar Park
South Africa	75	Letsatsi Solar Park
Germany	71.8	Lieberose Photovoltaic Park
Italy	70.556	Rovigo Photovoltaic Power Plant
India	70	Sakri solar plant
Japan	70	Kagoshima NanatsujimaMegasolar
Ukraine	69.7	Nikolayevka Solar Park
Canada	69	Sault Ste. Marie Solar Park
Germany	67.8	Solarpark Alt Daber
France	67.2	Gabardan Solar Park
China	66	Laowa Solar Park
USA	66	Alpine Solar
Germany	61	Green Tower
China	60.5	WulanchabuSiziwangqi Solar Park
Bulgaria	60.4	Karadzhalovo Solar Park
USA	60	Alpaugh Solar Plant
Spain	60	Olmedilla Photovoltaic Park
France	60	Crucey Solar Park
USA	60	Silver State North
USA	57.7	Avenal Solar Facility
France	56	Massangis Solar Park
Ukraine	54.8	Priozernaya Solar Park
Germany	54	Strasskirchen Solar Park

Table 2 Continued

Country	Nominal power (MW)	Photovoltaic power station
Germany	52.3	Walddrehna Solar Park
Germany	52	Tutow Solar Park
Germany	52	Waldpolenz Solar Park
Spain	52	Puertollano
Bulgaria	50.6	Pobeda Solar Park
India	50	Welspun Energy Rajasthan 50 MW Project
China	50	Qinghai Golmud Solar Park
China	50	Hongsibao Solar Park
China	50	HuanengGeermu Solar Park
China	50	Gansu Dunhuang Solar Park
China	50	Weidi Solar Park
China	50	Golmud CPV Solar Park

Table 3 shows the operational solar thermal power stations in the world (Civic Solar 2016). These include the Ivanpah Solar Power Facility with 392 megawatt (MW).Solar Energy Generating Systems power installation in the San Bernardino County of Californiawhich is the largest solar thermal power plant project currently in operation in the world. Solar Energy Generating Systems in Mojave Desert of California with 354 MW ranks second behind Ivanpah Solar Power Facility. Solana Generating Station in Arizona with 280 MW ranks third in the world. It is clear now that USA has a very high share of installing larger thermal plants in suitable regions of the country. Iran with excellent solar radiation has a very low share (0.25MW) of utilizing this renewable source of energy. USA and Spain are two leading countries which have highest shares of using solar thermal energy in the world. France with only 0.25 MW has the lowest share of operational thermal power plants in the world. Data indicate that there are plans to build larger solar thermal plants in Spain which has 30 plants in the country. USA with 10 operational plants is next to Spain.

Iran with almost 300 clear sunny days a year and a total annual average solar radiation of 1800-2200 kWh/m^2 has an excellent potential to harness solar energy. The world's first integrated solar combined cycle power station using natural gas and solar energy was built in city of Yazd in Iran which was operated in 2009 with capacity of 467 MW. At the Yazd power plant, there are two 159 MW gas turbines, one 132 MW steam turbine, and a 17 MW solar concentrator. Yazd thermal power plant is the largest plant in the Middle East and the eight largest in the world. Another plant which was operated in Iran was built in city of Shiraz which its initial capacity was 0.25 MW which is now upgraded to 5 MW. Shiraz plant is a solar power concentrating system which is unique in Iran (Wikipedia, 9 Aug. 2016).

Table 3 Operational solar thermal power stations in the world (Civic Solar 2016)

Country	MW	Name	Location
USA	392	Ivanpah Solar Power Facility	San Bernardino County, California
USA	354	Solar Energy Generating Systems	Mojave Desert, California

Table 3 Continued

Country	MW	Name	Location
USA	280	Solana Generating Station	Gila Bend, Arizona
USA	250	Genesis Solar Energy Project	Blythe, California
Spain	200	Solaben Solar Power Station[18]	Logrosán
Spain	150	Solnova Solar Power Station	Sanlúcar la Mayor
Spain	150	Andasol solar power station	Guadix
Spain	150	Extresol Solar Power Station	Torre de Miguel Sesmero
India	130	Welspun Solar MP project	Neemuch
Spain	100	Palma del Rio Solar Power Station	Palma del Río
Spain	100	Manchasol Power Station	Alcázar de San Juan
Spain	100	Valle Solar Power Station	San José del Valle
Spain	100	Helioenergy Solar Power Station	Écija
Spain	100	Aste Solar Power Station	Alcázar de San Juan
Spain	100	Solacor Solar Power Station	El Carpio
Spain	100	Helios Solar Power Station	Puerto Lápice
UAE	100	Shams	Abu Dhabi MadinatZayad
Spain	100	Termosol Solar Power Station	Navalvillar de Pela
USA	75	Martin Next Generation Solar Energy	Indiantown, Florida
USA	64	Nevada Solar One	Boulder City, Nevada
Spain	50	Puertollano Solar Thermal Power Plant	Puertollano, Ciudad Real
Spain	50	Alvarado I	Badajoz
Spain	50	La Florida	Alvarado (Badajoz)
Spain	50	Majadas de Tiétar	Caceres
Spain	50	La Dehesa	La Garrovilla (Badajoz)
Spain	50	Lebrija-1	Lebrija
Spain	50	Astexol 2	Badajoz
Spain	50	Morón	Morón de la Frontera
Spain	50	La Africana	Posada
Spain	50	Guzman	Palma del Río
Spain	50	Olivenza 1	Olivenza
Spain	50	Orellana	Orellana la Vieja
India	50	Godawari Green Energy Limited	Nokh
Spain	50	EnerstarVillena Power Plant	Villena
Spain	31.4	Puerto Errado	Murcia
Algeria	25	HassiR'Mel integrated solar combined cycle	HassiR'mel
Spain	22.5	Termosolar Borges	Borges Blanques
Spain	20	PS20 solar power tower	Seville
Egypt	20	Kuraymat Plant	Kuraymat
Morocco	20	AinBeniMathar Integrated Thermo Solar	AinBniMathar
Spain	19.9	Gemasolar	Fuentes de Andalucia (Seville)

Table 3 Continued

Country	MW	Name	Location
Iran	17	Yazd integrated solar combined cycle	Yazd
Spain	11	PS10 solar power tower	Seville
China	10	Delingha Solar Power Plant	Delingha
Australia	9	Liddell Power Station Solar Steam	New South Wales
Turkey	5	Greenway CSP Mersin Solar Tower Plant	Mersin, Turkey
USA	5	Kimberlina Solar Thermal Energy Plant	Bakersfield, California
USA	5	Sierra SunTower	Lancaster, California
Italy	5	Archimede solar power plant	Syracuse, Sicily
Thailand	5	Thai Solar Energy (TSE) 1	Huaykrachao
India	2.5	Acme Solar Thermal Tower	
USA	2	Keahole Solar Power	Hawaii
Germany	1.5	Jülich Solar Tower	Jülich
China	1.5	Beijing Badaling Solar Tower	Beijing
Turkey	1	Feranova CSP Plant	Aydin, Turkey
USA	1	Saguaro Solar Power Station	Red Rock, Arizona
China	1	Yanqing Solar Power Station	Yanqing County
Iran	0.5	Shiraz solar power plant	Shiraz
France	0.25	Augustin Fresnel Solar Power Station	Targassonne
Total	3650.8		

Fig. 3 Dorbid photovoltaic power plant in Yazd (Fereydooni 2013)

European Union and United States were active in the buildup of solar plants since 2005, but Spain started since 2009. Iran with 17 MW capacity started implementing concentrated solar power in 2010 (Wikipedia, 6 Sep. 2016). It is interesting that three African countries of Algeria, Morocco, and Egypt had higher solar power capacity than Iran, Italy, and Germany.

3.1 Solar power plants in Iran

The first use of photovoltaic systems in Iran dates back to the year 1982. This system was installed in Fars province including 45 silicone panels with capacity of 38 Watts for each. Then about 130 communication stations were equipped with total of 260 KW photovoltaic systems. By starting with a silicon cell production line in 1993, photovoltaic applications in other fields became popular in Iran. In 2012, solar plants with capacity of 20 kW were constructed at the same in the country's 17 universities including Yazd University in the Yazd province. The off grid system can supply required electricity of consumers in remote areas without need to the national grid electricity. These systems are suitable for remote areas that do not have access to grid electricity. Batteries are used for night time and also when it is cloudy (Zabihi *et al.* 1998). An example of these power plant systems with the capacity of 12 kW was initiated in village of Dorbid near Yazd city in 1980to supply electricity for 15 village households. Fig. 3 showsDorbid photovoltaic power plant in Yazd (Fereydooni 2013).

4. Methodology

DEA is a well-established non-parametric method to measure the relative efficiency of organizational units or Decision Making Units (DMUs), where there are multiple inputs and outputs that allow incorporating variables. The performance of each DMU is illustrated by a vector of variables that includes information for the evaluation. The selecting of input and output using variables is crucial since it has a direct impact on the efficiency valuation (Alzua-Sorzabal *et al.* 2015). Charnes *et al.* (1987) and Zhou *et al.* (2008) discussed DEA by operations research (OR) and management science (MS) researchers, economists, and efficiency experts from different fields like environmental and energy issues.

DEA was first introduced by Edward Rhodes and Cooper in 1976 to assess the students' achievements in public Schools of America. This technique was used by Farrell in 1957, considering one input and one output, for estimating the efficiency of agricultural sector in America. Edward Rhodes used this technique with multiple inputs and outputs which then was illustrated by Charnes, Cooper and Rhodes, so it is known as CCR model (Sadeghi 2012). Charnes *et al.* (1987) and Motameni (2002) presented a model for optimization that each DMU gets the optimal weight of each input and output for maximizing the efficiency which is the ratio of weighted sum of outputs to inputs which is known as CCR model. DEA is a linear methodology used for determining the relative efficiency of nearly homogeneous organizational units or Decision Making Units (DMUs) when multiple inputs and outputs are involved. The DEA method chooses an efficient known as the best practice DMUs for which the magnitude of inefficient DMUs are obtained by comparing with an initial chosen from of the best practice DMUs. An efficiency score of one is given to the efficient DMUs and lower score values than one is given to inefficient DMUs. This criterion cannot rank the efficient DMUs; although it can give score to inefficient DMUs. Various ranking methods were developed to rank DMUs during the past decades but each technique has some merits and some shortfalls for a specific application, none of the methodologies developed have so far presented a perfect solution to the ranking DMUs. Therefore, the selection of different ranking methods may be combined and utilized to properly address a particular problem. In this paper, the TOPSIS method is used for ranking DMUs because the method is specifically designed for when no preferences can be given into the best practice DMUs.

4.1 Data envelopment analysis (DEA)

The objective of DEA model is to maximize the relative score of a unit ***m*** by determining a set of weights for inputs and outputs and with respect to a set of constraints for objective function and variables. It can be illustrated as follows (Sadeghi 2012)

$$Zp = \text{Max}\ \frac{\sum_{j=1}^{J} v_{jm} y_{jm}}{\sum_{i=1}^{I} u_{im} x_{im}} \tag{1}$$

Subject to: $0 \leq \frac{\sum_{j=1}^{J} v_{jm} y_{jm}}{\sum_{i=1}^{I} u_{im} x_{im}} \leq 1$

n = 1,2,…,N
$v_{jm}y_{jm} \geq \varepsilon$
i = 1,2,…,I
j = 1,2,…,J

Where***Z*** is the relative efficiency of decision making for the unit ***m***, ***i*** is the input number, ***j*** is the output number, ***N*** is the number of decision making units, ***I*** is the number of inputs, and ***J*** is the number of outputs in the model. x_{im} is the i^{th} input of m^{th} unit and y_{im} is the j^{th} input of m^{th} unit which are different values for different units. Vectors V_{jm} and u_{im} are the weight factors that must be obtained in order to maximize the relative efficiency of DMU.V_{jm} is the weight of j^{th} output of m^{th} unit and u_{jm} is the weight of i^{th} output of m^{th} unit.

The first constraint reveals that the objective functions or the ratio of the sum of weighted outputs to the sum of weighted inputs to be between zero and one. Also, ε is a very small positive number which is added to the model as a constraint for the variables to ensure that all weights to be nonzero. The maximum value that the objective function can gain is 1 which shows that the DMU is efficient. If this value becomes less than 1, so the DMU is inefficient. So far, the objective function is nonlinear; in order to solve the problem the denominator gain value of 1 so it can be solved as a linear programming problem. Therefore, the denominator is considered as one of the constraints. The new model is as follows (Sadeghi 2012)

$$Zp = \text{Max}\ \sum_{j=1}^{J} v_{jm} y_{jm} \tag{2}$$

Subject to :$\sum_{j=1}^{I} u_{im} x_{im} = 1$

$\sum_{j=1}^{J} v_{jm} y_{jn} - \sum_{i=1}^{I} u_{im} x_{in} \leq 0$

n = 1,2,…,N
$v_{jm}y_{jm} \geq \varepsilon$
i = 1,2,…,I
j = 1,2,…,J

By using input oriented method, DMU's would be prioritized by obtaining efficiency scores, also the scores would be compared with each other. For objective function to reach the efficient frontier the weighted sum of inputs is kept constant and the weighted sum of outputs increase proportionately. In output oriented method the weighted sum of outputs are kept constant and the weighted sum of inputs decrease proportionately in order to increase the efficiency of weighted sum (Sadeghi 2012). Most DMUs is efficient when the total number of DMUs is not much difference than the total number of inputs and outputs, therefore the model is unrealistic while prioritization is unreliable.

In this study, numbers of DMUs are 10 and criteria are 10 for which none of Eqs. (1) and (2) can be applied. Therefore, the dual form of the above method isapplied. The dual form of the model is presented as (Motameni 2002)

$$CCR'p-I \tag{3}$$

Min $Z_p = \theta$
St
$\sum_{j=1}^{J} \lambda_j y_{rj} \geq y_{rp} r = 1,\ldots,s$

θx_{ip} - $\sum_{j=1}^{J} \lambda_j y_{rj} \geq 0$ $\quad i = 1,\ldots,k$

$\lambda_j \geq 0$ $\quad j = 1,\ldots,n$
θ: Unrestricted in sign

while, $\boldsymbol{z_p}$ is the efficiency of unit $\boldsymbol{p}$, $\boldsymbol{\theta}$ is the variable that isto be minimized, $\boldsymbol{y_{rj}}$ is the $\boldsymbol{r}^{th}$ output (r = 1 to s) of $\boldsymbol{j}^{th}$ unit (j = 1 to n), $\boldsymbol{x_{ij}}$ is the $\boldsymbol{i}^{th}$ input (I = 1 to k) of $\boldsymbol{j}^{th}$ unit (j = 1 to n), and $\boldsymbol{\lambda_j}$ are the factors that calculated for the establishment of constraints. In this model, a DMUis efficient if additional variablesare equal to zero ($Z_p^*=\theta^*=1$) (Pestana Barros and Wanke 2015, Wang and Wang 2014). In this model if again several DMU's become efficient and get value of 1, thencomparison between efficient DMUsis impossible (Anderson and Peterson 1993).

Andersen-Petersen (AP) method is then be used to resolve the above-mentioned problem to rank efficient DMUs. Efficient DMUs are able to obtain efficiency values of greater than 1. This is done by eliminating the $\boldsymbol{p}^{th}$ constraint in basic model or eliminating the $\boldsymbol{p}^{th}$ variable (weight) from the constraints of dual model, in each cycle of model. AP method can be used for both basic and dual DEA. In this study, the dual form of DEA for initial prioritizationis applied, so the dual form of AP for the prioritization of efficient DMU's is used. The only difference between this model and the previous model is that $\boldsymbol{p}^{th}$ term is removed from the constraints in each cycle of this model. The dual model described above is modified through AP technique with following small changes (Anderson and Peterson 1993)

$$CCR'p-I \tag{4}$$

Min $Z_p = \theta$
St:
$\sum_{j=1}^{J} \lambda_j y_{rj} \geq y_{rp}$ j≠p$r = 1,\ldots,s$

θx_{ip} - $\sum_{j=1}^{J} \lambda_j y_{rj} \geq 0$ $\quad$ j≠p$i = 1,\ldots,k$

$\lambda_j \geq 0$ $\quad$ j≠p$j = 1,\ldots,n$
θ: Unrestricted in sign

This model is used to prioritize the cities of Kermanprovince in Iran for the installation of the photovoltaic solar power plants. To achieve this objective, the criteria related to the construction plants must first be defined. Improper selection of criteria can significantly affect the final efficiency score and consequently the ranking of each unit.

4.2 Technique for ordering preference by similarity to ideal solution (TOPSIS)

TOPSIS is a MADM technique which has been used by many researchers because it has a simple and computationally efficient method (Tansel 2014). An important advantage of this technique is that the measures or indicators used in comparing the different measurement units can have a combination of positive and negative indicators. TOPSIS can be used for ranking and comparing various options and for choosing the best option in decision making problems (Goodarzi and Aghajani 2014). The concept of TOPSIS is based on positive and negative ideal alternatives.

The positive ideal alternative gains the best level for all considered attributes, but the negative ideal gets worst attributed values. Clearly, the ideal solution maximizes benefit and minimizes total costs. On the other hand, the negative-ideal solution minimizes benefit, and maximizes total cost (Pestana Barros and Wanke 2015).

TOPSIS is an uncertain MCDM technology which was first introduced in 1981 by Yang and Hung. This method orders the criteria according to the distances from the object to the ideal and the negative solutions. If there are m alternatives $A_1,A_2,\ldots,A_m$ and n stands for decision criteria/attributes $C_1,C_2,\ldots,C_n$. Also, x_{ij}denote the criteria/attribute value of A_i on C_j (i = 1,2,…,m; j = 1,2,…,n). All the values together form a decision matrix $X = (x_{ij})_{m\times n}$. The decision matrix can be standardized in the following form (Wang and Wang 2014)

$$R = \left(r_{ij}\right)_{m\times n} \tag{5}$$

Where $r_{ij} = x_{ij}\left(\sum_{i=1}^{m} x_{ij}\right)^{-1/2}$.

Then, the ideal solution S^+ and the negative ideal solution S^- are determined (Wang and Wang 2014)

$$S^+ = \{s_1^+, s_2^+, \ldots, s_n^+\},\ \ S^- = \{s_1^-, s_2^-, \ldots, s_n^-\} \tag{6}$$

Also, for the benefit index C_j, we have

$$s_j^+ = \max\{r_{ij}|1 \le i \le m\},\ \ s_j^- = \min\{r_{ij}|1 \le i \le m\} \tag{7}$$

Also, for cost index of C_J, we have

$$s_j^+ = \min\{r_{ij}|1 \le i \le m\},\ \ s_j^- = \max\{r_{ij}|1 \le i \le m\} \tag{8}$$

Then, the Euclidean distances of each alternative to the positive ideal and negative ideal solutions would be calculated. The distance between alternative A_i and the positive ideal solution is as following (Wang and Wang 2014)

$$d_i^+ = \sqrt{\sum_{i=1}^{n}\left(s_j^+ - r_{ij}\right)^2},\ \ i = 1,2,\ldots,m. \tag{9}$$

The distance between the negative ideal solution and alternative A_i can be calculated as (Wang and Wang 2014)

$$d_i^- = \sqrt{\sum_{i=1}^{n}\left(s_j^- - r_{ij}\right)^2},\ \ i = 1,2,\ldots,m. \tag{10}$$

Therefore, the relative closeness of each alternative to the ideal solution can be calculated (Wang and Wang 2014)

$$c_i = \frac{d_j^-}{d_j^- + d_j^+}, \quad i = 1,2, \dots, m. \tag{11}$$

Finally, the alternatives are ranked based on their relative closeness. The bigger C_i is, the better alternative A_i will be, and vice versa (Pestana Barros and Wanke 2015, Lourenzutti and Krohling 2014).

5. Data description

The selected case study for this research is 10 cities of Kerman province in Iran for installation of solar plants. For analysis, 10 different criteria were identified which 7 were inputs and 3 were considered as outputs. The criteria used for analysis are population, distance to main road, flood risk, wind speed, sunshine hours, air temperature, humidity, horizontal solar radiation, dust, and land cost. Table 4 presents the monthly and annual average of wind speed for 10 nominated cities in Kerman province.

Table 4 Monthly and annual average of wind speed (m/s) for 10 selected cities in Kerman province

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
Baft	4.61	4.97	5	4.68	5.14	5.34	6.02	5.83	5.21	4.42	4.15	4.54	4.99
Bam	4.45	4.84	4.84	4.61	5.12	5.56	6.24	6.08	5.59	4.73	4	4.42	5.04
Kahnouj	3.93	4.37	4.26	4.21	4.65	4.76	4.84	4.84	4.65	4	3.49	3.93	4.3
Kerman	4.57	4.9	4.99	4.61	5.14	5.58	6.46	6.29	5.45	4.48	4.13	4.51	5.09
Lalezar	4.61	4.97	5	4.68	5.14	5.34	6.02	5.83	5.21	4.42	4.15	4.54	4.99
Jiroft	4.13	4.55	4.5	4.33	4.78	5.01	5.4	5.35	4.95	4.17	3.67	4.12	4.58
Rafsanjan	4.87	5.15	5.27	4.87	5.32	5.6	6.25	5.97	5.24	4.56	4.47	4.76	5.19
Shahdad	4.57	4.9	4.99	4.61	5.14	5.58	6.46	6.29	5.45	4.48	4.13	4.51	5.09
Shahrbabak	4.87	5.15	5.27	4.87	5.32	5.6	6.25	5.97	5.24	4.56	4.47	4.76	5.19
Sirjan	4.72	5.05	5.11	4.81	5.24	5.31	5.86	5.62	5.05	4.41	4.29	4.63	5.01

Population, distance to the main road, flood events in 65 years, annual average of wind speed, and land cost for 10 nominated cities are shown in Table 5.

Table 5 Population, distance to main road, flood risk, annual average of wind speed and land cost for 10 selected cities in Kerman province

No	City	Population	Distance to Main road (km)	Flood events in 65 years (no.)	Average annual Wind Speed (m/s)	Land cost Ranking (IRR)
1	Baft	75940	0.8	35	4.99	2000000
2	Bam	195603	1.8	35	5.04	3000000

Table 5 Continued

No	City	Population	Distance to Main road (km)	Flood events in 65 years (no.)	Average annual Wind Speed (m/s)	Land cost Ranking (IRR)
3	Kahnouj	86290	1.43	20	4.3	2400000
4	Kerman	722448	1.13	69	5.09	4000000
5	Lalezar	2933	25.2	4	4.99	1800000
6	Jiroft	30000	2.98	27	4.58	2500000
7	Rafsanjan	287921	6.27	36	5.19	3800000
8	Shahdad	15842	66.36	0	5.09	1500000
9	Shahrbabak	45751	1.1	24	5.19	3100000
10	Sirjan	267697	0.8	13	5.01	3050000

Tables 6 to 10 illustrate other major criteria for 10 cities including:total number of sunshine hours per months and whole year, monthly and annual mean of average air temperature,monthly and annual mean of relative humidity, monthly and annual mean of horizontal global solar radiation, and total number of days per months and whole year with dust storm.

Table 6 Total number of sunshine hours per months and whole year (hour) for 10 selected cities in Kerman province (Eos Web 2016)

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Baft	220.3	218	239.7	268.5	326.4	309.6	299.6	317.8	296.4	294.6	249.6	228.4	3268.9
2	Bam	234.1	223.8	239.5	258.3	311.2	331.4	338.4	336.8	306.6	296.8	260.4	240.2	3377.5
3	Kahnouj	219.9	221.7	246.9	281.2	326.9	323.1	313.2	306.1	294.8	299.2	262.5	232.7	3328.2
4	Kerman	198.4	200	223.5	237.5	298	323.6	339.1	337.5	310.3	283.9	241.9	206.4	3200.1
5	Lalezar	226.3	216.8	265	261.9	298.3	272.5	300.1	307.3	287.9	278.2	240.8	225.1	3180.2
6	MiandehJiroft	205.9	202.2	227.9	266.8	311.8	306.5	308.1	313.6	284.8	288	247	217.3	3179.9
7	Rafsanjan	215.1	218.6	240.9	268.5	333.8	335.7	339.9	353.7	314.3	304.5	240.2	215.7	3380.9
8	Shahdad	204.6	203.3	241.2	250.1	297.1	329	348.6	343.1	313.3	297.2	248.3	221	3296.8
9	Shahrbabak	218.8	218.4	242.6	259.6	329.3	344.3	335.2	342	315	303.1	244.6	219.5	3372.4
10	Sirjan	226.9	225.5	247.7	271.5	331.2	347	333	339.3	317.3	306.3	250.7	218.9	3415.3

Table 7 Monthly and annual mean of average air temperature (℃) for 10 selected cities in Kerman province (Eos Web 2016)

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Baft	3.2	5.5	9.1	14.2	19.7	24	25.9	24.7	21.5	16.1	10.1	5.9	15
2	Bam	10.7	13.6	18.5	23.8	28.8	32.8	33.6	32	28.9	24	17.5	12.4	23
3	Kahnouj	14.2	17.3	21.5	27.5	33.2	36.5	37.1	35.9	33.1	28.4	21.8	16.3	26.9
4	Kerman	4.6	7.3	11.4	16.4	21.2	25.6	26.8	24.6	21.1	15.9	10	5.9	15.9
5	Lalezar	–0.6	2.6	6	9.7	14.1	17.8	19.5	18.1	15.4	11	5.6	1	10
6	Jiroft	12.7	15.7	19.5	25.3	30.7	34.4	35.7	34.6	31.4	26.1	19.9	14.9	25.1
7	Rafsanjan	6.8	9.5	13	18.8	23.6	28.3	30	28.1	24.6	19.1	13	8.9	18.6

Table 7 Continued

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
8	Shahdad	12.4	17.1	23.4	28.9	34.5	38.6	40.1	38.1	33.9	28.9	20.6	14	27.5
9	Shahrbabak	3.3	5.8	9.7	14.7	19.9	24.8	27.5	25.7	21.7	15.7	9.5	5.6	15.3
10	Sirjan	5.6	8.2	12	17	22.1	26.8	29	27.2	23.5	17.8	11.6	7.3	17.4

Table 8 Monthly and annual mean of relative humidity (%) for 10 selected cities in Kerman province (Eos Web 2016)

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Baft	56	51	47	40	30	27	29	28	30	35	43	52	39
2	Bam	46	41	36	31	26	21	21	21	22	27	34	42	30
3	Kahnouj	59	53	45	32	27	27	33	36	35	33	42	53	39
4	Kerman	53	46	41	34	26	19	19	20	21	28	37	48	32
5	Lalezar	37	36	31	36	29	28	24	23	22	29	35	37	30
6	Jiroft	62	58	51	39	31	30	35	36	38	36	45	56	43
7	Rafsanjan	49	40	36	30	24	19	19	18	19	25	36	43	29
8	Shahdad	38	29	22	20	15	12	11	12	13	16	25	33	20
9	Shahrbabak	54	47	42	37	27	19	20	20	20	28	39	50	33
10	Sirjan	54	47	43	36	27	22	24	24	25	31	39	51	35

Table 9 Monthly and annual mean of horizontal global solar radiation (kWh/m^2) for 10 selected cities in Kerman province (Eos Web 2016)

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Baft	3.62	4.61	5.16	6.09	7.13	7.24	6.98	6.84	6.04	5.09	4.07	3.41	5.52
2	Bam	3.73	4.51	5.01	5.96	6.65	7.05	7.05	6.7	6.08	5.05	3.95	3.31	5.42
3	Kahnouj	3.75	4.68	5.07	6.23	6.89	7.02	6.78	6.45	5.89	5.13	4.09	3.42	5.45
4	Kerman	3.52	4.45	5.08	5.98	6.89	7.24	7.11	6.84	5.98	4.96	3.84	3.24	5.43
5	Lalezar	3.62	4.61	5.16	6.09	7.13	7.24	6.98	6.84	6.04	5.09	4.07	3.41	5.5
6	Jiroft	3.77	4.66	5.05	6.21	7.00	7.04	6.72	6.47	5.91	5.12	4.13	3.44	5.43
7	Rafsanjan	3.57	4.55	5.21	5.98	6.92	7.28	7.04	6.75	5.94	4.93	3.89	3.28	5.44
8	Shahdad	3.40	4.22	4.84	5.83	6.70	7.15	7.14	6.83	6.01	4.95	3.77	3.15	5.33
9	Shahrbabak	3.57	4.55	5.21	5.98	6.92	7.28	7.04	6.75	5.94	4.93	3.89	3.28	5.47
10	Sirjan	3.74	4.68	5.19	6.02	6.93	7.25	6.97	6.62	5.86	4.88	3.95	3.38	5.46

Table 10 Total number of days per months and whole year with dust storm for 10 selected cities in Kerman province (Eos Web 2016)

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Baft	0.2	0.2	0.2	0.5	0.6	0.2	0.1	0	0	0.1	0.1	0	2.2
2	Bam	1.7	2.4	4	3.3	4.4	4.1	6.5	4.3	2	1	0.9	1.1	35.7
3	Kahnouj	0.7	1.4	2.5	2.8	2.5	3.6	4.8	3	2.1	0.5	0.7	0.7	25.3
4	Kerman	1.8	3.2	4.6	4.4	4.2	2.9	3.7	2	1	0.9	0.7	1	30.4
5	Lalezar	0	0.1	0	0	0	0	0	0	0	0	0	0.1	0.2

Table 10 Continued

No	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
6	Jiroft	0.1	1.4	2.9	2.9	2.7	2.1	3.4	2.5	1.7	0.6	0.4	0.7	21.4
7	Rafsanjan	0.3	1.4	2	2.1	2.5	1.4	0.9	0.4	0.1	0.2	0.6	0.1	12
8	Shahdad	0.1	1	1.1	1.7	2.9	2.1	2.2	2	0.8	0.4	0.6	0.4	15.3
9	Shahrbabak	0.9	3	2.9	2.4	2.2	1.3	1.3	1.1	0.5	0.3	0.4	0.6	16.9
10	Sirjan	0.1	0.5	0.8	0.3	0.4	0.2	0.3	0.1	0.1	0.2	0.0	0.1	3.1

Locations for installing solar farms were selected using Google Earth (Google 2016) which is shown in Fig. 4. It was tried to select the locations near the cities and without residential and commercial buildings.

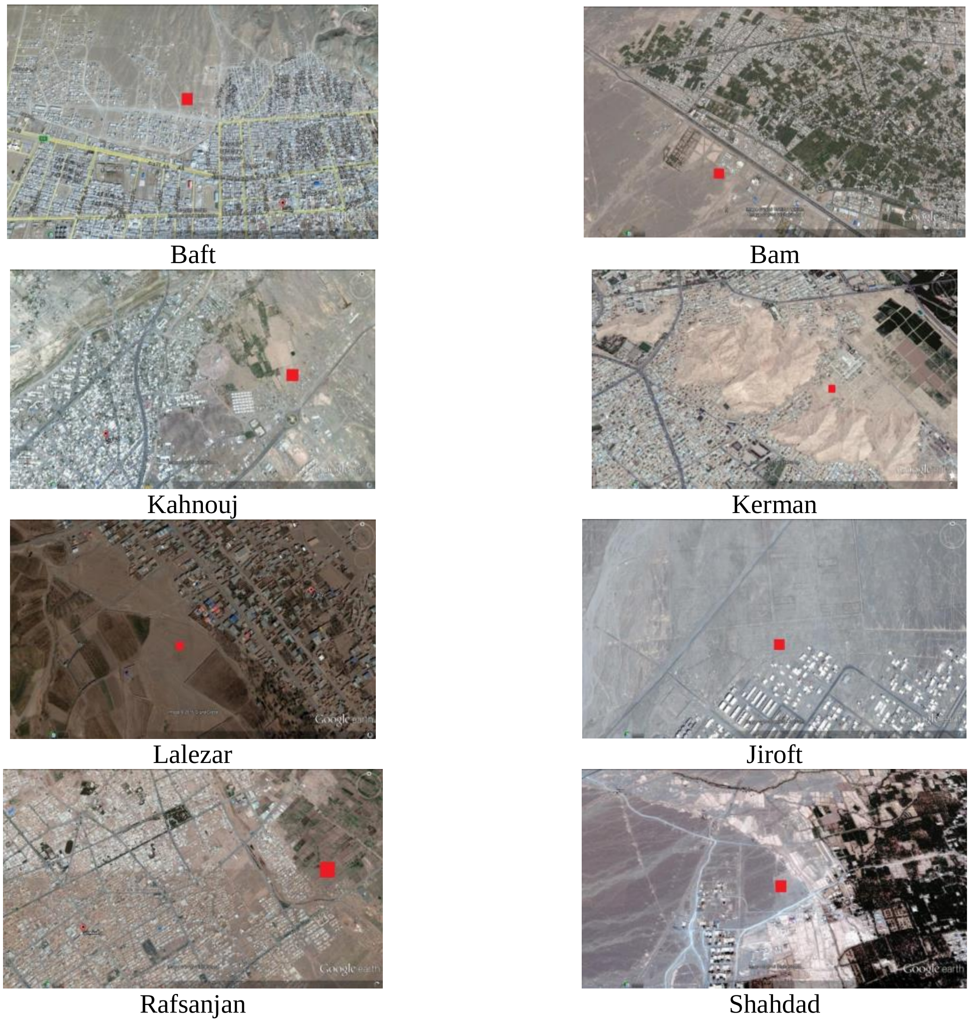

Fig. 4 Selected locations for installing solar power plants (Google 2016)

Shahrbabak

Sirjan

Fig. 4 Continued

5.1 Selecting inputs and outputs

Data for this analysis were determined by the availability of the data and the number of DMUs in the study. The following inputs and output variables were collected for Kerman Province.Input and output parameters and their descriptions are listed in Table 11.

Table 11 Input and output parameters

Notations	Parameters	Input	Output
X1	Population	*	
X2	Distance to main road	*	
X3	Flood risk	*	
X4	Land cost	*	
X5	Air temperature	*	
X6	Humidity	*	
X7	Dust storm	*	
Y1	Wind speed		*
Y2	Sunshine hours		*
Y3	Horizontal solar radiation		*

6. Analysis

Criteria used for analysis are population, distance to main road, flood risk, wind speed, sunshine hours, air temperature, humidity, horizontal solar radiation, dust, and land cost. There are 7 inputs illustrated by “X” and 3 output as “Y” shown in Table 12:

Table 12 Overall criteria values for cities

City	X1	X2	X3	X4	X5	X6	X7	Y1	Y2	Y3
Baft	75940	0.8	35	2000000	15	39	2.2	4.99	3268.9	5.52
Bam	195603	1.8	35	3000000	23	30	35.7	5.04	3377.5	5.42
Kahnouj	86290	1.43	20	2400000	26.9	39	25.3	4.3	3328.2	5.45

Table 12 Continued

City	X1	X2	X3	X4	X5	X6	X7	Y1	Y2	Y3
Kerman	722448	1.13	69	4000000	15.9	32	30.4	5.09	3200.1	5.43
LalezarBardsir	2933	25.2	4	1800000	10	30	0.2	4.99	3180.2	5.5
Jiroft	30000	2.98	27	2500000	25.1	43	21.4	4.58	3179.9	5.43
Rafsanjan	287921	6.27	36	3800000	18.6	29	12	5.19	3380.9	5.44
Shahdad	15842	66.36	0	1500000	27.5	20	15.3	5.09	3296.8	5.33
Shahrbabak	45751	1.1	24	3100000	15.3	33	16.9	5.19	3372.4	5.47
Sirjan	267697	0.8	13	3050000	17.4	35	3.1	5.01	3415.3	5.46

Given that the number of cities is 10 and the number of inputs and outputs are 3 and 7 respectively. Since it does not fit any of the following relationships, therefore dual model of DEA will be used.

$$\begin{gathered}(\text{No. of inputs} + \text{No. of outputs}) \times 3 \leq \text{No. of DMUs} \\ (\text{No. of inputs}) \times (\text{No. of outputs}) \times 2 \leq \text{No. of DMUs}\end{gathered} \tag{12}$$

Since all the cities or DMUs obtained value of 1 while using dual DEA model, therefore Anderson-Peterson (AP) method was used for ranking the DMUs.

Table 13 illustrates results of dual DEA and AP methods. Since all the cities were efficient while DEA was applies, therefore AP method was used. It shows that city of Lalezar ranks first, and Kahnouj gains last priority for installing solar plants. Cities of Baft, Kerman, Sirjan, Shahrbabak, Shahdad, Rafsanjan, Jiroft, and Bam rank second to ninth respectively.

Table 13 Results of ranking cities using dual DEA, and AP methods

	Baft	Bam	Kahnouj	Kerman	lalezarL	Jiroft	Rafsanjan	Shahdad	Shahrbabak	Sirjan
DEA	1	1	1	1	1	1	1	1	1	1
AP	2.731	1.079	1.06	2.622	11	1.34	1.371	1.544	2.145	2.39
Rank	2	9	10	3	1	8	7	6	5	4

6.1 Validation of results using TOPSIS method

Table 14 illustrates results of ranking cities using TOPSIS method. It shows that cities of Lalezar, Baft, and Sirjan have the highest scores from 1 to 3, respectively. Using TOPSIS model, it shows that city of Lalezar ranked first, and Rafsanjan gained last priority for installing solar plants. Cities of Kerman, Shahrbabak, Kahnouj, Shahdad, Bam, and Jiroftranke fourth to ninth, respectively.

Table 14 Results of ranking cities using TOPSIS method

	Baft	Bam	Kahnouj	Kerman	Lalezar	Jiroft	Rafsanjan	Shahdad	Shahrbabak	Sirjan
Topsis	0.2583	0.115	0.1435	0.2212	0.4426	0.0972	0.0626	0.1425	0.2083	0.2517
Rank	2	8	6	4	1	9	10	7	5	3

Table 15 shows validity of the results using AP-DEA and TOPSIS methods. Cities of Lalezar, Baft, and Shahrbabak have the same ranking. But, cities of Bam, Kerman, Jiroft, Shahdad, and Sirjan have almost same rankings which are close to each other.

Table 15 Results of ranking using TOPSIS and AP methods

	Baft	Bam	Kahnouj	Kerman	Lalezar	Jiroft	Rafsanjan	Shahdad	Shahrbabak	Sirjan
AP	2	9	10	3	1	8	7	6	5	4
Topsis Rank	2	8	6	4	1	9	10	7	5	3

6.2 Hydrogen production for the station at Lalezar

A solar plant with the surface area of 1000 m^2 and the fixed efficiency of 12% was considered for installing at the location of Lalezar. With regard to the uncertainty associated with the use of solar energy, storing this energy in the form of hydrogen reduces the risk to access renewable resources. A solar/hydrogen system is proposed as follows:

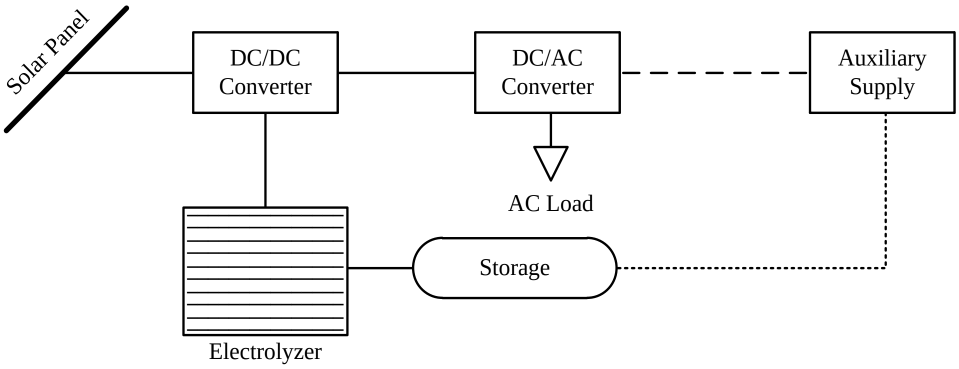

Fig. 5 The proposed solar/hydrogen conversion system

The designed energy conversion system
m consists of an alkaline electrolyzer, a hydrogen storage tank a fuel cell as auxiliary supply, one step-down DC-DC converter, and a DC-AC converter. The electricity generated by solar plant is needed to be shrunk by using a buck converter, and then the required electricity for supplying water electrolysis system will be applied through two electrodes. The outcome of this process is producing hydrogen. In practice, the hydrogen production system includes hydrogen storage and fuel cell subsystems for electricity production. Additionally, the effective factors on the amount of the hydrogen production are the efficiency of the DC/DC and DC/AC converters (η_c), and energy consumption of the examined electrolyzer (ec_{elec}). The efficiency of buck converters is almost 80-95%. Additionally, the commonly used electrolyzers have the energy consumption of 5-6 kWh/Nm^3. Therefore, the amount of hydrogen production from solar plant output electricity (E_{solar}) can be determined by (Gupta Ram 2009)

$$H_2 = \frac{E_{Solar} \times \eta_c}{ec_{elec}} \quad (13)$$

The considered assumptions for the solar/hydrogen system are the efficiency of 95% for the both converters ($\eta_c = \eta_{DC/DC} \times \eta_{DC/AC}$), and 5 kWh/$Nm^3$ for the energy consumption. 1 kg hydrogen is equal to 11.13 Nm^3 hydrogen (Ramage *et al.* 2004).

Table 16 The amount of hydrogen production for the considered solar plant installed in Lalezar

Month	Solar plant output energy (kWh)	Amount of hydrogen production (ton-H_2)
Jan	434.4	7.0
Feb	553.2	9.0
Mar	619.2	10.0
Apr	730.8	11.9
May	855.6	13.9
Jun	868.8	14.1
Jul	837.6	13.6
Aug	820.8	13.3
Sep	724.8	11.8
Oct	610.8	9.9
Nov	488.4	7.9
Dec	409.2	6.6

According to Table 16, it is obvious that the use of the considered solar plant in the city of Lalezar leads to a yearly hydrogen production of 128.9 ton-H_2, and this amount is considerable.

7. Conclusions

In this study, the efficiency of DEA is evaluated for localization of the photovoltaic solar power plants. It was applied to the Kerman province of Iran, where with the available data we utilized 7 inputs, 3 outputs, for 10 cities known as DMUs to measure the relative efficiency (rank) of these locations. The criteria used for analysis were population, distance to main road, flood risk, wind speed, sunshine hours, air temperature, humidity, horizontal solar radiation, dust, and land cost. The main finding of this research work can be listed as:

- The number of cities known as DMUs was 10 and the numberof selected inputs and outputs were 3 and 7 respectively, therefore it did not fit any of the relationships in Equations 1 and 2. Hence, dual model of DEA in Equation 3 was applied.
- Since all the cities obtained value of 1 while using dual DEA model, therefore Anderson-Peterson (AP) model was used for ranking the DMUs.
- Using Anderson-Peterson (AP) model, it was found that city of Lalezar ranked first, and Kahnouj gained last priority for installing solar plants. Cities of Baft, Kerman, Sirjan, Shahrbabak, Shahdad, Rafsanjan, Jiroft, and Bam ranked second to ninth, respectively.

• Based upon TOPSIS model, it was found that city of Lalezar ranked first, and Rafsanjan gained last priority for installing solar plants. Cities of Baft, Sirjan, Kerman, Shahrbabak, Kahnouj, Shahdad, Bam, and Jiroft rank second to ninth, respectively.

• Using AP and TOPSIS methods, cities of Lalezar, Baft, and Shahrbabak had the same ranking. But, other cities like Bam, Kerman, Jiroft, Shahdad, and Sirjan had almost same ranking which were close to each other.

• A measure of validity was obtained when results of the DEA model were compared with the results of TOPSIS and it was shown that the two methods produced similar results.

• A hybrid solar-hydrogen plant was considered for installing in the station at Lalezar. The amount of yearly hydrogen production for this station was determined to be about 129 ton-H_2.

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