



# Analyzing water crisis through the water footprint approach; case of Isfahan province, Iran

Hossein Mokhtari Hashi<sup>1</sup> 

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## Abstract

This study examines the impact of an increasing water footprint on exacerbating water scarcity and the crisis in Isfahan province, Iran. It highlights the significance of considering the water footprint approach in water resource management. To achieve this goal, a comprehensive analysis of water availability limitations, population growth, the agricultural sector, and the industrial sector was conducted. The methodology employed for this research involved a combination of qualitative and quantitative data collection approaches, including literature review and statistical data analysis. The findings of this study reveal that Isfahan province faces a significant water crisis due to an imbalance between water supply and demand. The limited renewable water resources in the region exacerbate the challenges associated with meeting the water demands of a continuously expanding population and human activities. The conclusions drawn from this research indicate that focusing on transferring water from adjacent basins as a solution for water scarcity, and even transferring more water if it is available in those basins, regardless of the increasing trend of the water footprint in the province, is not only an unsustainable solution, but also exacerbates the unsustainability of the source water transferred adjacent basins. Some recommendations to improve the water footprint approach in Isfahan province for long-term sustainability include raising awareness to reduce household water usage, promoting efficient irrigation and sustainable agricultural practices, implementing regulations, and encouraging the adoption of water-efficient technologies in the industrial sector. Collaborative efforts between the government, stakeholders, and the public, continued research and data monitoring.

**Keywords** Water resources management · Water scarcity · Water crisis · Water footprint · Isfahan province

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✉ Hossein Mokhtari Hashi  
h.mokhtari@geo.ui.ac.ir

<sup>1</sup> Faculty of Geographical Sciences and Planning, University of Isfahan, Isfahan, Iran

## 1 Introduction

Water scarcity is one of the most pressing global challenges, exacerbated by climate change, population growth, urbanization, and economic development. This situation poses significant challenges to human development, environmental sustainability, and social stability. The increasing demand for limited freshwater resources is a major concern in many countries. Mekonnen and Hoekstra (2016) found that two-thirds of the world's population (4 billion people) live under conditions of severe water scarcity for at least one month of the year, and 1.8 billion people experience these conditions for at least six months of the year. The UN estimation (2015) shows that over half of the world's population will live in water-stressed areas by 2050. According to the World Water Assessment Programme (2014), global water demand is projected to increase by 55% in 2050 compared to 2000, driven by rising demand from manufacturing (400%), thermal power generation (140%), and domestic use (130%) in terms of withdrawal. The World Economic Forum (2015) has also reported water stress as one of the top current risks in the world. The causes of water scarcity are complex and multifaceted, including natural factors such as climate change, as well as human factors such as overconsumption, wasteful water use, and inefficient water management practices (Kummu et al., 2010). Water scarcity can have serious impacts on human well-being, economic development, and the environment. These impacts include reduced agricultural productivity, increased food prices, and water-related diseases (UN-Water, 2006). In many regions, water scarcity has led to conflicts over water resources and forced migration (Boretti & Rosa, 2019).

The complexity and multifaceted nature of water issues have led to the use of various approaches and solutions to address them (World Wildlife Fund, 2023). These include water conservation, sustainable water management, education and awareness, investment in water infrastructure, and effective policy and governance (Gleick, 2003). There are also promising new technologies like wastewater recycling, energy-efficient desalination plants, solar and UV water filtration, nanofiltration, and rainwater harvesting systems that can help address water scarcity (Shannon et al., 2008). Furthermore, innovative policies and new technologies that reduce water waste are helping countries across the Middle East and North Africa deal with chronic water shortages (Sowers et al., 2011). Other solutions include defining meaningful indicators for water management, such as the water footprint approach, which has been increasingly recognized as a valuable tool for examining water issues due to its comprehensive and holistic nature (Hoekstra & Mekonnen, 2012), was developed from the concept of virtual water introduced by Allan (1993). This concept was further developed by Hoekstra and Hung (2002) into the concept of the water footprint. This approach considers both the quantity and type of water used or polluted during different stages of production. It classifies water into three categories: blue (surface and groundwater), green (rainwater), and gray (polluted water that requires treatment before reuse) (Wang et al., 2021).

The water footprint approach considers the entire lifecycle of a product or service, from production to consumption, taking into account the amount of water used directly and indirectly at each stage (Hoekstra & Chapagain, 2007). It differentiates between direct and indirect water footprints. The direct water footprint is associated with water consumed and polluted within households, while the indirect water footprint considers water used and polluted throughout the entire supply chain of products consumed (Hoekstra et al., 2012). The sum of the direct and indirect water footprints represents an individual's overall water

footprint, while the water footprint of a specific geographical area indicates the total amount of freshwater used and polluted within that region (Hoekstra et al., 2011).

The water footprint, which serves as an appropriate indicator of human occupation of freshwater resources (Fu et al., 2019), is a valuable tool for quantifying the overall volume of freshwater utilized in the production of goods and services consumed by individuals, communities, and nations (Chapagain & Hoekstra, 2008). The inclusion of this indicator as a water management strategy allows communities to recognize the importance of efficient water resource utilization in their territories (Vargas-Pineda et al., 2020). It can also help to raise awareness among consumers and businesses about their water usage and encourage them to take action to reduce their impact and adopt more sustainable production and consumption practices (Hoekstra & Wiedmann, 2014).

The concept of water footprint has been utilized and implemented extensively in different contexts and sectors to elucidate the complex relationship between human activities, water resource management, and water scarcity (Kumar & Singh, 2005; Erchin et al., 2013; Le Roux et al., 2017; Qu et al., 2018). Factors that influence a country's water footprint include the volume of consumption, climate conditions affecting crop growth, and the efficiency of water use in agriculture (Hoekstra & Chapagain, 2007). The average water consumption per person in the global economy is about 5,000 L per day, ranging from 1,500 to 10,000 L per day, depending on location and diet (Water Footprint Network, 2023) while the average direct and indirect water consumption per capita worldwide are 167 and 3496 L, respectively (Vanham & Bidoglio, 2013).

The water footprint concept is a valuable tool for analyzing water usage and management. It has been applied to various sectors and regions, providing insights into water usage and pollution. Hoekstra and Chapagain (2008) highlighted its ability to identify water-intensive products and processes. Meanwhile, Hoekstra and Mekonnen (2012) calculated the water footprint of humanity and found that human activities, such as agriculture, industry, and domestic use, contribute significantly to global water consumption. Studies have also examined the water footprint under different climate scenarios and in different countries, including China, the United States, and Turkey (Liqiang et al., 2016; Zhuo et al., 2020; Konar & Marston, 2020; Erchin et al., 2011). Tuyishimire et al. (2022) examined the drivers of increasing water footprints in 23 African countries, attributing the rising water scarcity problems to population growth, climate change, and the water-intensive agriculture sector. Hu et al. (2022) investigated the changes and drivers of the water footprint in Central Asia from a global trade perspective. In Isfahan province, agriculture was found to have the highest water footprint (Operajouneghani & Nasrollahi, 2021). These studies demonstrate that the water footprint approach is emerging as a critical tool in the quest for sustainable water management and the mitigation of water scarcity.

Iran, located in the Earth's arid belt, has a long-term average annual rainfall of 228 mm, approximately one-third of the global average, with an unbalanced distribution across the country (Saatsaz & Rezaie, 2021). Isfahan province, in central Iran, experiences significant water scarcity due to its arid and semi-arid climate and high water demand. Despite seven decades of water transfer projects from adjacent basins to mitigate water shortages, the region's water scarcity continues to intensify. While these efforts have been well-documented, there is a lack of comprehensive studies analyzing the role of the water footprint in exacerbating this crisis. This study aims to fill this gap by examining the water scarcity and crisis in Isfahan province through the lens of the water footprint approach. The research

question guiding this study is: What role does the increased water footprint play in exacerbating water scarcity and the crisis in Isfahan province?

## 2 Study area

Isfahan province, which covers an area of 107,045 square kilometers, is situated in the heart of Iran. It has a predominantly arid and semi-arid climate, with a long-term average annual rainfall of 190.4 mm (Isfahan Province Meteorological Administration, 2016), providing 20.3 billion cubic meters (BCM) of water. About 71% of that amount is lost through evaporation and transpiration, leaving only 29% (5.9 BCM) as renewable water resources (Pourasghar Sangachin & Askari, 2015; Isfahan Regional Water Company, 2019). This accounts for approximately 4.3% of the country's total renewable water resources (137.5 BCM) (Pahlevan & Karimimanesh, 2021). As shown in Fig. 1, over 90% of the area of the Zayandeh Roud basin is located in Isfahan province. The Zayandeh Roud is the largest river in the central part of the country, with a length of 350 km and an average annual discharge of 1.26 BCM (Hajian & Hajian, 2015).

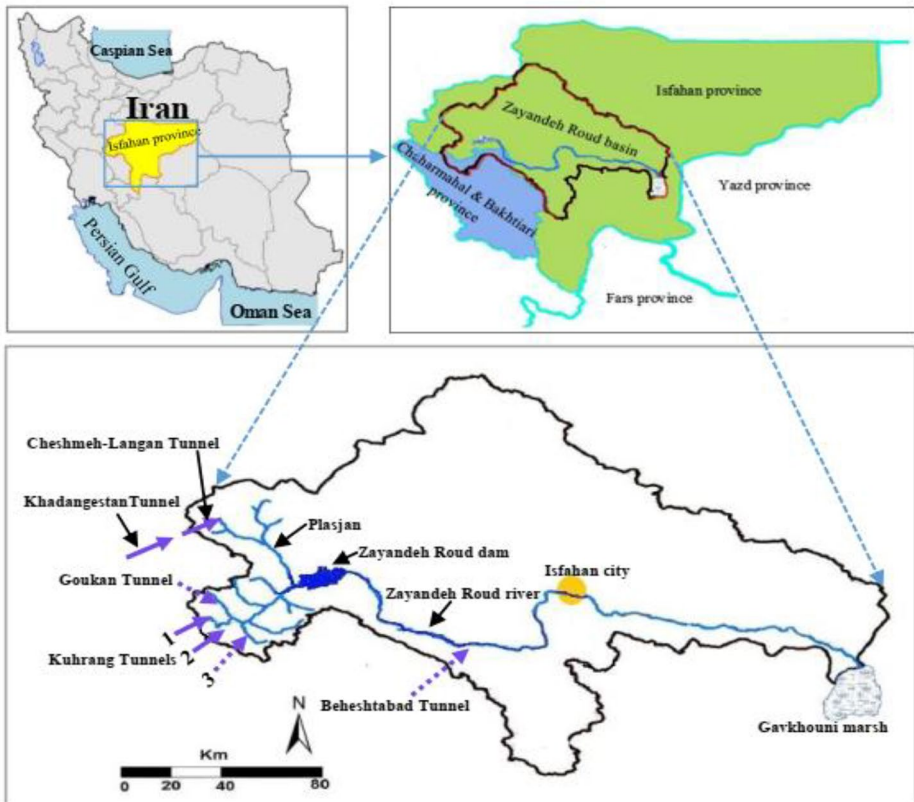


Fig. 1 An overview of the Zayandeh Roud basin and the locations of water transfer tunnels

Since the 1950s, Isfahan province has been designated as one of the leading hubs for agriculture, industry, and services in the country. Simultaneously, with the establishment of large workshops in this province, several water transfer projects have been implemented from adjacent basins such as Karun and Dez to the Zayandeh Roud basin to meet the increasing demand for water, as shown in Table 1.

Despite the implementation of water transfer projects, the signs and consequences of water scarcity began to appear approximately 25 years ago. Since 2007, the river has lost its permanent flow in approximately 250 km of its riverbed, indicating the onset of a water crisis in the province. The current water situation in Isfahan province is concerning. The river that used to flow through the city of Isfahan has dried up, resulting in a lack of groundwater replenishment. This has led to the degradation of the aquifer and land subsidence (Sedaghat et al., 2020). Urban lawns and forestry are limited and often irrigated by municipal water tankers. The drying up of the Gavkhouni marsh at the mouth of the river has increased the risk of fine particles being displaced by wind from its dry bed (Ebrahimi et al., 2017).

### 3 Research methodology

#### 3.1 Water footprint calculation

In order to demonstrate the correlation between the increased in water footprint in Isfahan province over time and the worsening of water scarcity, as well as the emergence of indications of a water crisis, three primary water-intensive sectors were selected. These sectors have reliable statistics for the fifty-year period studied (1966–2016). These three sectors, which utilize local water resources in the province for their production processes, are in line with the concept of the “internal water footprint” as defined by Chapagain and Hoekstra (2004). These sectors include: (1) population growth; (2) the agricultural sector, which encompasses three major products: wheat, meat, and milk; and (3) the industrial sector, which involves three water-intensive products: steel, cement, and electricity. In this study,

**Table 1** Water transfer projects to Isfahan province and Zayandeh Roud basin (Gohari et al., 2013; Qomshi, 2021)

Name of project	Annual transfer capacity (million cubic meters - MCM)	Year of operation	Donor basin
Kuhrang 1	330	1954	Karun
Kuhrang 2	250	1985	Karun
Cheshmeh Langan	164	2005	Dez
Khadangestan	84	2014	Dez
Kuhrang 3 <sup>a</sup>	250	Under construction	Karun
Goukan	180	Under construction	Dez
Beheshtabad	1,100 <sup>b</sup>	Under construction	Karun
Total	2,358	-	-
Total	2,358	-	-

<sup>a</sup>. Despite the news of the opening of this project in 2021, it has not been officially opened yet

<sup>b</sup>. Although this project is designed to transfer water to different cities and provinces, news reports indicate that approximately 250 MCM of water will be transferred to the Zayandeh Roud basin

the water footprint was calculated using the Water Footprint Network (WFN) approach developed by Hoekstra et al. (2009).

To calculate the water footprint of population growth, the average per capita water footprint per country was considered. Then, the figure of the country was generalized to Isfahan province. Due to the introduction of the concept of water footprint in 2002 and the lack of recorded figures for direct and indirect water footprint prior to that, the reverse calculation method was employed to obtain historical data. For this purpose, the figures for the year 2016 were first calculated for the direct and indirect water footprint as a benchmark. Then, the calculation by Otto and Schleifer (2020) was used as a criterion for the reverse calculation, which indicates a 600% increase in household water consumption in 2014 compared to the 1960s. For example, the direct and indirect water footprint figures for 1960 are assumed to be 600% lower than the figures for 2016, and the same ratio was calculated for the subsequent years. Since the figure has increased by 600% over 5 decades, the average rate of increase for each decade is assumed to be 120%. The calculated figures for each decade are shown in Table 2, which is calculated as follows: For 2016, (A) Indirect water footprint calculation: Mekonnen and Hoekstra (2011a) calculated the annual per capita indirect water footprint for Iran between 1996 and 2005 to be 1,861 m<sup>3</sup>. According to Worlddata (2022), the projected average per capita gross income of Iranians in 2022 will be \$3530. Entering this figure into the Personal Water Footprint Calculator section of the Water Footprint Network website (2022), the average annual per capita water footprint of Iranians in 2022 is calculated to be 2,257 m<sup>3</sup>. To calculate the indirect water footprint for 2016, the average of the two figures mentioned above (2,059 m<sup>3</sup>) was used for the entire country and then generalized to Isfahan province. (B) Direct water footprint calculation: According to Madani et al. (2016), the per capita amount of Iran's direct water footprint is 250 L per day (91.25 m<sup>3</sup> per year). This figure has been generalized to Isfahan province. For 2006, the indirect and direct water footprint figures (1,715 and 76 m<sup>3</sup>) were obtained through reverse calculation based on Otto and Schleifer's research (2020) for the country, and then generalized to Isfahan province. Mekonnen and Hoekstra (2011b) also calculated the annual per capita indirect water footprint for Iran during 1996–2005 to be 1864 m<sup>3</sup>, which is similar to the reverse calculation mentioned earlier. The indirect and direct water footprints for the years 1996 (857.9 and 38 m<sup>3</sup>), 1986 (571.9 and 25.33 m<sup>3</sup>), 1976 (428.9 and 18.98 m<sup>3</sup>), and 1966 (343.1 and 15.18 m<sup>3</sup>) were calculated in reverse based on Otto and Schleifer's (2020) research for the country and generalized to the Isfahan province.

In order to calculate the water footprint of the agricultural sector, three major agricultural products in the province were examined: wheat, meat (beef, sheep, goat, and chicken), and milk. Mekonnen and Hoekstra (2010a) estimated that the average water footprint for each

**Table 2** Annual per capita direct and indirect water footprint of the population in Isfahan province (The author's calculation, based on generalizations from previous studies)

Year	Direct (household) water footprint (m <sup>3</sup> )	Indirect water footprint(m <sup>3</sup> )
1966	15.18 (41.6 L/day)	343.1
1976	18.98 (52 L/day)	428.9
1986	25.33 (69.4 L/day)	571.9
1996	38 (104.1 L/day)	857.9
2006	76 (208.3 L/day)	1,715
2016	91.25 (250 L/day)	2,059
Growth rate from 1966 to 2016	600%	600%

**Table 3** The water footprint of studied agricultural products in Isfahan province

Agricultural products (kg)	Water footprint (liters)
Wheat	3,690
Meat (beef, sheep, and goat)	9,685
Chicken	4,987
Milk	956

**Table 4** The amount of water footprint of the studied industrial products in Isfahan province. (Calculated by the author based on Iranian Ministry of Energy, 2017)

Industrial products	The water footprint is measured in m <sup>3</sup> /ton for steel and cement, and in each 1000 MWh for electricity
Steel	14.8 m <sup>3</sup> /ton
Cement	2.126 m <sup>3</sup> /ton
Electricity	700 m <sup>3</sup> /h (for the years 1976 and 1986). 373 m <sup>3</sup> /h (for the years 1996, 2006, and 2016).

kilogram of wheat produced in Iran is 3,690 L. In a separate study Mekonnen and Hoekstra (2010b) calculated that the average water footprint for each kilogram of various types of meat production (beef, sheep, and goat) is 9,685 L. They also calculated the water footprint of each kilogram of chicken production to be 4,987 L, and the water footprint of each kilogram of milk to be 956 L. The figures mentioned above were generalized to Isfahan province. Based on this, the production quantity of each product was multiplied by its corresponding water footprint. The water footprint figures for agricultural products presented in Table 3 are based on the aforementioned studies, which have been generalized to Isfahan province and assumed to be constant throughout the study period.

In order to calculate the water footprint of the industrial sector in Isfahan province, three industries were studied: steel, cement, and electricity production. The water footprint of each product is determined based on Table 4, which provides a generalization for the province. The calculation method used by Nezamoleslami and Hosseini (2020) resulted in a water footprint of 19.61 m<sup>3</sup> per ton for steel production in Isfahan province. According to the Deputy of Operations of Mobarakeh Steel Company (2018), the company uses 16 m<sup>3</sup> of water for each ton of steel production. On the other hand, the water supply manager of Zobahan Steel Company (2021) announced that 9 m<sup>3</sup> of water is used for each ton of steel production in the company. Due to the disparity in the aforementioned figures, the average of these three values (14.8 m<sup>3</sup>) is taken into account and generalized to represent the steel production in the province. For cement production, according to the calculation by Hosseini and Nezamoleslami (2018), 2.126 m<sup>3</sup> of water is required per ton in Isfahan province. According to the Iranian Ministry of Energy (2017), the water consumption per hour for producing 1000 megawatt hours (MWh) of electricity in different types of power plants is as follows: steam power plants require 700 m<sup>3</sup>/h, combined cycle power plants require 300 m<sup>3</sup>/h, and gas power plants require 120 m<sup>3</sup>/h. In 1966, Isfahan province primarily relied on diesel generators for electricity production because there were no power plants. In 1976 and 1986, there was only one steam power plant in Isfahan province. This facility served as the reference point for calculating the water footprint during that time. In 1996, 2006, and 2016, the province had various types of power plants, including steam, combined cycle, and gas. Therefore, the average water consumption of these power plants is taken into account, which is 373 m<sup>3</sup>/h.



## 3.2 Data collection

The rainfall and water resources data were obtained from various sources, including the Statistical Center of Iran yearbooks, Iran Meteorological Organization, Isfahan Province Meteorological Administration, and Isfahan Regional Water Company. The population data of Isfahan province was obtained from the Statistical Center of Iran yearbook, Management and Planning Organization of Isfahan province yearbook, and the Isfahan Municipality yearbook for various years. The data for agricultural products was obtained from the Statistical Center of Iran yearbooks, the Ministry of Agricultural Jihad and the Organization of Agricultural Jihad of Isfahan province. The data for industrial products was obtained from various sources, including the Statistical Center of Iran yearbooks, Mobarakeh Steel Company, Zobahan Steel Company, Iranian Mines & Mining Industries Development & Renovation Organization (IMIDRO), National Iranian Steel Company (NISC), Iranian Ministry of Energy, Isfahan Regional Electricity Company, and Cement Scientific Monthly.

## 4 Results

### 4.1 Physical water scarcity in Isfahan province

The study period involved an investigation into the water scarcity situation in Isfahan province, focusing on two indicators: annual water availability per person and the proportion of total water resources used.

#### 4.1.1 Annual water availability per person (falkenmark indicator)

According to Falkenmark et al. (1989), the index of annual water availability per person can be used to determine if a geographical area is experiencing water stress. The threshold of annual per capita water availability is an indicator of water stress. The threshold of annual per capita water availability is an indicator of water stress.  $>1700 \text{ m}^3$  indicates no water stress;  $1700\text{--}1000 \text{ m}^3$  indicates a state of water stress;  $1000\text{--}500 \text{ m}^3$  indicates a state of chronic water scarcity; and  $<500 \text{ m}^3$  indicates a state of absolute water scarcity. Table 5 shows the changes in annual per capita available water in Isfahan province, which is experiencing water stress. In this table, the two main tributaries of the Zayandeh Roud river have been included in the calculations. One is called Plasjan, originating from within Isfahan province and having an average annual natural discharge of 140 MCM (Isfahan Regional Water Company, 2023). The other tributary, called Cheshmeh Dimeh, is larger and originates from Chaharmahal and Bakhtiari province. The Kohrang 1 and 2 tunnels, which transfer water from the Karun basin to the headwaters of Cheshmeh Dimeh, as well as the Cheshmeh Langan and Khadangeastan tunnels, which transfer water from the Dez basin to the headwaters of Plasjan, have also been calculated and considered. The change in per capita available water from the first year to the last year of the study period does not align with the total renewable water and rainfall levels in the province. At the end of the period, the natural flow of the Zayandeh Roud river, which originates from Chaharmahal and Bakhtiari province, has reached its lowest level. On the other hand, the total amount



**Table 5** Water resources of Isfahan province

Year	Annual rainfall (mm)	The Natural flow of the Zayandeh Roud river (MCM)	The amount of water in the Zayandeh Roud river that originates from outside Isfahan province			Zayandeh Roud river discharge at the entrance of Zayandeh Roud dam (MCM)	Total renewable water in Isfahan province, including precipitation and inflow from external sources (BCM)	Per capita available water (m <sup>3</sup> )
			The amount of natural flow originating from Chaharmahal and Bakhtiari province (MCM)	Total transferred water from other basins (MCM)	Total incoming water originating from outside Isfahan province (MCM)			
1966	170.4	734	594	336	930	1,070	4,375	
1976	277.6	1,563	1,423	320	1,743	1,883	4,751	
1986	333.1	1,025	885	400	1,285	1,425	3,516	
1996	243	956	816	613	1,429	1,569	2,275	
2006	211.1	1,480	1,340	656	1,996	2,136	1,885	
2016	179.8	681	541	731	1,272	1,412	1,341	
Percentage of change between 1966 and 2016	+5.5	-7.8	-9.8	+117.6	+36.8	+32	-226	

Note. The data for rainfall are from Statistical Center of Iran, Meteorological Organization of Iran and Isfahan Province Meteorological Administration yearbooks. The data for Zayandeh Roud river waters and the transferred waters are from Isfahan Regional Water Company reports, and Hajian, & Hajian, 2015. The author also has performed some calculations

of water transferred from the adjacent basins to the Zayandeh Roud river has exceeded its natural flow volume.

Regarding the impact of climate change on water resources in Isfahan province, the Isfahan Regional Water Company (2019) reported that the 10-year average rainfall in the province (2006–2016) has decreased by 9.5% compared to the long-term average. In terms of temperature increase caused by climate change, a study by Rayatpishe and Masoodian (2015) found that the average daily temperature in Iran has risen by 1 °C compared to 50 years ago, which is twice the global average. Every 1-degree increase in the average daily temperature in Iran raises the permanent snow line by 160 m (Masoodian, 2004). The increase in the average daily temperature also leads to a shift in precipitation from snow to rain in mountainous regions. This change has a detrimental impact on both the hydrological cycle and river flow. Research shows that the effects of climate change in Iran began in the southwest of the country and gradually spread to the northeast. The central Zagros Mountain range, which serves as the source of the Zayandeh Roud river, is located in this direction. According to Mirzaei and Mehrab (2014), the amount of snowfall in this region has decreased by over 60% in the last 15 years compared to the previous 15 years. This decrease in snowfall has led to a 30% reduction in the amount of water in rivers. The report from the Isfahan Regional Water Company (2019) also indicates that the province's 10-year average runoff (2006–2016) has decreased by 39% compared to the long-term average. In general, as temperature increases, the amount of evaporation and transpiration increases. These processes are particularly important for agricultural products, and as a result, the water demand for products has also increased (Sadeghi & Ahmadi, 2022).

#### 4.1.2 Proportion of total water resources used

The proportion of total water resources used indicator was essentially developed to monitor Goal 7 of the Millennium Development Goals (to ensure environmental sustainability) and the related target: “Integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources” (United Nations, 2007). This indicator is an important measure of a country's vulnerability to water scarcity. It shows the extent to which total renewable freshwater resources are being used to meet the country's water needs. Three levels of water stress were considered as thresholds for this indicator: 25%, below which there is no water scarcity; 60%, which indicates approaching scarcity; and 75%, above which there is severe water scarcity (UN-Water, 2015). Table 6 displays the data on water withdrawal in Isfahan province. Although the figures for the years 1966 and 1976 are not available, the figures for the subsequent years also indicate the state of water withdrawal. The index measuring the proportion of total water resources used in the province has been indicating a state of approaching scarcity since 1996 and is now on the brink of severe water scarcity. The total amount of water withdrawal in the province, as well as its share in the country's total withdrawal, has decreased. This decrease is primarily due to a reduction in withdrawals from deep and semi-deep wells. In general, the number of deep and semi-deep wells increased from 1986 to 2016. However, the loss of the permanent flow of the Zayandeh Roud river in the mid-2000s has led to an almost doubling of the number of wells in a 10-year period from 2006 to 2016. Also, despite the increase in the number of wells, both the total withdrawal from the wells and the average withdrawal per well have decreased. Overall, the proportion of withdrawals from deep and semi-deep wells compared



to the total withdrawal in the province during this period was more than 50%. However, it peaked at 70% in 2006 and then gradually declined to its lowest level of 58% in 2016.

In arid and semi-arid regions, there is a concern about long-term groundwater overexploitation (Chen et al., 2010). Overexploitation of groundwater resources in Isfahan province has caused the water table in most of the plains to drop by an average of 20 m (Javdanian & Ahmadi Darani, 2016; Isfahan Regional Water Company, 2019). As a result of this drop, land subsidence continues to occur in the province. According to the Director General of the Geological Center of Isfahan province, 27 out of the 35 plains in the province are experiencing land subsidence. This phenomenon is particularly severe in approximately 10% of the province's area. The Director General announced that the annual land subsidence in the affected plains ranges from 8 to 19 centimeters. He also mentioned that the global average for land subsidence is approximately 1 centimeter (Islami, 2021). The latest case of land subsidence reported in Isfahan province is in the Kashan plain, where the length of the gap created is reported to be 76 km (Asriran, 2023).

The province has considered the application of modern technologies, such as wastewater treatment, to address the water shortage. According to the Isfahan Regional Water Company (2019), the total volume of wastewater in cities with treatment plants (20 cities) is approximately 200 MCM. Currently, 170 MCM of this wastewater is collected, treated, and reused, particularly in steel production companies. The use of various modern irrigation methods on agricultural land has also increased in the province. According to the Statistical Center of Iran (2016), the proportion of agricultural land in the province that was irrigated using modern methods increased from 3.4% in 2003 to 21.2% in 2016.

## 4.2 Increase of water footprint in Isfahan province

### 4.2.1 Water footprint of the population

Population growth is the primary cause of water scarcity (FAO, 2020). Table 7 shows that the population of Isfahan province has increased by 260% during the study period, with an average annual growth rate of 5.2%. The acceleration of population growth was higher in the first two decades. The water footprint calculations in this table, which are based on Table 2, also show that the water footprint increased by 2,063% during this period (an average increase of 41.3% per year). Comparing these figures shows that the growth rate of the water footprint was almost eight times that of population growth.

### 4.2.2 Water footprint of the agriculture sector

Iran has a long history of food insecurity. The last major famine began during World War I and resulted in the death of nearly half of the country's population. Since then, achieving national food self-sufficiency has been a major goal of the Iranian regimes. After the 1979 Islamic Revolution, achieving national food self-sufficiency became an imperative goal of the government and was enshrined in the constitution. Iran's pursuit of food self-sufficiency has come at a considerable cost to the country, as food subsidies increased from 0.7% of GDP in 1973 to 2.8% in 2006. The subsidy regime distorts economic signals for producers and consumers, providing little incentive to economize. As a result, the agricultural sector claims 92% of the country's water withdrawals, leading to inefficient irrigation practices

**Table 7** Population growth and water footprint increase in Isfahan province

Year	Population	Annual direct water footprint (MCM)	Annual indirect water footprint (BCM)	Total annual water footprint (BCM)
1966	1,424,000	21.6	0.489	0.511
1976	2,176,694	41.3	0.933	0.974
1986	3,294,916	83.4	1.88	1.96
1996	3,923,255	149	3.36	3.51
2006	4,559,256	346.5	7.82	8.17
2016	5,120,850	467.2	10.54	11
Growth from 1966 to 2016	260%	2063%	2063%	2063%
Average annual growth rate	5.2%	41.3%	41.3%	41.3%

Note. The data for population are from Statistical Center of Iran, Management and Planning Organization of Isfahan province and Municipality of Isfahan yearbooks. The author also has performed some calculations

(Michel, 2019). Karandish and Hoekstra (2017) analyzed Iran's water and food security policy from 1980 to 2010. Their findings revealed that Iran's emphasis on achieving food self-sufficiency, coupled with a lack of attention to water use efficiency, has resulted in an increase in its water footprint. Furthermore, according to their findings, the blue share of the water footprint of crop production in Isfahan province is 74%. As shown in Table 8, which is calculated based on Table 3, there has been a significant increase in agricultural production in Isfahan province, despite the climatic constraints. This has resulted in a 513% increase in the total water footprint during the study period, averaging 10.26% per year. Among agricultural products, milk production has increased significantly by 59,017%. This increase can be attributed to the rise in milk production volume in modern factories, as well as the milk supplied to the factories by small producers and households.

#### 4.2.3 Water footprint of the industry sector

The water footprint of the industrial sector refers to the amount of water consumed or polluted directly or indirectly during the manufacturing process of a product. Isfahan province is second only to Tehran province in terms of hosting large industrial workshops (with ten or more employees) in the country. It produces more than 60% of the country's steel (Industry, Mining, and Trade Organization of Isfahan Province, 2020). The study focused on the trends of increasing production and water footprint of two large steel production companies (Zobahan and Mobarakeh Steel), two cement factories (Isfahan and Sepahan), and power plants in the province. These industries are known for their high-water consumption. Despite having only 4.3% of the country's renewable water resources and 6.4% of the country's population, Isfahan province accounts for 12.1% of large industrial workshops (with 10 or more employees) and 11.7% of the total number of employees in these workshops, as shown in Table 9. However, due to a lack of data, it is not possible to calculate the water footprint of all industrial workshops in the province. However, a 732% increase in the number of large industrial workshops and a 393% increase in their employees over four decades (1976–2016) indicates that the water footprint of the industrial sector has increased significantly.

According to the Iran Small Industries and Industrial Parks Organization (2021), Isfahan province is home to 73 of the country's 823 industrial cities (8.8% of the total). As shown in

**Table 8** The agricultural products growth and water footprint increase in Isfahan province

Year	Wheat production (ton)	Water footprint of wheat production (MCM)	Meat (beef, sheep, and goat) production (ton)	Water footprint of meat production (MCM)	Chicken production (ton)	Water footprint of chicken production (MCM)	Milk production (ton)	Water footprint of milk production (MCM)	Total water footprint of the three agricultural products (BCM)
1966	141,390 (1971) <sup>a</sup>	521.7	11,681 (1968)	113.1	NA	NA	2,018 (1971)	1.9	0.636
1976	328,180	1210.9	16,293	157.7	NA	NA	8,973	8.5	1.377
1986	441,115	1627.7	24,439 <sup>b</sup>	236.6	29,500	147.1	28,703	27.4	2.038
1996	364,000	1343.1	32,450	314.2	74,353	370.7	131,000	125.2	2.153
2006	588,734	2172.4	50,000	484.2	110,000	548.5	602,000	575.5	3.780
2016	312,808	1154.2	67,500	653.7	192,000	957.5	1,193,000	1140	3.905
Growth from 1966 to 2016	121%	-	477%	-	550	-	59,017%	-	513%
Average annual growth rate	2.42	-	9.54%	-	11	-	1180%	-	10.26%

<sup>a</sup>. Years in parentheses indicate the year when the figures became available

<sup>b</sup>. The author's estimation, based on the years before and after

NA = Not available

Note. The raw data for wheat, meat, chicken, and milk production are from Statistical Center of Iran, Ministry of Agricultural Jihad and Organization of Agriculture Jihad of Isfahan province yearbooks. The author also has performed some calculations

**Table 9** Share of Isfahan province in the country's large industrial workshops (with 10 or more employees) and their employees

Year	Number of large industrial workshops		Share of Isfahan province (%)		Number of employees in large industrial workshops		Share of Isfahan province (%)	
	The country	Isfahan province	Isfahan province	NA	The country	Isfahan province	Isfahan province	NA
1966	NA	NA	NA	NA	NA	NA	NA	NA
1976	5,432	456	10	10	359,488	42,524	11.8	11.8
1986	6,127	650	10.6	10.6	558,985	72,463	12.9	12.9
1996	13,247	1,649	12.4	12.4	882,763	117,590	13.3	13.3
2006	16,057	2,273	14.1	14.1	1,071,383	123,796	11.5	11.5
2016	31,309	3,795	12.1	12.1	1,788,651	209,718	11.7	11.7
Growth from 1966 to 2016	476%	732%	-	-	397%	393%	-	-

NA = Not available

Note. The raw data presented in this table are from Statistical Center of Iran and Planning Organization of Isfahan province yearbooks. The author also has performed some calculations



Table 10, the number of industrial towns increased by 23.7% and their water consumption increased by 118% over a decade (2006–2016).

Table 11, calculated on the basis of Table 4, demonstrates a 34,689% increase in the total water footprint of the three industries analyzed. Furthermore, 66.9% of this total is attributed to steel production.

Figure 2 illustrates the overall quantity of renewable water in Isfahan province, as well as the total water footprint of the three sectors under study. As can be seen, the water footprint in 2006 exceeded the province's renewable water resources, and over time, the gap between these two values has continued to grow.

## 5 Discussion

The present study aimed to address the water scarcity and crisis through the water footprint approach. Isfahan province was chosen as a case study because, despite the implementation of several water transfer projects from adjunct basins to this province in the past seven decades to overcome the water scarcity, indicators show that water scarcity and crisis is worsening in the region. Therefore, adequate attention must be given to the increasing trend of the water footprint in the province. Otherwise, the efforts to solve the water shortage will not yield the desired results.

The analysis of water resources in the province showed that during the study period (1966–2016), although the natural flow of the Zayandeh Roud river has decreased by 7.8%, the total renewable water has increased by 11.3% and the amount of the river's flow at the entrance of the Zayandeh Roud dam has also increased by 32% thanks to the implementation of water transfer projects. Nevertheless, the annual water availability per person indicator has declined by 226% and now the province is in a water stress situation. The proportion of total water resources indicator showed that the province is in a state of severe water scarcity. Following the loss of the permanent flow of the Zayandeh Roud river in the mid-2000s, the number of deep and semi-deep wells has almost doubled in the following decade. Although data from the first two decades of the studied period were unavailable, the comparison of the number of deep and semi-deep wells and the amount of water withdrawn from them between 1986 and 2016 indicates that, despite an increase in the number of wells, there has been a decrease of over 330% in the amount of water withdrawn per well. This suggests an intensive extraction of groundwater and a decline in the water table, resulting in land subsidence in the province. The findings of this study align with the Isfahan Regional Water Organization's (2019) report of physical water scarcity in the province over time as a result of increased domestic, agricultural, and industrial usage.

The effects of climate change on water resources in Isfahan province have also been considered in some studies, the results of which show these effects in the form of increasing temperatures, decreasing snowfall in mountainous regions, the disruption of the hydrological cycle, and the reducing flow of rivers. The analysis of specific regions, such as Turkey (Ercin et al., 2011) and China (Liqiang et al., 2016), revealed the potential exacerbation of water scarcity due to climate change. This underscores the urgency of addressing climate issues and developing adaptation strategies to minimize negative impacts on water resources. Furthermore, understanding the dominant types of water footprints (e.g., green

**Table 10** The number of industrial towns in Isfahan province and their water consumption

Year	Number of industrial towns	Water consumption (liters/day)	Annual water consumption (MCM)
2006	59	305	9.6
2016	73	665	21
Growth from 1966 to 2016	23.7%	118%	118%

Note. The raw data presented in this table are from Iran Small Industries and Industrial Parks Organization (2021) and Management and Planning Organization of Isfahan province yearbooks. The author also has performed some calculations

water footprint) in different regions allows for targeted interventions to address specific challenges related to water availability and quality.

Regarding the effect of population growth on the increase of the water footprint in Isfahan province, the province's population increased by 260% during the period studied, more than half of which (131%) occurred in the first two decades of the period (1966–1986). In the first decade, this amount of growth was because of immigration due to the establishment of large and small industries in the province and increased employment opportunities. In the second decade, in addition to the continued migration to the province due to job opportunities, the revolutionary government implemented population growth policies. The Iran-Iraq war (1980–1988) brought a wave of war refugees from affected provinces, particularly from Khuzestan province, to Isfahan province, and a significant portion of these refugees settled in the region permanently. During the study period, the water footprint of the province's population increased more than 20-fold. The comparison of population growth rates and water footprint increases showed that for every 1% increase in the province's population, the water footprint increased by approximately 8%. According to Otto and Schleifer (2020), between the 1960s and 2014, there was a 4.2% increase in household water use on a global scale, for every 1% increase in the world's population. In the case of African countries, Tuyishimire et al. (2022) highlighted the impact of population growth and changing dietary patterns on increasing water footprint.

The agriculture sector is a major contributor to the increase in the water footprint and this sector has negative implications for water availability and quality, as well as for the environment and human health. The use of water-intensive agricultural practices, such as flood irrigation and excessive use of fertilizers and pesticides, further exacerbates the problem. On the other hand, the agriculture sector plays a critical role in ensuring food security, particularly in developing countries where a significant portion of the population relies on subsistence farming. This sector can provide sufficient and nutritious food for the population, while also generating income and employment opportunities. Iran's historical experience with famine has led to a strong emphasis on achieving national food self-sufficiency, which has come at a considerable cost to the country in terms of subsidies and inefficient water use. The country's focus on food self-sufficiency has resulted in an increase in its water footprint, particularly in Isfahan province where agriculture claims a significant portion of the region's water resources. Despite climatic constraints, agricultural production in Isfahan province has increased significantly over the study period, leading to a 513% increase in the total water footprint. Based on Operajouneghani and Nasrollahi (2021), the agriculture sector has the highest water footprint in the province. Karandish and Hoekstra (2017) showed

**Table 11** The growth in industrial products and the increase of water footprint in Isfahan province

Year	Steel production			Cement production			Electricity production		Total water footprint of the three industries / MCM
	Zobahan company / ton	Water footprint of Zobahan company / MCM	Mobarakeh Steel company / ton	Water footprint of Mobarakeh Steel company / MCM	Cement production (Isfahan and Sepahan companies) / ton	Water footprint of cement production / MCM	Electricity production / MWh	Water footprint of electricity production / MCM	
1966	1,118	0.016	NA	NA	182,500	0.387	NA	NA	0.403
	(1972)*								
1976	526,299	7.789	NA	NA	960,000	2.040	150	0.919	10.7
1986	723,125	10.702	NA	NA	3,369,000	7.162	200	1.226	19.1
1996	1,316,037	19.477	1,611,287	23.847	3,369,000	7.162	1,694	5.535	56
	(1968)		(1968)						
2006	2,200,000	32.560	4,200,000	62.160	3,626,500	7.709	3,242	10.593	113
2016	2,241,439	33.173	5,660,274	83.772	4,124,000	8.767	4,332	14.154	139.8
Growth from 1966 to 2016	200,386%	200,386%	251%	251%	2159%	2159%	2788%	2788%	34,689%
Average annual growth rate	4007%	4007%	5%	5%	43%	43%	56%	56%	693%

\* Years in parentheses indicate the year when the figures became available

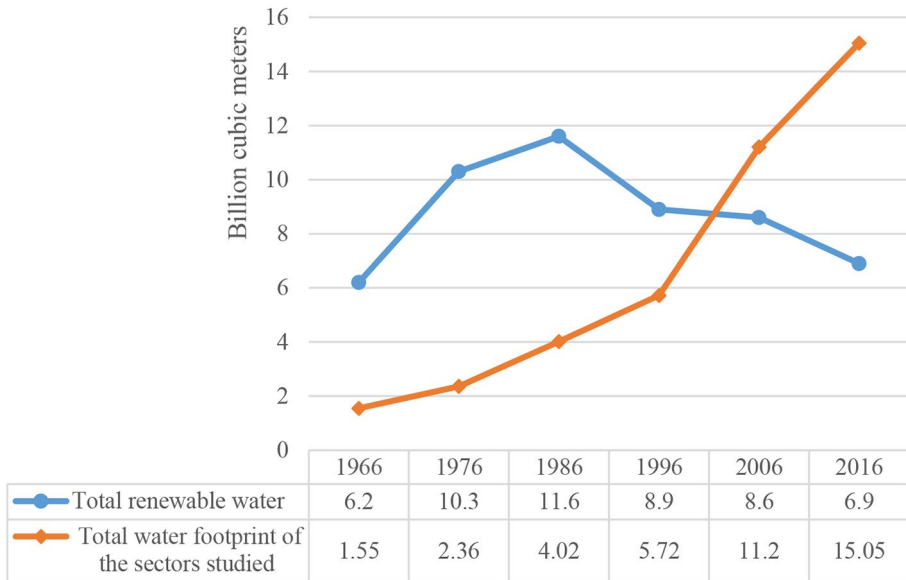
NA = Not available

Note. The data for steel production are from Statistical Center of Iran yearbooks, Mobarakeh Steel Company, Zobahan Company and Iranian Mines & Mining Industries Development & Renovation Organization (IMIDRO and National Iranian Steel Company (NISC), (2023) report. The data for cement production are from Statistical Center of Iran yearbooks and Cement Scientific Monthly (2021). The data for electricity production are from Statistical Center of Iran yearbooks and Isfahan Regional Electrical Company reports. The author also has performed some calculations

that between 1980 and 2010, Iran's water footprint in the agricultural sector increased by 122%. The results showed a sharp increase in the water footprint of the agricultural sector in the province, and if this trend continues, the water situation will become more critical. Promoting sustainable agricultural practices and efficient water use is critical to mitigating the negative environmental impacts of agriculture while achieving sustainable food security.

The establishment of industries in Isfahan province in the 1960s was mainly due to its central location in the country, which protected large industries from the threat of the former Soviet Union to the north, Iraq to the west, and maritime powers to the south (Persian Gulf and Oman Sea). In the following decades, the Iran-Iraq war led to the continuation of the policy of concentrating industries in the center of the country, and over time, chains of related industries were also established around them, which include about 12% of the industries and 8.8% of the industrial towns of the country. Over the past 5 decades, Isfahan province has been one of the major industrial hubs of the country, despite having limited renewable water resources. This suggests that the water footprint of the industrial sector in this region is substantial. The studied steel, cement, and power generation industries are known to have high water consumption rates, leading to a significant increase in the water footprint of the industrial sector. The increasing demand for electricity from the growing industrial sector also led to the establishment of power plants in the province, resulting in a more than 27-fold increase in electricity production during the study period. The results underscore the need for policies and practices that promote sustainable industrial development and efficient water use in Isfahan province and other regions with similar characteristics. Such policies could include measures to encourage the adoption of water-saving technologies and practices in industrial processes, as well as regulations to limit the discharge of pollutants into water sources. In addition, efforts to raise public awareness about the importance of water conservation and the negative impacts of industrial activities on water resources could help to promote more responsible behavior among industrial stakeholders. This study highlights the urgent need for action to address the growing water footprint of the industrial sector in Isfahan province. Failure to take action could lead to serious environmental and health consequences, as well as economic losses due to water scarcity and pollution.

This study contributes to the existing body of knowledge by highlighting the significant contribution of human activities, such as agriculture, industry, and domestic use, to the increase of the water footprint in Isfahan province. Although water transfer projects from adjacent basins have been implemented to compensate for the water shortage in this province, the sharp increase in water footprint due to intensive economic activities and population growth has neutralized the effect of water transfer projects and Isfahan province is facing chronic water shortage that is turning into a water crisis. The water footprint approach provides a valuable tool for analyzing water use, managing water resources, and addressing water scarcity. By recognizing the impact of different sectors, understanding regional variations, and considering the influence of global trade and population dynamics, we can work toward a more sustainable and water-secure future.



**Fig. 2** Comparison of renewable water resources and water footprint in Isfahan province

## 6 Conclusion

This research has provided an in-depth analysis of the water crisis in Isfahan province, Iran, through the lens of the water footprint approach. The discussion focused on various aspects contributing to the water crisis, including water availability limitations, population growth, the role of the agricultural sector, and the impact of the industrial sector. Isfahan province, despite having a relatively small share of the country's renewable water resources, faces significant challenges related to water availability. The imbalance between water supply and the growing population poses a serious threat to sustainable water usage. Efforts should be directed towards managing and distributing water resources efficiently to meet the needs of the expanding population while minimizing the water footprint. The research also showed that focusing on transferring water from adjacent basins as a solution for water scarcity, and even transferring more water if it is available in those basins, regardless of the increasing trend of the water footprint in the province, is not only an unsustainable solution, but also worsens the unsustainability of the source water transferred adjacent basins. The agriculture sector in Isfahan province plays a crucial role in the water footprint increase. The cultivation of water-intensive crops and the need for extensive irrigation contribute to substantial water consumption. Implementing efficient irrigation techniques and promoting sustainable agricultural practices is essential for reducing water wastage and minimizing the overall water footprint of the agricultural sector. Furthermore, the industrial sector in Isfahan province also significantly contributes to the water footprint. The presence of numerous industrial workshops, particularly those involved in steel production, cement factories, and power plants, results in high water consumption and water pollution. The rapid growth of industrial activities further exacerbates the water crisis. Therefore, it is crucial to implement appropriate strategies and to regulate industrial water usage and promote sustainable prac-

tices to mitigate the water crisis caused by industrial activities. Such measures could include promoting the adoption of water-saving technologies and practices in industrial processes, regulating the discharge of pollutants into water sources, and increasing public awareness about water conservation and the negative impacts of industrial activities on water resources. The combination of population growth, agricultural practices, and industrial activities has resulted in a considerable increase in the water footprint of Isfahan province. The demand for water surpasses the available resources, putting a strain on the region's water supply. Urgent action is required to address the water crisis in Isfahan province through sustainable water management practices, efficient water allocation, and the implementation of advanced technologies. Overall, this research sheds light on the severity of the water crisis in Isfahan province and the role of increasing water footprint in this issue, and emphasizes the need for collaborative efforts among government agencies, stakeholders, and the public to address and mitigate water-related challenges. Further researches are needed to investigate the effectiveness of these policies and practices in reducing the water footprint of human activities in Isfahan province. Data collection and monitoring are essential to understanding the dynamics of the water crisis and in formulating effective solutions to ensure a sustainable water future for the province and its inhabitants.

#### **Data availability** **Population data**

The population data of Isfahan province obtained from Statistical Center of Iran yearbook and Isfahan municipality yearbook in different years, these websites are in Persian and the data is publicly available. Statistical Center of Iran available at: <https://www.amar.org.ir/statistical-information>.

Isfahan municipality yearbook (population part) is available at: [https://plan.isfahan.ir/sites/default/files/statistics\\_content/23898/files/98-2.pdf](https://plan.isfahan.ir/sites/default/files/statistics_content/23898/files/98-2.pdf).

#### **Agriculture data**

The data for agricultural products obtained from Statistical Center of Iran yearbook and Ministry of Agricultural Jihad and Organization of Agriculture Jihad of Isfahan province statistical yearbooks in different years. Ministry of Agricultural Jihad Statistics available at: <https://maj.ir/page-amar/FA/65/form/pld3352>.

Organization of Agriculture Jihad of Isfahan province statistics available at: <http://agri-es.ir/Default.aspx?tabid=1927>.

#### **Industrial data.**

The data for industrial products obtained from Statistical Center of Iran yearbooks, Mobarakeh Steel Company, Zobahan (Steel) Company, Iranian Mines & Mining Industries Development & Renovation Organization (IMIDRO), National Iranian Steel Company (NISC), Isfahan Regional Electricity Company and Cement Scientific Monthly.

#### **Electricity data.**

The data for electricity obtained from Statistical Center of Iran yearbooks and Isfahan Regional Electrical Company, Available at: <https://www.erec.co.ir/fa/history.aspx>.

All data used in this paper obtained from official sources that are published and open to public access. The data are in Persian.

## **Declarations**

**Conflict of interest** As the only author of the paper, declare that I have no conflict of interest.

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