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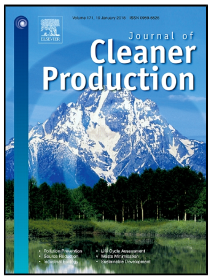

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Water Footprint and Virtual Water Assessment in Cement Industry: A Case Study in Iran

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Abstract:

To reduce the water footprint of a cement plant is one of the most important clean production performance indicators of the manufacturer. This paper proposes a comprehensive model for evaluating water footprint of cement production based on the type of energy consumption, transportation and human effects using a system boundary analysis. A cement plant located on western Iran is analysed to demonstrate the application of the proposed model and a sensitivity analysis is conducted to show the effects of different parameters on the performance of the model. The paper shows that the total water footprint of the selected cement plant accounts for 3.614×10^6 m^3 in 2016 with water consumption intensity of 2.126 m^3 per each ton of cement production indicating the risk of surviving cement industry in dry regions. The paper also shows that in the selected cement plant virtual water consumption contributes to the 90 percent of the total water footprint value. In addition, the paper demonstrates that the majority of the virtual water consumption is related to the energy sources which is 9.3 times more than the direct water consumption of the case study plant. Furthermore, the paper shows that water footprint can be most effectively reduced by shifting to greater contributions of wind and solar energy. This paper will be of interest to academics and practitioners interested in cleaner production of cement plants. It provides an understanding of water consumption of the cement industry broader than is currently available.

Keywords: Water footprint, energy consumption, cement industry, water saving.

Nomenclature

C_i	Cost of each item of a food
C_m	Cost of a meal
DWC	Direct water consumption
F	Annual fuel consumption
FEE	Fuel energy equivalent
F_i	Cost contribution (in percent) of each food item of a meal
HHV	Higher heating value
h_m	Working hours of personnel in one shift
N_h	Total working hours of personnel during a period (for example one year)
VWC	Virtual water consumption
WF	Water footprint
WF_{FOOD}	WF of personnel food
WF_i	WF of each food item of a meal (L/kg)
WF_{meal}	WF of a meal

1. Introduction

Owing to economic and technical benefits of cement products interest has increasingly developed in enhancing the cement properties and in addressing any challenges associated with cement production. Recently increased public awareness of the problems posed by global warming has led to greater concern over the environmental impact of cement manufacturing (Huntzinger and Eatmon, 2009). This has encouraged many studies focusing on alleviating the environmental problems of the cement industry. Among many problems in this arena, alleviating water consumption problems of cement production is indubitably of particular importance for the effective use of cement products particularly in dry regions.

The production of cement involves the consumption of large quantities of energy and the energy generation needs a huge amount of water consumption (Doe, 2006; Mielke et al., 2010), for example for extraction of oil and gas (Goodwin et al., 2012; Jordaan et al., 2013) or cooling down power plants (Doe, 2006). Sustainable development of water and energy are tied to each other and energy after agriculture is considered as the second water consumer sector (Hightower and Pierce, 2008). Water consumption in the energy sector is typically considered as the portion of withdrawn water not returned to the surface or groundwater in the same drainage basin from which it was abstracted.

Iran as a large cement producing country with a production of approximately 76 million ton per year ranks 4th in the world following China, India and the USA. Cement production equivalents to 0.8 percent of the Iran gross domestic product (Bod, 2014). However, Iran with limited water resources is considered as a dry territory and lack of enough water resources might become a major risk for cement industry in Iran and other dry countries in the future (Chehreghni, 2004).

Typically water consumption of cement industry is measured based on the amount of direct fresh water used for producing one ton cement. The term 'fresh water' is used here to refer to fresh tap water, groundwater, or surface water added to the water system of a cement plant, excluding the circulating water required for cooling. Such measurement, which is called the direct water consumption intensity, included recycled and reclaimed water, mainly depends on the process of cement production and equipment used (Huntzinger and Eatmon, 2009). The capacity of the cement plant also affects the water consumption but such effect is not considerable and can be ignored (Chehreghni, 2004). Valderrama et al. (2012) discuss the role of the cement line technology on the direct water consumption. They show that by using new technologies direct water use decreases from 0.556 m^3/ton in the regular line to 0.139 m^3/ton in a new built line according to the best available techniques. The research of Chen et al. (2010) estimates the direct water use of a French cement plant production as 0.200 m^3/ton. A study in 2004 in Iran shows that a cement plant near a small city, called Ghaen, needs daily water of 2300 m^3 which is equivalent to the water consumption of 15,000 to 20,000 residents of this city (Chehreghni, 2004).

Although direct water consumption measurement can be useful for providing insight about water usage of cement manufacturing, such measurement fails to provide information about virtual water consumption associated with cement's life cycle. Virtual water is adopted here in the sense of Allan (1998) and Verma (2009) to represent the water used in the supply chain of a product (cement here), for instance, water used for generation of energy (electricity, gas and so on) required by a cement plant (Gao et al., 2011). In order to consider both direct water and virtual water used in the supply chain of a product the concept of water footprint (WF) was proposed by Hoekstra (2002) and developed by Ridoutt and Pfister (2010). Now the WF concept is implemented for the analysis of production processes and services and includes three different water types, namely, blue, green and gray (Gu et al., 2015). Blue WF refers to surface water and groundwater that are withdrawn from the environment for human uses and is the focus of this study.

A comprehensive survey of research literature reveals that WF assessment has been well developed in agricultural industry (Mekonnen and Hoekstra, 2014; Zhuo et al., 2016) but it still is in an early stage in other industries (Hoekstra et al., 2011, 2012). Although a number of studies have looked at WF of products, including food and beverage (Ercin et al., 2011, 2012), fiber (Chico et al., 2013), paper (Van Oel and Hoekstra, 2012) and steel (Gu et al., 2015) no research has been conducted concerning WF of cement production. Mack-Vergara and John (2017) claim that water consumption data for cement production is limited. They call for more research for water consumption assessment of the cement industry. In the same vein, Finnveden et al. (2009) argue that industrial water use is hardly documented. The reports of Cemex (2015), Holcim (2015) and Lafarge (2012) give the figures of 0.366, 0.185 and 0.314 m^3/ton, respectively, for WF of cement production. However, it sounds that in such reports water withdrawals in cement plants are considered as WF of the plant. Available data related to cement life cycle is mostly concerned with CO_2 emissions and energy consumption (Mack-Vergara and John, 2017; World Business Council for Sustainable Development, 2009).

In such light this paper proposes a comprehensive model for evaluating WF of cement production based on the type of energy consumption, transportation and human effects using a system boundary analysis. The relationship between WF and energy consumption is highlighted and solutions for the water consumption problem in cement industry are provided. To show the application of the proposed model one of the large cement plants in Iran, with 1.7 million ton cement production per year, located on western Iran, is considered as a case study. A sensitivity analysis is conducted to show the effects of different parameters on the performance of the proposed WF model. High-quality direct and virtual water consumption data gathered from different sources (Williams and Simmons, 2013; Mekonnen et al., 2015) are provided and a novel method is developed to calculate the WF of the plant personnel's food using idea from food ecological footprint.

The paper is organized as follows. First WF measurement is described. Then the methodology is introduced which is followed by proposing the WF model of cement production. Finally, the case study is analyzed to show the application of the model.

2. WF measurement

There are two approaches to measure WF of a product, namely chain-summation and stepwise accumulative (Herath, 2011). The chain-summation approach is primarily used for production systems which provide only one end product (Hoekstra et al., 2011) and the WF of the various steps in the production system is entirely related to the end product. In comparison, the stepwise accumulative approach is more general which considers WF of processing and final steps in the production of a product as well as its necessary products (Hoekstra et al., 2011). Both approaches need detailed information, for calculating WF, which is typically confidential especially in large plants. This is considered as a main barrier for research concerning WF of a product. In this paper, the stepwise accumulative approach due to its popularity is utilized.

3. Method

For the development of a common and feasible cement production WF model a life cycle assessment (LCA) method is utilized (Jeswani and Azapagic, 2011) following the stages outlined by International Organization for Standards (ISO) 14040 and 14044 (2006), as well as those described by Hunt et al. (1992), Owens (1997), and Huntzinger and Eatmon (2009). The objective is to calculate WF of cement production based on the type of energy consumption, transportation and human effects using a system boundary analysis. The reason is to provide more detailed water consumption information. In this study blue water footprints (direct and virtual) are calculated as it considers surface water and groundwater that are withdrawn from the environment for human uses. In comparison, green water footprint is typically calculated for agricultural productions as it focuses on rainwater that has been consumed directly on the landscape. The main information obtained from the case study cement plant includes: annual production; sources of energy and energy usage per year; annual direct water consumption; wasted and discharged water; number of employees and their working time; and distance to the nearest center of population. The main steps of the LCA applied in this paper comprise: determination of the model boundary; selection of model outputs and inputs; assessment of water consumption based on data gathered and the model proposed; and interpretation of results and suggestions for water saving. In the following first model boundary is presented which is followed by proposing the WF model. Next the virtual water consumptions of natural gas, heavy fuel oil, transportation and personnel food are presented. Then the case study is analysed. This is followed by providing discussion, sensitivity analysis and model validation.

3.1. Model boundary

In order to show the boundary of the proposed model a system boundary analysis is adopted. Fig. 1 demonstrates a system boundary for calculating WF of plants which can be applied to any product. The water consumption of the plant is divided into two parts, namely direct and virtual. For direct water consumption, direct water used for production process, personnel and services in the plant is considered. For virtual water consumption, virtual water used for energy supply of the plant and the personnel food is calculated.

The considered system boundary is mainly focused on the WF of the production process of a plant and therefore, does not need any long-term assessment and a large amount of data. In addition to the WF of the plant's production process, the WF of different parameters (such as raw material supply, plant construction and demolition, equipment manufacturing, transportation and product consumption) can be considered as virtual water consumption of the plant in the system boundary. In the case of availability of reliable data for such parameters the WFs of them can be considered in WF calculations.

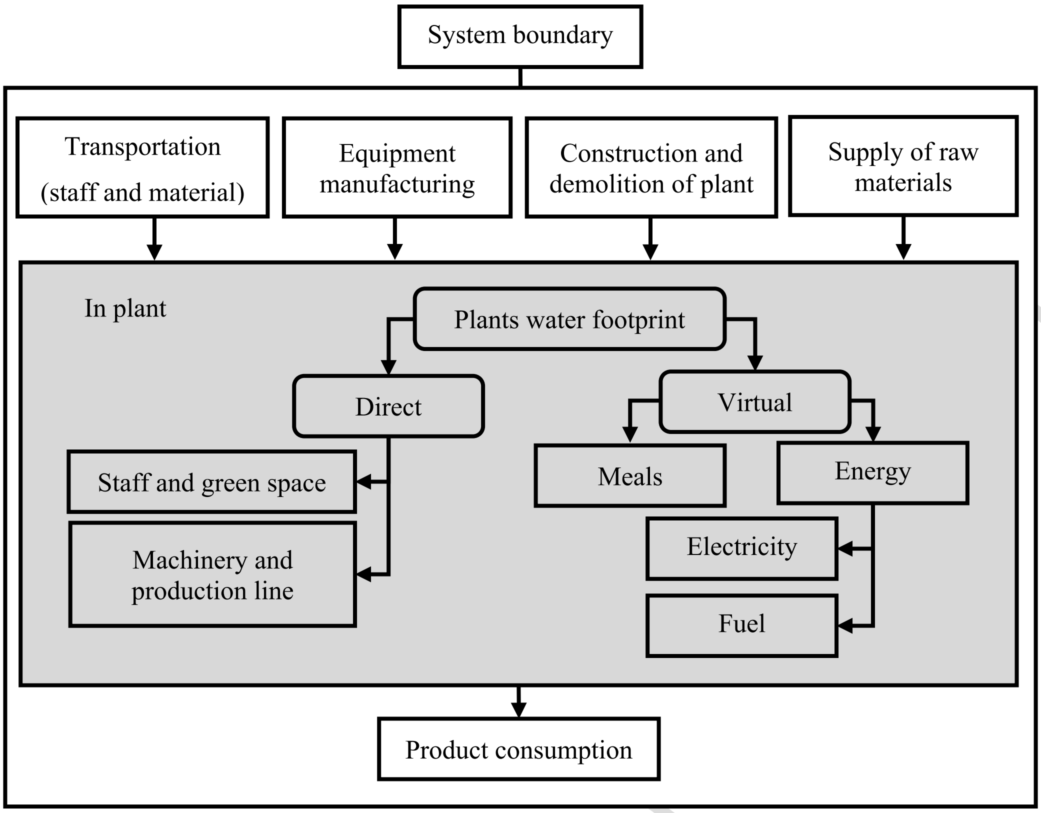

Fig. 1. System boundary for WF calculation of a plant

4. Proposed WF model

To propose the WF model for cement plants first the cement production is briefly outlined then the model is provided.

Manufacturing of cement involves mixing of raw material (dry or wet), burning, grinding, storage and packaging (Schneider et al., 2011). The most common way to manufacture cement in Iran is through a dry process which is the focus of this paper.

The life cycle of cement is complex and includes quarries of raw materials (lime stone and clay), cement manufacturing, transportation, use of cement, and disposing and recycling of the cement products (Schneider et al., 2011). In each step a considerable amount of energy and water is consumed (Huntzinger and Eatmon, 2009). Therefore inventory analyses and complete LCA can be quite complicated.

Based on the system boundary, shown in Fig. 1, and cement production steps, Fig. 2 presents the WF model for cement plants. As mentioned before the production process is considered as the main focus, which is the most important part that manufacturers should consider when they decide to manage water risk, in industrial WF assessments. WFs of raw materials are difficult to obtain for cement plants as the extraction and transportation of raw materials might be very diverse depending on the sources and are typically not well documented. So they are not considered here. Also the consumption of cement varies remarkably depending on the end use. Furthermore, the water used in the construction and demolition of cement plants is not typically tracked, so there is no data available for this part. Given the multi-decade life of most plants, this is likely a small portion of the overall WF, and thus it is not calculated here.

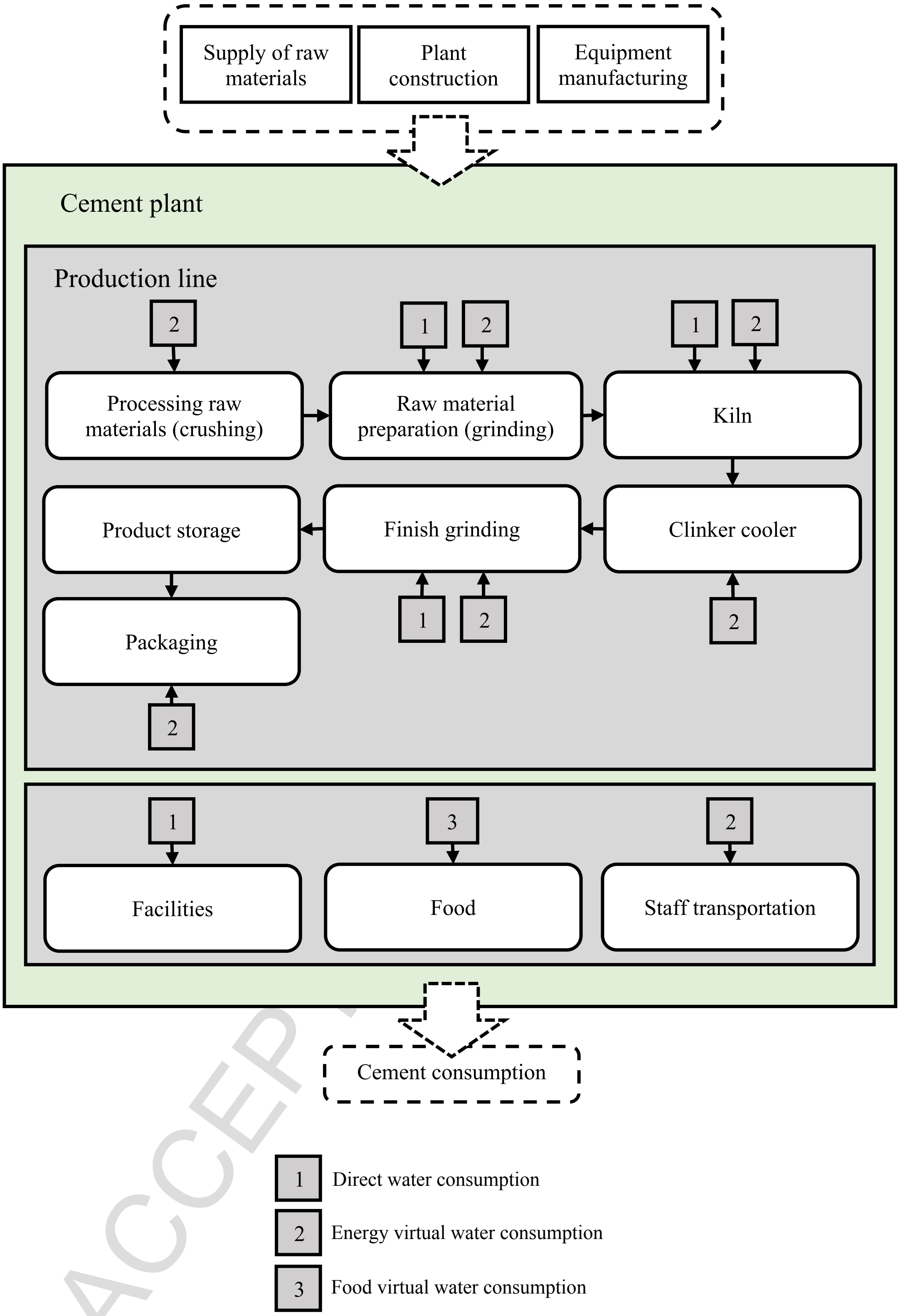

Fig. 2. WF model for cement plants; dashed lines are not considered in the model

It follows directly form Fig. 2 that the WF amount can be calculated by (Gu et al., 2015),

$$WF = DWC + VWC \quad (1)$$

where DWC and VWC represent direct water and virtual water consumption, respectively.

The amount of direct water consumption varies from one plant to another due to the technology and equipment used, cement production process, plant capacity and water used by personnel (Huntzinger and Eatmon, 2009). The picture is different in the case of the virtual water consumption as it mainly depends on the energy used in the cement plant. There is a close interlink between energy and water, which requires a nexus approach to ensure a sustainable supply of both. In recent years, the link between energy and water has provided great research interest (Scown et al., 2011). However, the assessment of WF of energy consumption of the production process is quite difficult because of limited data availability.

Energy is typically selected based on the price and availability. The contribution of different energy sources differs per country. In Europe and in Asia (excluding China and India), natural gas is the preferred source of energy, contributing to the 39 and 40 percent of the total electricity and heat production of the regions, respectively. Iran depends largely on oil and natural gas for its electricity and heat production. Accordingly, in the proposed model these two fuel types (oil and natural gas) are considered as the main sources of energy. Iran-specific estimates or regional estimates in the absence of country specific data are used in the modeling.

4.1. Natural gas

Natural gas stands as the main source of energy of most plants in Iran as Iran has one of the world's largest reserves of natural gas. Water is used in the exploration and production processes of natural gas (Williams and Simmons, 2013). The WF of natural gas refers to the water volumes consumed and polluted in the different stages of the supply chain of natural gas. The data for water consumption in the literature are often expressed in different units. For natural gas is generally expressed in terms of water volume per unit of volume (m^3/m^3).

WFs can also be provided in terms of water volume per unit of embedded heat energy or electricity (m^3/TJ). The annual amount of fuel (F), used to produce electricity and/or heat (expressed in mass or volume per year) can be expressed in terms of fuel energy equivalent (FEE) (GJ per year), which can be obtained by multiplying F by the higher heating value (HHV) of the fuel (Mekonnen et al., 2015),

$$FEE = F \times HHV \quad (2)$$

The HHV of natural gas is estimated to be 0.034 GJ/m^3 (Enerdata, 2014). Following Mekonnen et al. (2015) the value of FEE for Asian countries (China and India excluded) is equivalent to 5965 PJ/year (for the period 2008-2012). Accordingly, using Equation (2), the F value for Asian countries is calculated as 175441 Gm^3/year. For this period, according to Mekonnen et al. (2015) the consumptive WF of heat production (operations and supply chain) from natural gas in Asian countries is 1623 million m^3 per year.

There follows the water intensity of natural gas (the water needed for the production of a unit of natural gas) can be calculated by (Mekonnen et al., 2015),

$$\text{Water intensity} = WF/F \quad (3)$$

which for Asian counties is equivalent to 9.251 L water per cubic meter of natural gas. As Iran located in this region such water intensity value is used here for calculating the WF of natural gas.

4.2. Heavy fuel oil

As reported by Williams and Simmons (2013) from refining of a barrel of crude oil (159 L) about 3.8 L of heavy fuel oil can be obtained. Fig. 3 illustrates a typical product mix refined from a barrel of crude oil. Accordingly, one liter heavy fuel oil is obtained from refining of 41.84 L (0.2631 barrel) of crude oil. Water used in the extraction of one barrel of crude oil is 85.5 L and for refining it ranges between 31.35 L and 148.2 L (Williams and Simmons, 2013). This implies that for the extraction of 41.84 L of a crude oil (equivalent to one liter of heavy fuel oil) 22.5 L water and for refining such amount of heavy fuel oil between 8.25 L and 40 L water are required. Accordingly, total WF required for the extraction and refining one liter of heavy fuel oil is estimated to be between 30.75 L and 62.5 L.

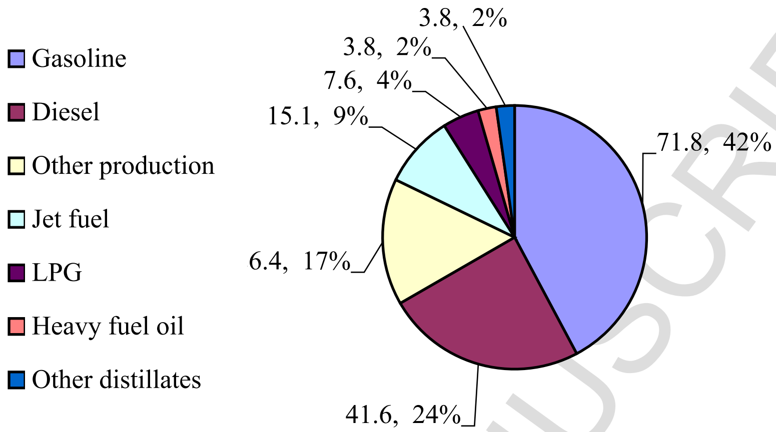

Fig. 3. Typical product mix refined from a barrel of crude oil

4.3. Transportation WF

King and Webber (2008) investigated the water intensity of transportation. Their research showed that vehicles with petroleum based in average use 0.16 L to 0.33 L water/km and vehicles with gasoline based in average consume 0.18 L/km to 0.26 L/km.

4.4. Electricity WF

The research of Mekonnen et al. (2015) assessed the consumptive WF of electricity generation per world region in three main stages of the production chain; that is fuel supply, construction and operation. WF of electricity in power plants is generally dependent on the type of energy sources used for electricity generation such as coal, lignite, natural gas, oil, uranium or biomass as well as wind, solar, geothermal energy and hydropower. Based on this research the electricity generation in Iran is located in low water consummative regions with 0 to 500 m^3 water consumption per TJ. This is equivalent to 0 to 1.8 m^3 water per MWh (1 TJ = 277.778 megawatt hour, MWh).

4.5. Virtual WF of personnel

The virtual WF of personnel is measured by the WF of their consumed food during their working hours. Due to the lack of any advance method for calculating the WF of the personnel's food a novel method is developed here using idea from food ecological footprint (Spiess, 2014). The WF of food includes the water volume used for production and processing. A large amount of WF of food is related to the production (agriculture) sector and that of the processing sector is small and can be ignored (Spiess, 2014). The WF of personnel food (WF_{FOOD}) in a plant can be obtained by,

$$WF_{FOOD} = WF_{meal} \times \left(\frac{N_h}{h_m} \right) \quad (4)$$

where WF_{meal} represents the WF per each meal (water intensity); h_m is the working hours of personnel (for example a working shift) which one meal (for example lunch) is eaten in the plant; N_h is the total working hours during a period (for example one year); and (N_h/h_m) represents the number of meals. In Equation (4) WF_{meal} can be calculated by,

$$WF_{meal} = C_m \sum_{i=1}^{n} \frac{F_i}{100} \times \frac{1}{C_i} \times WF_i \quad (5)$$

where C_m represents the cost of one meal which is considered 10,000 Toman (Toman is the Iran currency, \$1 = 3,700 Toman) based on the Iran food market; F_i is the cost contribution (in percent) of each food item of the meal (Domenech Quesada, 2007); C_i is the cost of each item of the food; and WF_i is the WF of each food item of the meal (for example L/kg) (Hoekstra, 2008). Table 1 provides the information required for calculating the WF of personnel's food (Domenech Quesada, 2007; Hoekstra, 2008; Ercin et al., 2011; Spiess, 2014).

Table 1. Information about ingredients and WF of a meal

Components	F_i %	C_i (Toman/kg)	WF_i (L/kg)
Beef	25	30000	15500

Chicken	25	6000	3900
Beans	12	6000	2125
Beverages (soft drinks)	10	2000	500
Vegetables	8	2000	380
Bread	6	1750	1300
Corn oil	5	5000	2575
Dairy (cheese)	5	10000	5000
Tee	4	200 (Toman/cup)	30 (L/cup)

Using Table 1 and Equation (5), WF per a typical meal (WF_{meal}) is equivalent to 4756.88 L.

5. Summary of virtual water consumption intensity

Based on the above development Table 2 summarizes the virtual water consumption intensity information for the parameters used in the proposed model.

Table 2. Virtual water consumption intensity information for different parameters

Parameter	Sources	Gathered data	Form of calculation	Water intensity
Natural gas	Mekonnen et al. (2015); Enerdata (2014)	WF of natural gas production, FEE and HHV of natural gas	Using Equations (2) and (3)	9.251 L/m^3
Heavy fuel oil	Williams and Simmons (2013)	Products refined from a barrel of crude oil, water consumption in the extraction and refining of one barrel of crude oil	Mathematical calculation	30.75-62.5 L/L
Transportation	King and Webber (2008)	Water intensity of transportation	Mathematical calculation	Petroleum-based Vehicles: 0.16-0.33 L/km, Gasoline-based vehicles: 0.18-0.26 L/km
Electricity	Mekonnen et al. (2015)	WF of electricity generation in Iran	Using unit conversion (1 TJ = 277.778 MWh)	0-500 m^3/TJ = 0 - 1800 L/MWh
Meals	Domenech Quesada (2007); Hoekstra (2008); Ercin et al. (2011); Spiess (2014)	Components of a meal; their cost contribution and WF	Using Table 1 and Equation (5)	4756.88 L/meal

6. Case study

In this section a case study, a large cement plant located on the western part of Iran, manufacturing Portland cement, is analyzed and the application of the model is presented. The distance of the case cement plant to the nearest center of population is about 15 km. The annual capacity of the plant is 1.7 million ton cement and the annual direct water consumption of the plant is 300,000 m^3. One percent of the direct water is wasted, based on the cement plant experts' opinion. Having this information the amount of direct water consumption after excluding one percent water waste (as it is not used in the cement production process) is equal to 297,000 m^3. The water discharge of the plant is small and after treatment is used for watering the plant green area (lawn, flowers and so on). Table 3 presents the annual amount of different energy sources along with their corresponding WF amounts. In this table the information of WF is obtained from Table 2.

Table 3. Annual energy use and WF of energy of the case cement plant

Energy type	Energy consumption	WF of energy	Average WF of energy
Natural gas	1.57×10^8 m^3	0.00925 (m^3/m^3)	1.452×10^6 m^3
Heavy fuel oil	2.1×10^4 m^3	30.75 – 62.5 (m^3/m^3)	9.8×10^5 m^3
Electricity	1.8×10^5 m^3	1.8 (m^3/MWh)	3.2×10^5 m^3
Total	-	-	2.752×10^6 m^3

Table 3 illustrates that the total virtual WF of the energy used in the cement plant is equal to 2.752×10^6 m^3 for one year.

For calculating the WF of the personnel transportation services it is required to mention that around 430 people are employed by the plant. Based on the date collected the majority of the personnel travel from the nearest center of the population to the plant and 18 vehicles with 20 people capacity are used each day for the personal transportation. Around 80 percent of the personnel take these vehicles and the rest use their own cars. In average the vehicles travel 160,000 km yearly for the personnel transportation. The fuel used for the vehicles is diesel.

With 0.18 to 0.26 L water consumption per one kilometer travel of each vehicle, based on Table 2, the virtual WF of personnel transportation is equal to 28.8 to 41.6 m^3 in one year.

To calculate the virtual WF of the personnel food, one meal is considered for each working shift (8 hours) of the personnel. Based on the information obtained from the plant the total working time of all personnel is 950,000 hours per year. Accordingly, the number of meals eaten in the plant during a year (N_h/h_m) can be calculated (118750). Having this and using Equation (4) and Table 2, the total WF of the personnel food is estimated to be 565,000 m^3.

7. Discussion

The WF of the case study plant with the current production rate (1.7 million ton cement per year) is estimated to be 3.614 million m^3.

Fig. 4 illustrates direct and virtual WF of the plant. This figure demonstrates that a huge amount of water withdrawn from water sources. The virtual water consumption of the case study plant, which is estimated to be 3.317 million m^3, is 11 times larger than direct water consumption and contributes to the 90 percent of the total WF of the cement plant. This implies that a large water consumption proportion is related to virtual water which is a key point and a missing part of the water consumption calculation in the cement industry. Virtual water may be consumed far away from the industrial facility, with no direct impact on local water resources. However, it affects national, regional and even the global water resources.

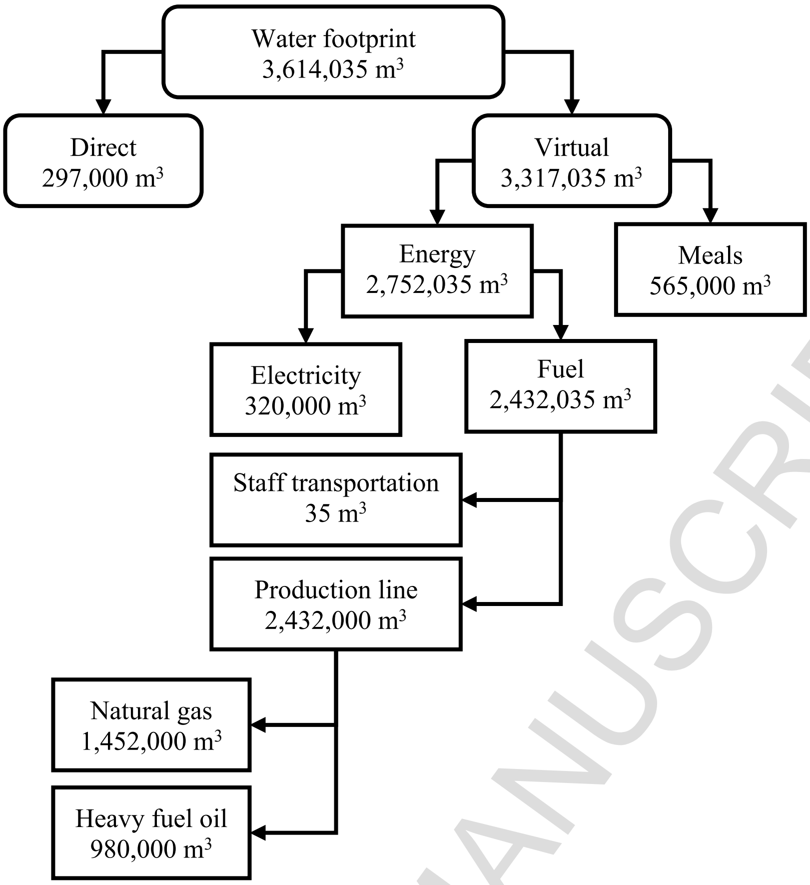

Fig 4. Direct and virtual WF of the cement plant

Fig. 4 also shows that the majority of the water consumption is related to the virtual water of the energy sources which is 9.3 times larger than the direct water consumption of the case study plant. This suggests that emphasis should be placed on energy efficiency measures, which not only contribute to carbon footprint reduction but also are related to the WF reduction.

The value of WF of the personnel food shows the relationship between the number of employees and the virtual water consumption. The results illustrate that more than 0.5 million m^3 WF is related to the personnel food which contributes to the 15 percent of the total water and 17 percent of the virtual water consumption. An increase in the number of employees contributes to a rise in WF similar to the energy sources usage. With reducing the number of personnel, through for example using automation or upgrading the plant equipment, the virtual WF of the personnel is reduced. However, this may lead to an increase in the WF of energy sources due to the replacement of human by machine. Investigating of this issue can be a subject of the future research. The results indicate that the WF of the personnel transportation services in comparison with other WFs has relatively little impact on the overall WF and can be ignored for this cement plant.

The results (in Fig. 4) show that electricity, heavy fuel oil and natural gas, respectively, contribute to 10, 30 and 43 percent of the virtual water consumption of the cement plant. In the case study plant natural gas is the main fuel and the heavy fuel oil is used in the case of any shortage of the natural gas. The WF of the crude oil, coal and natural gas as three main fossil fuels are, respectively, 497, 495 and 241 m^3/Tj (Mekonnen et al., 2015). Accordingly, natural gas has the lowest WF in comparison with other fossil fuels. The WF of refining of natural gas is also considerably lower than that of the other fossil fuels. Thus use of natural gas results in a considerable WF reduction compared to the other fossil fuels.

In the case cement plant, the WF of electricity is close to the direct water consumption. With utilizing renewable energy sources for generating electricity the WF of electricity can be reduced significantly. The research of Mekonnen et al. (2015) shows that the best type of renewable energy in terms of WF is wind power. Table 4 demonstrates that the average value of the WF of the energy generated from wind power is very low 1.3 m^3/Tj (4.68 L/MW); though it is not practical to generate electricity from wind in any part of a country.

Table 4. Average global WF of electricity and heat generated from different energy types (2008-2012) (Mekonnen et al., 2015)

Energy type	WF (m^3/TJ)
Wind	1.3
Solar	140
Natural gas	247
Geothermal	342
Coal & lignite	495
Oil	342
Nuclear	678
Hydropower	15100

Firewood	156400
Total	4241

Generating electricity by use of solar is more practical in Iran due to its climate conditions. Table 4 shows that the WF of the electricity generated by solar equals to 140 m^3/Tj (504 L/MWh).

Among fossil fuels natural gas accounts for the lowest WF (Mekonnen et al., 2015). Owing to the large natural gas reservoirs of Iran this fuel is considered as the most appropriate type, based on the WF concept, for providing the energy required by cement plants in Iran. However, care should be exercised about the carbon footprint of such fuels.

Large plants need to upgrade their equipment to enhance their efficiency to reduce energy consumption. In addition, large plants based on their local conditions need to produce part or all of their energy demand through renewable energy sources.

The plant's direct water is supplied from groundwater resources. Based on the Regional Water Authority report the annual water withdrawals of the region's basin water reserve (for agricultural, industrial, urban consumption, and so on) is equal to 3.486×10^6 m^3 (RWA, 2017). Therefore, the cement plant with an annual direct water withdrawal of 300,000 m^3, contributes in average to 8.61 percent of the basin groundwater withdrawals. RWA (2017) claims that the groundwater withdrawal in the region is around 3 times more than the groundwater discharge. Accordingly, the plant poses a serious risk on the region's basin water reserve.

Considering Iran's annual cement production, 76 million ton (Bod, 2014), the WF of the cement industry in Iran is estimated approximately to be 162×10^6 m^3 which accounts for 0.16 percent of the total WF in Iran. The total blue WF of Iran was estimated to be $40,912.76\times10^6$ m^3 and the per capita WF was 588.83 m^3/year in 2005 (knoema, 2005). It means that the cement industry accounts for about 0.39 percent of the total blue WF. In comparison, Gu et al. (2015) showed that the iron and steel industry sector in China accounts for about 0.4 percent of the total WF. It appears that the WF intensity of cement industry is significant compared with other water related industries. As cement is vital for the construction industry, reducing WF of the cement industry will greatly improve the sustainability of construction activities in Iran and around the world. This confirms the necessity of this study to calculate the WF of a specific cement plant.

This paper demonstrates a practical WF model within cement industry. The WFs of energy consumption, transportation, and human are presented to give an original model for the WF calculation of cement production. The paper addresses a real-environment problem in cement industry and presents a very neat argument usable by practitioners. The results can readily be applied to the WF calculation of any cement plant within limitations such as lack of considering the WFs of raw materials (lime stone and clay), cement plant construction and demolition, and cement products consumption.

8. Sensitivity analysis

As discussed before there are six parameters, natural gas, heavy fuel oil, food, electricity, direct water consumption and transportation, which affect the WF of the cement plant. It is of practical significance to assess the sensitivity of the WF value against these parameters. This can be achieved through conducting a sensitivity analysis of the WF of the plant with respect to affecting parameters (Saltelli et al., 2008). In doing so, following Ditlevsen and Madsen (1996) a parametric sensitivity factor method is used. Due to a low value of WF of the transportation of the personnel this parameter is not considered in the analysis.

The corresponding results are illustrated in Fig. 5. As expected, the relative WF value, ΔWF/WF, increases with the increase of relative such parameters values, denoted by ΔP/P. When natural gas, heavy fuel oil, food, electricity and direct water consumption increases by 10 percent, ΔWF/WF approximately increases by 4.0, 2.7, 1.56, 0.9 and 0.8 percent, respectively. This reveals that among these parameters, natural gas is the most important one influencing the WF of the cement plant which is followed by heavy fuel oil and personnel food.

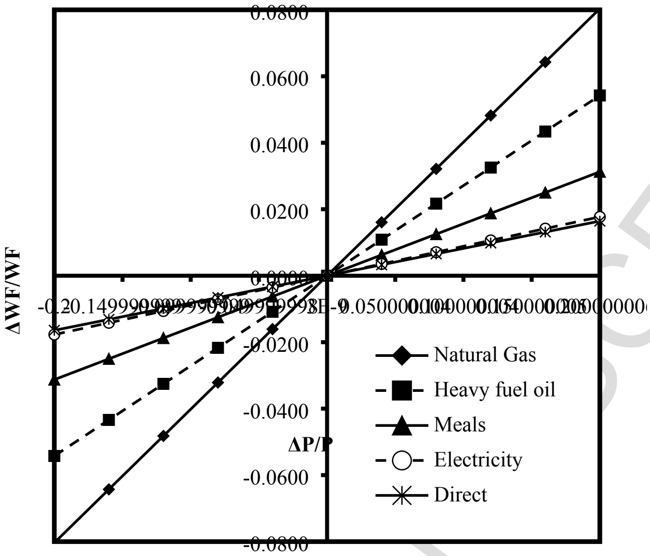

Fig 5. Sensitivity analysis results for WF parameters

9. Model validation

Based on the past research which mainly focused on the direct water consumption, the direct water intensity of this plant (direct water consumption) is estimated to be 0.2 m^3 per each ton cement produced. This research shows that by using the WF model the water intensity of the selected plant is estimated to be 2.126 m^3/ton which is around 10 times more than that of the direct water intensity. Unfortunately, there is no similar research concerning WF of cement plants to compare the results. The research of Gu et al. (2015), discussing WF in an iron plant, shows that without considering the virtual WF concept the direct water intensity of the iron plant is equivalent to 0.435 m^3 per each ton of iron produced. With the use of the virtual water and WF concepts such value rises to 5.471 which is 12.5 times larger than that of the direct water consumption (common measurement). This is close to the finding of this research (10 times) which provides support for the paper results.

10. Conclusion

Due to the water shortage in Iran, conducting studies concerning water consumption of products are of particular usefulness. Cement plants are considered as huge water consumers. Little effort has been dedicated to develop the WF concept and its relationship to the energy consumption in the cement industry. This paper proposed a feasible model for evaluating WF in cement industry based on the type of energy consumption, transportation and human effects using a system boundary analysis. The relationship between WF and energy consumption was highlighted and solutions for the water consumption problem in the cement industry were provided. To demonstrate the application of the proposed method a cement plant located on western Iran was analysed. A sensitivity analysis was conducted to show the effects of different parameters on the performance of the proposed WF model.

The paper demonstrates:

- The total WF in the selected cement plant accounts for 3.614 million m^3 with 2.126 m^3 water consumption intensity and 0.2 m^3 direct water consumption intensity in 2016 indicating a high contribution of the cement industry to water consumption and risk of surviving such industry in dry regions.
- In the selected cement plant virtual WF is 11 times larger than that of direct water consumption contributing to the 90 percent of the total WF affecting national, regional and even the global water resources.
- The majority of the water consumption is related to the virtual water of the fossil energy usage which is 9.3 times larger than the direct water consumption of the case

plant highlighting the role of energy efficiency measures and use of renewable energy sources in WF reduction.

- The personnel's food contributes to the 15 percent of the total water and 17 percent of the virtual water consumptions highlighting the role of employment on increasing the water consumption amounts.

It can be concluded that the WF assessment can serve as a useful reference for decision makers within the cement industry to evaluate the cement industry's draw, dependence and responsibilities on water resources. Thereby, the paper contributes to knowledge on water management and sustainable cement products. The paper results provide an understanding of actual water consumptions of the cement industry broader than is currently available. The development of industrial WF assessment methodologies is considered as another contribution of the paper. As the WF of cement industry is significant compared with other water related industries reducing water consumption of cement production is vital to achieve sustainability in construction activities.

Although efforts were made to provide high-quality WF data, limitations occur due to the lack of reliable data. Much of the WF will depend on energy and heat input amounts that vary between processes.

A number of directions towards comprehensive WF assessments of cement industries are possible, for example considering the WF of raw materials of cement plants in the proposed WF assessment model. Another direction could be made to assess the WF of different cement types. The case investigation in the paper was conducted on one cement plant sample. Another direction possibility is to consider different cement plants to enlarge the sample, and to provide further persuasive support for the paper's results. Investing the WF of the cement industry in different regions and countries could be considered as a direction to assist in providing worldwide data sets to allow the cement industry and its clients to take measures to minimize the associated environmental impacts. Much of WF assessments will depend on energy and heat input amounts that vary between technological routes. Differences on various technological routes were not covered in the current study; this might be the subject of the future research.

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