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A system dynamics model for analyzing energy consumption and CO_2 emission in Iranian cement industry under various production and export scenarios

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HIGHLIGHTS

- ► We have developed a system dynamics model to analyze the demand, production, energy consumption and CO2 emission of cement industry in Iran.
- ► Various production and export scenarios have been simulated to project the energy demand of Iranian cement industry over next 20 years.
- ► A causal structure is used to show how subsidy reform would affect energy consumption in the cement industry over the long term.
- ► Producing blended cement, using waste materials as an alternative fuel and recycling wasted heat for electricity generation are the main corrective policies discussed herein.

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ABSTRACT

Cement industry is one of the six energy intensive industries in Iran accounting for 15% of total energy consumption in the industrial sector. The sudden reform of energy prices in Iran is expected to have a great impact on production and energy consumption in this industry. In this paper, we present a system dynamics model to analyze energy consumption and CO_2 emission in Iranian cement industry under various production and export scenarios. We consider new energy prices to estimate possible energy demand by this industry over next 20 years. The model includes demand for cement, production, energy consumption and CO_2 emission in an integrated framework with emphasis on direct natural gas consumption. Producing blended cement, production using waste materials as alternative fuel, and wasted heat recovery for electricity generation in cement industry are three main corrective policies simulated and discussed herein. Simulation result show that complete removal of energy subsidy and implementation of corrective policies in the cement industry could potentially lead to reductions of 29% and 21%, respectively in natural gas and electricity consumptions and 22% reduction in CO_2 emission.

1. Introduction

Cement industry is the second energy intensive industry (after steel industry) in Iran accounting for 15 % of total energy consumption and 18% of total natural gas consumption in the industrial sector (Avami and Sattari, 2007). This industry is one of the main sources of CO_2 emission (IEF, 2010). Most carbon dioxide emission from cement manufacturing results from clinker production. Clinker is the main component of the cement that is produced after calcination of limestone. In cement industry, CO_2 emission comes from fuel consumption and calcination process (IETIS, 2010).

Three kinds of cement are produced in the country: ordinary Portland cement (OPC), Portland Pozzolana cement (PPC) and Portland slag cement (PSC).

The production shares of different kinds of cement and their ingredients are shown in Table 1(Iranian Cement Association, 2011). Dry process is the main production technology which accounts for 97% of cement production in the country (IEEO, 2010).

Cement production has increased dramatically in the last decade from 24 million tons in 2001 to 58 million tons in 2011. It covers 53 million tons of domestic demand and 6.9 million tons of export (Iranian Cement Portal, 2011). The average energy consumption for cement production in Iran is 840 kcal per one kilogram of clinker and 112 kW h per each ton of cement (Ministry of Energy, 2010).

Natural gas and electricity are main energy sources in the industry. Due to high proportion of natural gas usage for generating electricity in the country, higher cement production leads to more

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Table 1
Share of different kind of cement in production and their ingredients.

	Additives	Amount of additive per ton of cement (%)	Share in production (%)
OPC	Gypsum	4–5	95
PPC	Gypsum, pozzolana	35	3
PSC	Gypsum, slag	70	2

natural gas consumption indirectly. The long time subsidized energy has led to low energy efficiency in Iran (Wuppertal Institute, 2010). The sudden subsidy reform of energy prices in December 2010 is expected to have a great impact on production and energy consumption in this industry.[1] In this paper, we present a system dynamics (SD) model to study the impact of the subsidy reform policy on energy consumption and CO_2 emission of the cement industry under various production and export scenarios over the next 20 years.

Many researchers have studied energy consumption and CO_2 emission in cement industry (Riccardi et al., 2012; Szabo et al., 2006; Hasanbeigi et al., 2010a, 2010b). Hua et al. (2012) analyzed energy consumption and CO_2 emission in China cement industry and its driving factors over the period of 1990–2009. They showed that the growth of cement production is the most important factor which drives energy consumption and CO_2 emission. The study also showed that the decline of clinker production and process structural shift drive energy consumption down. Oggioni et al. (2011) provided an eco-efficiency measure for 21 prototypes of cement industries operating in many countries by applying both data envelopment analysis (DEA) and a directional distance function approach. Their results show that countries which utilize an advanced kiln and alternative fuel and raw material in their production process are eco-efficient. Pardo et al. (2011) analyzed the potential for improvement in energy efficiency and reduction of CO_2 emission in European cement industry up to 2030.

Mikulčić et al. (2012) analyzed energy consumption and CO_2 emission in Croatian cement industries. Three different scenarios were evaluated to project the achievable reduction in CO_2 emission until 2020. Reduction of clinker ratio to cement by adding different additives, the replacement of fossil fuels with alternative and biomass fuel, and improvement in energy efficiency of the exciting kiln process were discussed in their paper. Jing et al. (2012) analyzed current energy and carbon dioxide emission trend in Chinese cement industry. Moya et al. (2011) performed a cost effectiveness analysis of some of the best available technologies to decrease energy consumption and CO_2 emissions in the European Union's cement industry. Mandal (2010) estimated energy efficiency of the Indian cement industry using data envelopment analysis (DEA).

Energy system modeling in an industrial sector is a complex problem due to the presence of multiple decision makers, complexity of consumers' behaviors, feedback processes among module, technological limitations and various kinds of delays. System dynamics is a suitable approach to model such complexities.

System dynamics is a powerful methodology and modeling technique for understanding and exploring the feedback structure in complex systems. It was originally developed in the 1950s to help corporate managers improve their understanding of industrial processes. System dynamics has been widely used in various socio-economic studies (Radsicki and Taylor, 1997).

In energy related subject, Nail (1973) developed a SD model for the United States gas industry. Li et al. (2011) used a SD approach to forecast natural gas demand in China. In transportation sector, the SD model presented by Han and Hayashi (2008) was used for policy assessment and CO_2 mitigation potential analysis of intercity passenger transport in china. Kiani and Pourfakhraei (2010) considered feedbacks among supply, demand and oil revenue in Iran and projected future oil and gas consumption and production under various scenarios using system dynamics. In industrial sectors Anand et al. (2005) used SD to estimate CO_2 emission in Indian cement industries. They presented some policy options for stabilizing population growth, energy conservation and manufacturing processes for CO_2 mitigation. In Anand et al.'s (2005) model, energy price and dynamics of production capacity expansion have not been considered. Furthermore, the amount of cement production was assumed to grow with fix growth rate.

In this paper, we present a SD model to identify and capture key feedback loops affecting energy consumption and CO_2 emission of Iranian cement industry with a special focus on subsidy reform and natural gas consumption in the country.

The proposed SD model is composed of four main modules:

(1) cement demand module,
(2) production module considering production capacity expansion ,
(3) energy consumption module and,
(4) CO_2 emission module.

The model includes the interactions among these modules in an integrated manner. A co-flow structure is used to show how subsidy reform would affect consumers' behavior and energy consumption in the long run. Blended cement production, using waste materials as an alternative fuel in the cement industry as well as wasted heat recovery (WHR) for electricity generation are the main corrective policies evaluated in this paper.

Our analysis covers the following important issues that are elaborated in the proposed SD model:

1) the impacts of population and GDP growth on cement demand and production over the next 20 years,
2) the structure of direct and indirect energy consumptions and CO_2 emission under various production and export scenarios under the new subsidy regime,
3) the potential energy saving and reduction in CO_2 emission obtained by combinations of the above-mentioned corrective policies.

2. Methodology

2.1. The proposed system dynamics model

As discussed earlier, our methodology is based on system dynamics. A SD model has been constructed to analyze energy consumption and CO_2 emission of cement industry in Iran. Four main modules of the SD model are explained in this section. In each module, the stock and flow diagram is presented. The feedbacks among the four modules are also explained in this section. The mathematical notations and nomenclatures are shown in Table 2.

2.2. Modeling the demand for cement

The structure of cement demand is presented in Fig. 1. Cement demand increases with the growth of population and demand per capita as shown in Eq. (1). Per capita cement demand (PCCD)

[1] No new data was available after 2010 at the time of this study.

Table 2
Mathematical notations and nomenclatures.

Module of the model	Notation	Nomenclature	Type of variable or parameter
Demand module	CD	Cement demand	Endogenous
	PCCD	Per capita cement demand	Endogenous
	P	Population	Endogenous
Production module	DPPC	Dry process production capacity	Endogenous
	DPCCR	Dry process capacity completion rate	Endogenous
	DPCDR	Dry process capacity discard rate	Exogenous
	DRNCOR	Dry process new capacity order rate	Endogenous
	NCO	New capacity order rate	Endogenous
	DPCD	Dry process construction delay	Exogenous
	SODP	Share of dry process (in new capacity order)	Exogenous
	DPC	Desired production capacity	Endogenous
	FOCD	Forecast of cement demand	Endogenous
	DSIDS	Desired share in domestic supply	Exogenous
	DE	Desired export	Exogenous
	PPC	Perceived percent condition(of cement demand)	Endogenous
	PT	perceived trend (of cement demand)	Endogenous
	ECD	Expected construction delay	Exogenous
	TTPPC	Time to perceived present condition	Exogenous
Energy consumption module			
	DPER	Dry process electricity requirement	Endogenous
	DPNCER	Dry process new capacity electricity requirement	Endogenous
	DPDCER	Dry process discarded capacity electricity requirement	Endogenous
	DPRCER	Dry process renovated capacity electricity requirement	Endogenous
	DPRCPER	Dry process renovated capacity previous (before renovation) electricity requirement	Endogenous
	DPEECPT	Dry process expected electricity consumption per ton	Endogenous
	DPAECPT	Dry process average electricity consumption per ton	Endogenous
	DPCDR	Dry process capacity discard rate	Exogenous
	DPRC	Dry process renovated capacity	Endogenous
	EEC	Expected electricity cost	Endogenous
	EP	Electricity price	Exogenous
	PAT	Price adjustment time	Exogenous
	GC	Gas consumption	Endogenous
	OC	Oil consumption	Endogenous
	GPTES	Gas proportion in thermal energy supply	Exogenous
	TECDP	Thermal energy consumption in dry process	Endogenous
	TERDP	Thermal energy requirement in dry process	Endogenous
	CPCU	Clinker production capacity utilization	Endogenous
	CPDP	Cement production in dry process	Endogenous
	CRDP	Clinker requirement in dry process	Endogenous
	POPC	Proportion of ordinary Portland cement in cement production	Exogenous
	PPPC	Proportion of Portland Pozzolana cement in cement production	Exogenous
	PPSC	Proportion of Portland slag cement in cement production	Exogenous
	DPCPC	Dry process clinker production capacity	Endogenous
	OPTES	Oil proportion in thermal energy supply	Exogenous
	GCTGE	Gas consumption to generate electricity	Endogenous
	GCPKWH	Gas consumption per kW h	Exogenous
	PGIEG	Proportion of gas in electricity generation	Exogenous
	TEC	Total electricity consumption	Endogenous
	TCO_2E	Total CO_2 emission	Endogenous
CO2 emission module			
	CO_2ETGE	CO_2 emission to generate electricity	Endogenous
	CO_2EFCP	CO2 emission from clinker production	Endogenous
	CO_2EFFC	CO_2 emission from fuel consumption	Endogenous

increases by growth in gross domestic product (GDP) per capita.

$$CD = PCCD \times P \tag{1}$$

2.3. Modeling production capacity

The proposed SD model includes three kinds of production technologies: dry process, wet process and semi-dry process. As mentioned before, dry process is the main technology used in Iran which accounts for 97% of total production. The production capacity module contains two stock variables for each technology: under construction capacity stock and existing production capacity stock as shown for dry process in Fig. 2. The under construction capacity is converted to capacity stock over time modeled by delay functions (see Eqs. (2) and (3)). The new capacity order rate for each production technology is determined by the share of that technology in the new capacity expansion plan (see Eq. (4)). Producers, being aware of the construction delay, make their decisions about capacity expansion based on the expected demand in future.

$$DPPC = INTEGRAL(DPCCR - DPCDR, DPPC(t_0)) \tag{2}$$

$$DPCCR = DELAY(DPNCOR, DPCD) \tag{3}$$

$$DPNCOR = NCO \times SODP \tag{4}$$

$$DPC = FOCD \times DSIDS + DE \tag{5}$$

$$FOCD = PPC \times e^{\wedge}(PT \times ECD) \times (1 + PT \times TTPPC) \tag{6}$$

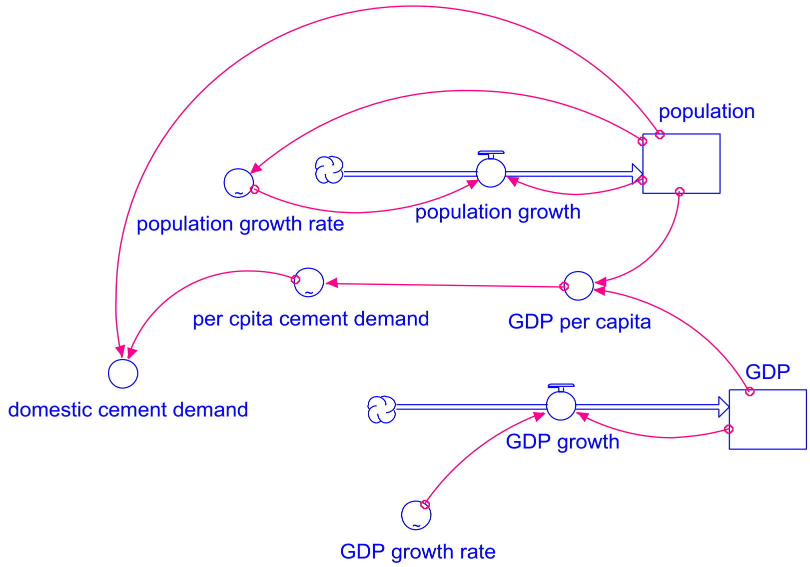

Fig. 1. The stock and flow diagram for cement demand.

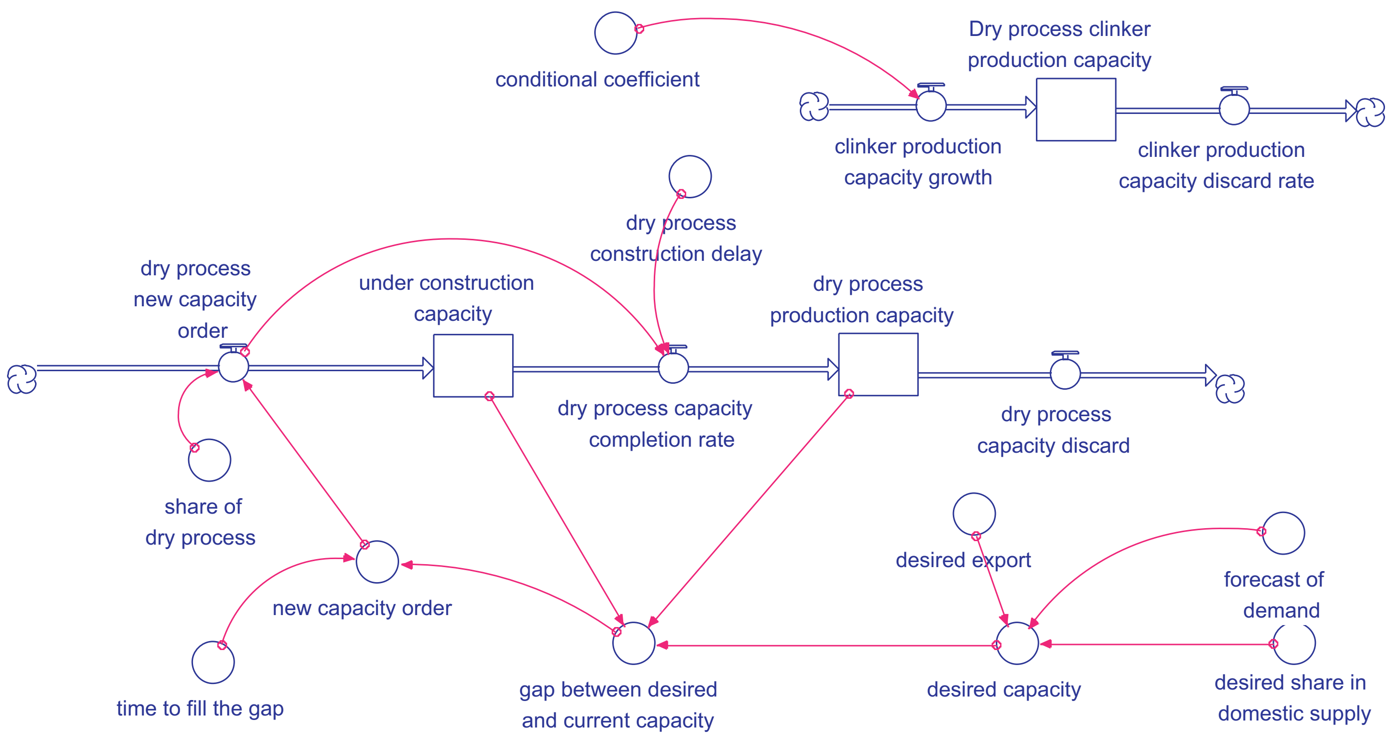

Fig. 2. The stock and flow diagram for cement production capacity.

It is a common practice in SD modeling to use a trend function for formalizing human expectation (Sterman, 2000). We have used a trend function for forecasting cement demand in future as shown in Fig. 3.

The desired production capacity for the cement industry depends on a forecast of domestic demand, desired share of domestic production to the total demand and desired amount of export (see Eqs. (5) and (6)). Desired share of domestic supply and desired export are determined exogenously in the model under various scenarios explained in Table 6. The cement price, import and export tariffs are under government control. The future trend of production capacity expansion in the cement industry depends on the government policy in supporting the industry development. The proposed model seeks to fill the gap between the desired and actual production capacity over time as shown in Fig. 2. The actual production depends on production capacity and capacity utilization. The clinker production capacity growth depends on the policy on mix of products. The proportions of different kinds of cement (OPC, PPC and PSC) in production are determined exogenously in model under various scenarios explained in Table 7. When blended cement proportion increases, less clinker production capacity expansion would be needed.

2.4. Modeling the energy consumption

2.4.1. Direct energy consumption

Energy requirement is divided to thermal energy and electricity and is determined by energy efficiency. Energy efficiency is a

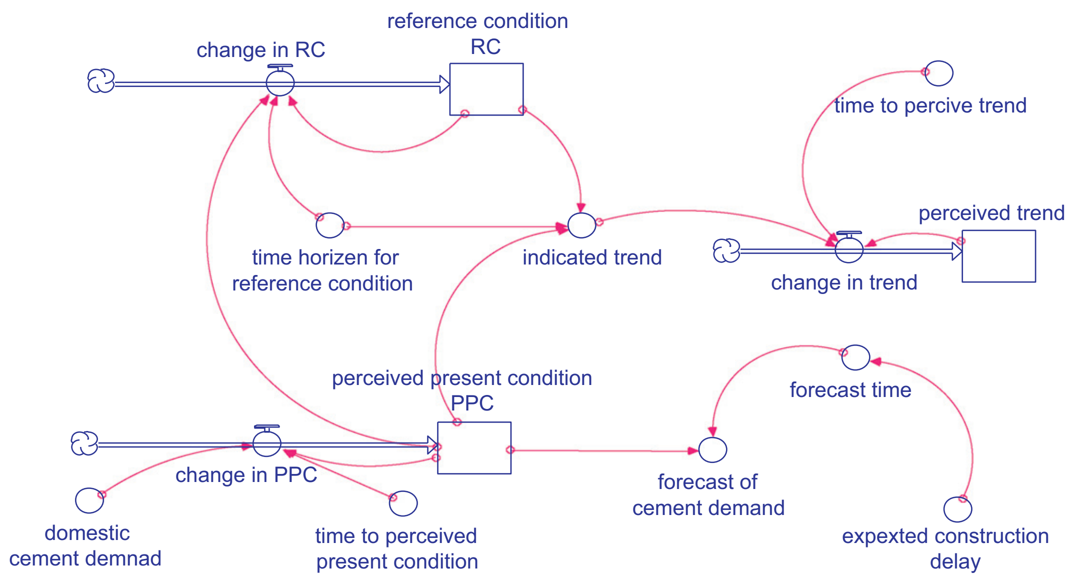

Fig. 3. The stock and flow diagram for cement demand forecasting.

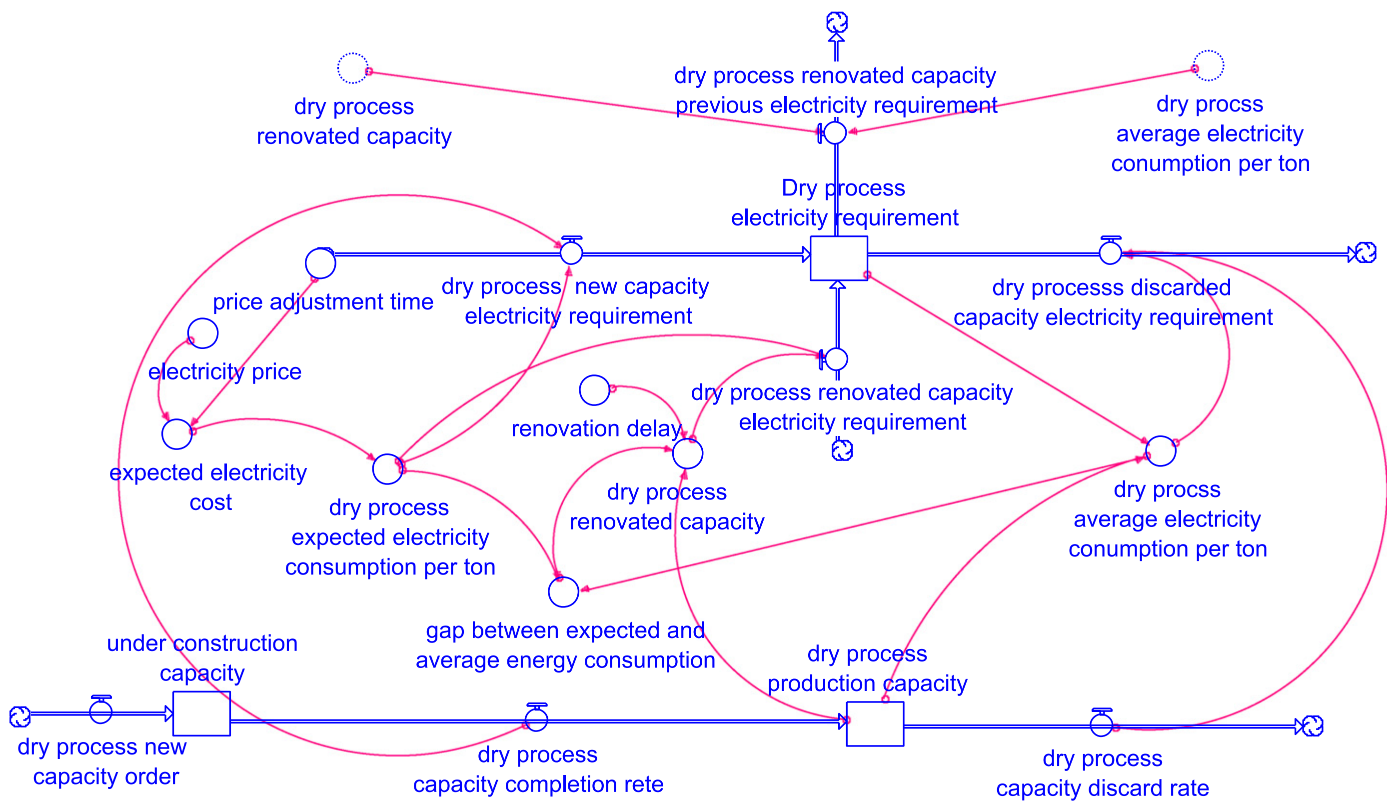

Fig. 4. The stock and flow diagram for electricity requirement.

key feature of the installed capacity using each kind of technology. To model energy consumption, we need to keep track of the energy requirement for every unit of capacity added or discarded. Co-flow structures are used herein to keep track of energy requirement following capacity expansion variables (See Eqs. (7) to (14)). The stock and flow diagram for electricity requirement is shown in Fig. 4. Energy price is the key determinant factor on the expected energy consumption per ton of production. Energy price in Iran before subsidy reform was so low in comparison to other countries and thus consumer sensitivity to energy price was low (Wuppertal Institute, 2010). After implementing subsidy reform, it is expected that energy price would be going to reach to the average price in the world. We assume that the same trend would be followed by energy consumption. We have benchmarked cement producer behavior in response to energy price by collecting data on energy price and energy consumption per ton of cement production in several regions of world (Avami and Sattari (2007); CSTEP, 2008; IEA, 2010; IFCO, 2011; Iran Energy Balance Sheet, 2008; STEMSON, 2009; Worrel et al., 2008). As a result, we have built a table function as shown in Eq. (14) which defines the relationship between electricity price and the expected electricity consumption. Similar equation has been used for thermal energy consumption for clinker production.

Average energy consumption per ton of production represents the current energy consumption of the installed capacity (see Eq. (12)). When energy price rises, the expected level of energy consumption will become less than current values and thus investment in energy efficient technology would become profitable. In addition to new capacity construction, higher energy prices would encourage producers to renovate current machineries to fill the gap between the expected energy and current energy consumption (see Eq. (8)–(11)). As shown in Fig. 4, every time a new unit of capacity is added to capacity stock, the total electricity requirement for operating full capacity is increased by the expected electricity consumption per ton (see Eqs. (7) and (8)) and vice versa (see Eqs. (7) and (9)). Similar equations have been used in the model for thermal energy requirement for clinker production which are not shown here for brevity.

$$\mathrm{DPER} = \mathrm{INTEGRAL}(\mathrm{DPNCER} - \mathrm{DPDCER} + \mathrm{DPRCER} - \mathrm{DPRCPER}) \tag{7}$$

$$\mathrm{DPNCER} = \mathrm{DPEECPT} \times \mathrm{DPCCR} \tag{8}$$

$$\mathrm{DPDCER} = \mathrm{DPAECPT} \times \mathrm{DPCDR} \tag{9}$$

$$\mathrm{DPRCER} = \mathrm{DPRC} \times \mathrm{DPEECPT} \tag{10}$$

$$\mathrm{DPRCPER} = \mathrm{DPRC} \times \mathrm{DPAECPT} \tag{11}$$

$$\mathrm{DPAECPT} = \mathrm{DPER}/\mathrm{DPPC} \tag{12}$$

$$\mathrm{EEC}(\$) = \mathrm{SMTH}(\mathrm{EP}, \mathrm{PAT}) \tag{13}$$

$$\mathrm{DPEECPT}(\mathrm{kWh/ton}) = \mathrm{GRAPH}(\mathrm{EEC})(0.0175,112),(0.07,100),(0.087,95),(0.1,93),(0.12,88) \tag{14}$$

Energy requirement stocks account for energy demand in full capacity utilization using each technology. To calculate the actual energy consumption, energy requirement estimated by this co-flow structure is multiplied by capacity utilization coefficient as shown in Eqs. (15)–(17)) for thermal energy consumption. As mentioned before the proportions of different kinds of cement (OPC, PPC and PSC) in production are determined exogenously, when blended cement proportion increases, less clinker production would be needed (see Eq. (16)).

The amount of natural gas consumption by each technology is determined by the actual thermal energy produced from natural gas as shown in Fig. 5 for dry process (see Eqs. (18) and (19)). Natural gas proportion in thermal energy supply (GPTES) is

Table 3
Natrual gas proportion in thermal energy supply (Management Gas Distribution, 2010).

Milestone year	Natural gas proportion in thermal energy supply (%)	Milestone year	Natural gas proportion in thermal energy supply (%)
2000	29	2016	91
2001	33	2017	91.5
2002	35	2018	92.5
2003	40	2019	93
2004	46	2020	93.5
2005	56	2021	94.5
2006	64	2022	96
2007	70	2023	96
2008	73	2024	97
2009	77	2025	97
2010	80	2026	98
2011	82	2027	98
2012	84.5	2028	98
2013	87.50	2029	98
2014	89.50	2030	98
2015	91		

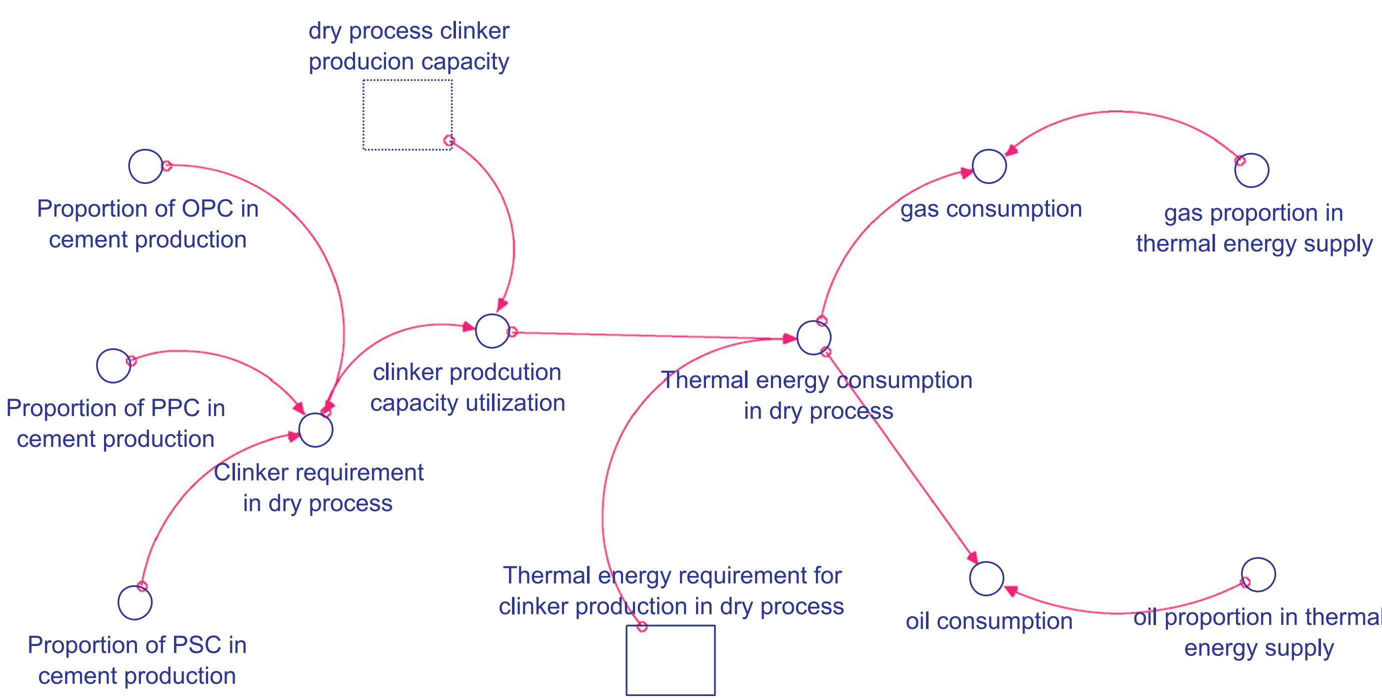

Fig. 5. The stock and flow diagram for natural gas and fuel oil consumption.

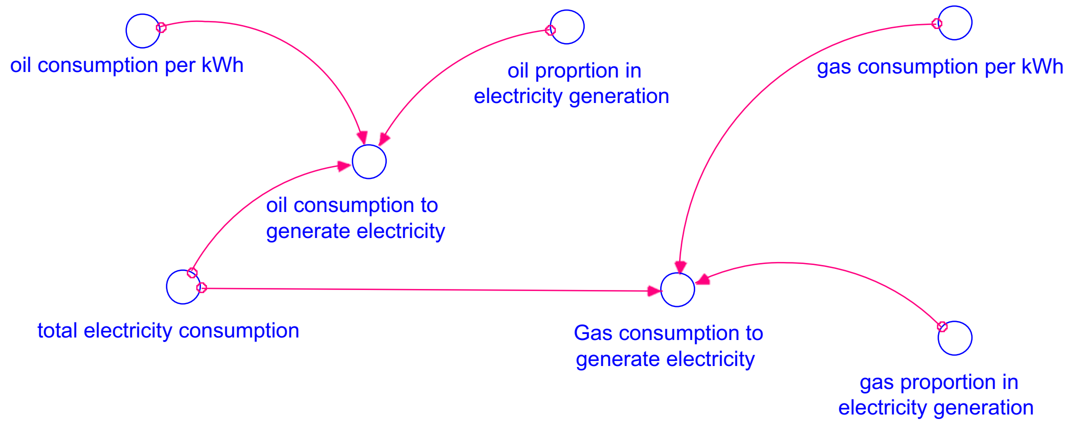

Fig. 6. The stock and flow diagram for indirect energy consumption for electricity generation.

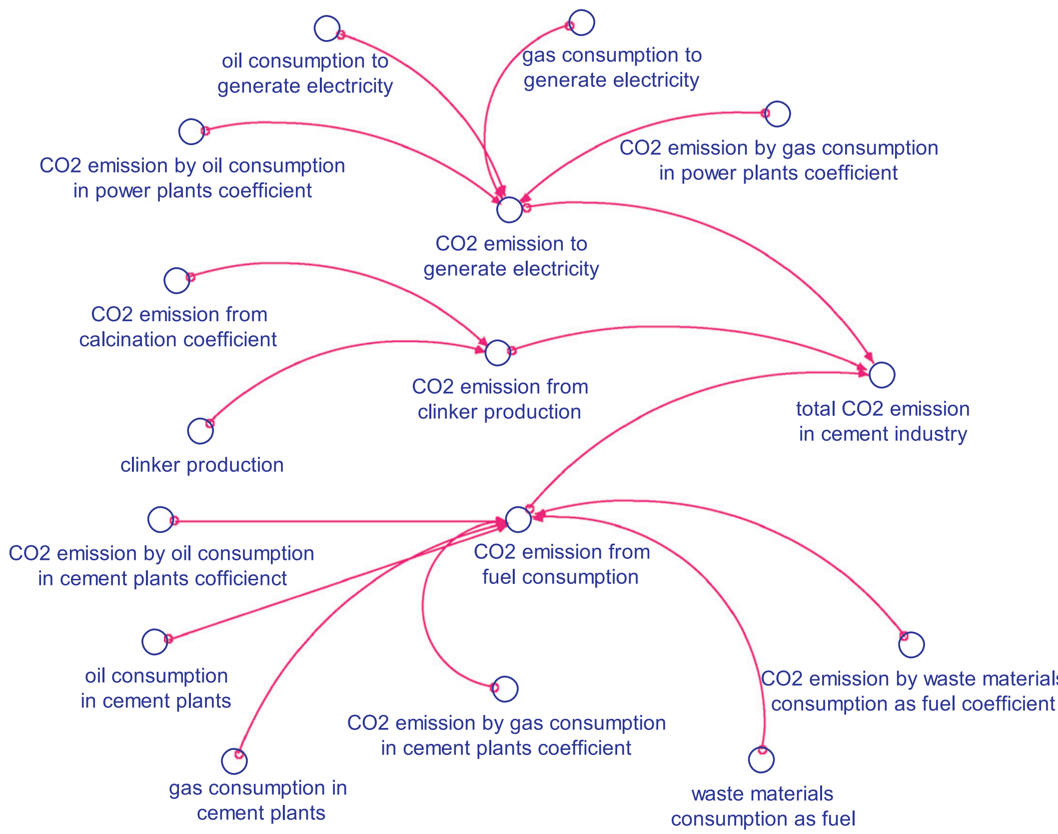

Fig. 7. The stock and flow diagram for CO_2 emission.

Table 4
The values of input parameters used for model validation (Ministry of Energy, 2010; Iranian Cement Association, 2011).

Milestone year	GDP growth rate (%)	Natural gas share in thermal energy supply (%)	Fuel oil price (Rial/L)	Natural gas price (Rial/m^3)	Electricity price (Rial/kW h)	Mix of production (%)	Desired share in domestic supply of cement demand
2000	5	29	100	100	130		
2001	3.30	33	110	100	134		
2002	2	35	115	100	147		
2003	2	40	122	110	163		
2004	2	46	131	115	185		
2005	7	56	130	140	140	OPC=95 PSC=2 PPC=3	100%
2006	7	64	130	140	139		
2007	5	70	130	140	139		
2008	1	73	140	140	160		
2009	3	77	150	160	159		
2010	6	80	165	160	210		

Table 5
Simulated data versus historical data.

	Cement demand			Cement production			Gas consumption		
Milestone year	Real data (thousand ton)	Simulated data (thousand ton)	% Error (%) *	Real data (thousand ton)	Simulated data (thousand ton)	% Error (%)	Real data (thousand cubic meters)	Simulated data (thousand cubic meters)	% Error (%)
2000	22,370	21,773	2.67	23,967	23,195	3.22	675,000,	675,000	0.00
2001	22,500	23,092	2.63	26,640	25,746	3.36	821,000	804,580	2.00
2002	27,600	23,849	13.59	28,600	29,267	2.33	994,000	994,000	0.00
2003	29,700	26,064	12.24	30,500	32,250	5.74	1227,000	1202,460	2.00
2004	30,500	29,227	4.17	32,000	34,470	7.72	1354,958	1505,000	11.07
2005	31,000	32,044	3.37	32,500	36,322	11.76	1832,901	1927,000	5.13
2006	35,300	36,161	2.44	35,300	39,094	10.75	1833,763	2358,000	28.59
2007	40,200	40,777	1.44	40,000	41,314	3.29	2331,471	2694,000	15.55
2008	44,000	43,364	1.45	44,400	44,606	0.46	3165,650	3264,000	3.11
2009	46,100	46,060	0.09	52,100	48,497	6.92	3791,880	3511,000	7.41
2010	52,000	49,454	4.90	58,000	53,010	8.60	4291,920	3974,000	7.41

* Error = absolute value of (((simulated data/real data) − 1) × 100).

Table 6
Cement production scenarios.

	Desired share in domestic supply of cement demand	GDP growth rate		Desired export
Production scenarios	2011–2030	2011–2012	2011–2030	2011–2030
Low production	70%	1.5%	3.5%	0
Base production	100%	4.5%	4.5%	15 million tons
High production	100%	4.5%	7%	50 million tons

determined exogenously in model as shown in Table 3.

$$TECDP = TERDP \times CPCU \tag{15}$$

$$CPCU = CRDP/DPCPC \tag{16}$$

$$CRDP = (POPC \times 0.955 + PPPC \times 0.65 + PPSC \times 0.30) \times CPDP \tag{17}$$

$$GC = GPTES \times TECDP/37.26 \tag{18}$$

$$OC = OPTES \times TECDP/6.119 \tag{19}$$

2.4.2. Indirect energy consumption

The proportion of natural gas to the net electricity supply in the country is more than 80% (Iran Energy Balance Sheet, 2008). The stock and flow diagram for indirect energy consumption for electricity generation is shown in Fig. 6. Natural gas and fuel oil consumption for generating electricity needs of the cement industry depends on the electricity consumption of cement industry and the proportion of natural gas and fuel oil used for electricity generation as shown in Eq. (20).

$$GCTGE = GCPKWH \times PGIEG \times TEC \tag{20}$$

2.4.3. Modeling CO_2 emission

The CO_2 emission of the cement industry is estimated as the sum of CO_2 emission from fuel consumption, from calcination for clinker production and from electricity generation (sees Eq. (21)). The CO_2 emission from fuel consumption depends on the type and amount of the fuel used. The stock and flow diagram for CO_2 emission is shown in Fig. 7.

$$TCO_2E = CO_2EFFC + CO_2EFCP + CO_2ETGE \tag{21}$$

3. Model validation

The proposed SD model explained in the previous section has been simulated using Ithink ®7.0.2 software. Ithink is a modeling tool commonly used to build, simulate and analyze system dynamics models. It provides a flexible way of building simulation models based on causal loops or stock and flow diagrams. For the historical validation, we have chosen demand, production and natural gas consumption in the cement industry. The input parameters for historical validation are shown in Table 4. The simulation results show good conformity with historical trends as shown in Table 5.

4. Production and energy efficiency scenarios

In this section, we introduce three production scenarios that are considered as possible trends of cement production in the future. Then, we relate these production scenarios to energy efficiency scenarios resulting from the industry renovation plans and corrective policies.

4.1. Production scenarios

The three production scenarios, shown in Table 6, are described below:

Low production scenario: Planning for capacity expansion is based on supplying 70% of the domestic demand. This scenario is considered due to the fact that the subsidy reform will increase production cost which hinders previous capacity expansion plans. The GDP growth rate is pessimistically estimated to be 1.5 % for 2011 and 2012[2] and assumed to be 3.5% beyond 2013.

[2] No official data on GDP growth was available for 2011 and 2012 at the time of this study.

Table 7
Energy efficiency scenarios.

Energy efficiency scenarios	Milestone year	Energy price (Rial)			Mix of production			Share of waste materials in thermal energy supply	Percentage of electricity supply from wasted heat recovery
		Fuel oil price (Rial/L)	Natural gas price (Rial/m^3)	Electricity price (Rial/kW h)	OPC (%)	PPC (%)	PSC (%)		
Base energy efficiency	2011	160	165	210	95	3	2	0	0
	2012	160	165	210					
	2013	160	165	210					
	2014	160	165	210					
	2015	160	165	210					
	2016	160	165	210					
	2017	160	165	210					
	2018	160	165	210					
	2019	160	165	210					
	2020	160	165	210					
	2021	160	165	210					
	2022	160	165	210					
	2023	160	165	210					
	2024	160	165	210					
	2025	160	165	210					
	2026	160	165	210					
	2027	160	165	210					
	2028	160	165	210					
	2029	160	165	210					
	2030	160	165	210					
Moderate energy efficiency	2011	700	1000	400	95	3	2	0	0
	2012	795	1145	640					
	2013	918	1322	760					
	2014	1222	1758	950					
	2015	1246	1794	1150					
	2016	1361	1959	1400					
	2017	1476	2124	1700					
	2018	1640	2360	1900					
	2019	1640	2360	1900					
	2020	1640	2360	1900					
	2021	1640	2360	1900					
	2022	1640	2360	1900					
	2023	1640	2360	1900					
	2024	1640	2360	1900					
	2025	1640	2360	1900					
	2026	1640	2360	1900					
	2027	1640	2360	1900					
	2028	1640	2360	1900					
	2029	1640	2360	1900					
	2030	1640	2360	1900					
High energy efficiency	2011	700	1000	400	95	3	2	20%	20%
	2012	795	1145	640	93	4.50	2.50		
	2013	918	1322	760	91	6	3		
	2014	1222	1758	950	89	7.50	3.50		
	2015	1246	1794	1150	87	9	4		
	2016	1361	1959	1400	85	10.50	4.50		
	2017	1476	2124	1700	83	12	5		
	2018	1640	2360	1900	81	13.50	5.50		
	2019	1640	2360	1900	79	15	6		
	2020	1640	2360	1900	77	16.50	6.50		
	2021	1640	2360	1900	75	18	7		
	2022	1640	2360	1900	73	19.50	7.50		
	2023	1640	2360	1900	71	21	8		
	2024	1640	2360	1900	69	22.50	8.50		
	2025	1640	2360	1900	67	24	9		
	2026	1640	2360	1900	65	25.50	9.50		
	2027	1640	2360	1900	63	27	10		
	2028	1640	2360	1900	61	28.50	10.50		
	2029	1640	2360	1900	59	30	11		
	2030	1640	2360	1900	57	31.50	11.50		

Base production scenario: This scenario is the continuation of existing condition which aims at expanding manufacturing capacity to fully supply the country's demand and 15 million ton cement export per year. GDP growth rate is assumed to be 4.5% based on average GDP growth rate reported from 2006 to 2010 (Iran Energy Balance Sheet, 2008).

High production scenario: It is optimistically assumed that the GDP growth will be 7% so that the capacity expansion will be based on satisfying domestic demand and extra 50 million tons per year for export.

4.2. Energy efficiency scenarios

These scenarios include combinations of possible projections in energy price, mix of production (shares of PPC, PSC and OPC in cement production), the thermal energy generated from waste materials and the share of wasted heat recovery in electricity generation. All of these quantities are model input parameters that are somehow related to energy efficiency. It is assumed that in all three scenarios the production capacity expansion is based on dry process technology. Three energy efficiency scenarios, as shown in Table 7, are described below.

Base energy efficiency scenario: this scenario is the continuation of low energy efficiency that has been inherited from low energy prices in the past and serves as a basis for comparison with other scenarios.

Moderate energy efficiency scenario: Energy prices have suddenly jumped in 2011 due to a major subsidy reform policy (International Monetary Fund, 2011). As mentioned before, energy price is the key determinant factor for the expected energy consumption. In a low energy price scenario, there is not enough motivation to improve energy efficiency. Under the new subsidy regime, energy prices are expected to increase to reach world energy prices in 2016. As a result, the expected energy consumption per ton is determined by Eq. (14). The current average energy consumption is 840 kcal/kg of clinker and 112 kW h/ton of cement in the country while the standard level of energy consumption is 730 kcal/kg of clinker and 88 kW h/ton of cement (IFCO, 2011).

It is assumed in this scenario that the mix of cement production is the same as current situation similar to the base model. Furthermore, natural gas and fuel oil proportions in thermal energy and electricity supply will follow the same trend as in Scenario 1.

High energy efficiency scenario: The same trend of improvement in energy efficiency is expected to take place as in Scenario 2. In addition, higher efficiency is gained by using waste materials as fuel in cement production, producing more blended cement, and wasted heat recovery for electricity generation. It is further assumed in this scenario that the proportion of OPC decrease from 95% to 57%, proportion of PPC increase from 3% to 31% and proportion of PSC increase from 2% to 12% as shown in Table 7.

Countries around the world are adapting the practice of using waste materials as alternative fuel in cement manufacturing. Industrialized countries succeed to derive 20% to 70% of their energy needs from alternative fuels in cement plants (Murry and Price, 2008).

It is assumed that 20% of thermal energy consumption in Iranian cement industry could be supplied by waste materials in this scenario. Due to high thermal energy consumption in cement industry, it is possible to produce electricity by wasted heat recovery (WHR), it is assumed that 20% of electricity demand in cement industry is supplied by WHR in this scenario.

5. Computational results and discussion

The proposed model has been run under every possible combination of production and energy efficiency scenarios using

Table 8
Cement production and demand under different scenarios (thousand tons).

Production scenarios		2015	2020	2025	2030
Low production and import	Production	64,853	64,853	64,853	64,853
	Demand	59,027	70,724	81,423	90,448
Base production and domestic Supply	Production	74,711	88,996	100,318	110,292
	Demand	64,780	78,100	89,536	101,000
High production and export	Production	81,741	118,181	142,883	155,409
	Demand	76,461	85,594	98,000	103,000

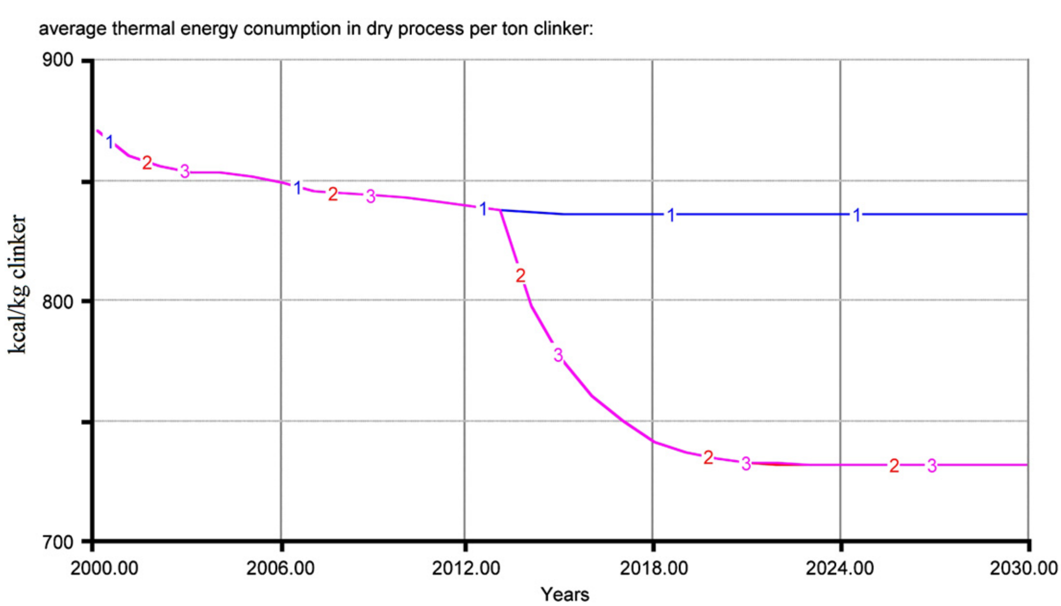

Fig. 8. The average thermal energy consumption in dry process (kcal/kg clinker) 1-base 2-moderate and 3-high energy efficiency scenario.

Ithink ®7.0.2. The results of cement production and demand under different production scenarios are shown in Table 8.

In low production scenario, cement production will be freezed from 2015 to 2030 due to no motivation for capacity expansion as shown in Table 8. Under base and high production scenario, cement production will reach to 110 and 155 million tons and domestic demand will reach to 100 and 103 million tons in 2030, respectively.

The results of implementing three energy efficiency scenarios under base production and domestic supply scenario are shown in Figs. 8 to 14. Lines 1, 2 and 3, respectively, represent the results of base, moderate and high energy efficiency scenarios. Figs. 8 and 9 show average thermal energy consumption per ton of clinker and average electricity consumption per ton of cement production in dry process. It is seen in Figs. 8 and 9 that under base scenario, a huge gap exists between the existing country's trend and world standard energy consumption in the cement industry. However, under moderate and high energy efficiency scenarios, energy consumption per ton of production will reach to the world standard level. Similar trends in energy consumption have been observed using other production technology that is not reported herein for the sake of conciseness.

As Fig. 10 shows thermal energy consumption will reach respectively to 366, 320, 268 million giga joules in base, moderate and high energy efficiency scenarios under base production scenario by 2030. As shown in Figs. 8 and 9, energy consumption per ton of production in high and moderate energy efficiency scenarios have the same trend but due to blended cement production and less clinker production, less thermal energy consumption would be needed under high energy efficiency scenario in comparison to that of the other scenario as shown in Fig. 10. It is shown in Fig. 11 that 9.6, 8.4 and 5.6 billion cubic meters of natural gas will be consumed, under base, moderate and high energy efficiency scenarios, respectively, to supply the amount of thermal energy

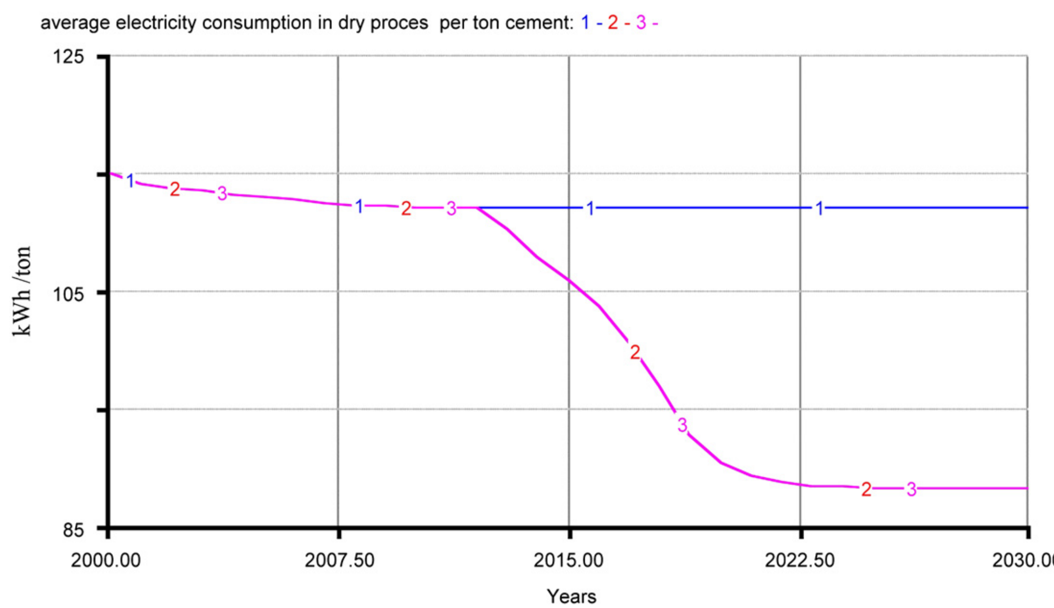

Fig. 9. The average electricity consumption per ton (kW h/ton) 1-base 2-moderate and 3-high energy efficiency scenario.

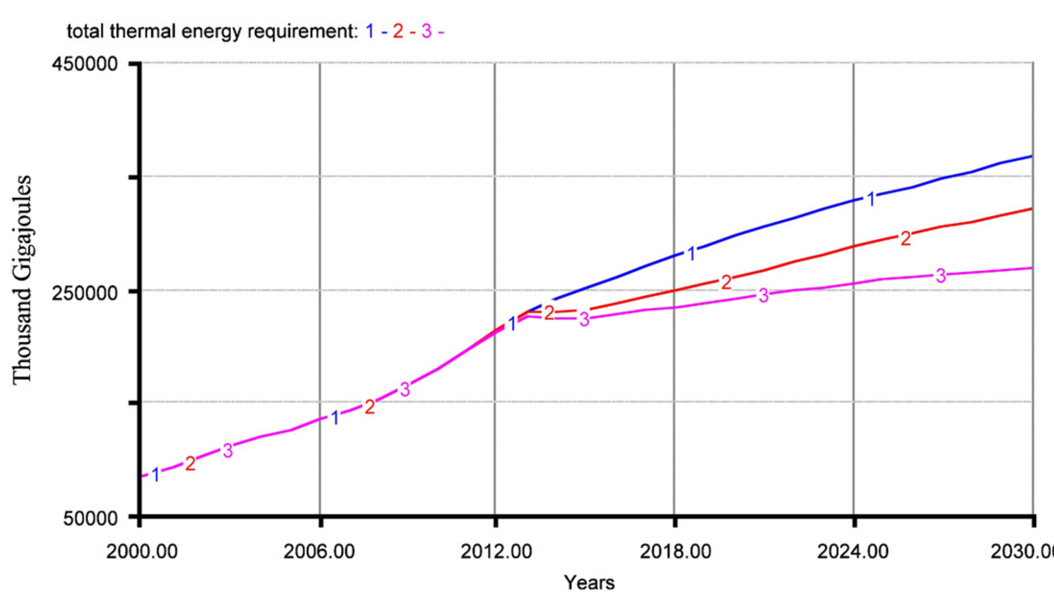

Fig. 10. Total thermal energy consumption (thousand gigajoules) 1-base 2-moderate and 3-high energy efficiency scenario.

consumption shown in Fig. 10. We observe that, under a high energy efficiency scenario, less natural gas and fuel oil would be needed to supply thermal energy in comparison to those under moderate energy efficiency scenario due to blended cement production (less clinker production) and using waste materials.

Fuel oil consumption is not reported herein for brevity. Fuel oil consumption in cement industry decreases rapidly and reaches to a small amount because the government policy is to substitute oil by natural gas in the domestic consumption.

As Fig. 12 shows, electricity consumption will reach to 12357, 9726 and 9726 million kilowatt hours in base, moderate and high energy efficiency scenarios under base production and domestic supply scenario by 2030. As Fig. 13 shows, if the current trend of gas turbine electricity generation continues, to supply such electricity demand, the indirect natural gas consumption will reach respectively to 3.84, 3, 2.4 billion cubic meters under base, moderate and high energy efficiency scenarios.

As Fig. 14 shows, total CO_2 emission would reach to 87 million tons in base scenario, 83 million tons in moderate scenario and 69 million tons in high energy efficiency scenario, under base production scenario by 2030.

Table 9 shows direct natural gas, fuel oil and electricity consumptions required for total cement production reported in Table 8 under various scenarios. The results show that there is a considerable difference between energy consumption under base and moderate energy efficiency scenarios which could be thought of as a direct impact of subsidy reform. Cumulative natural gas consumption gives more obvious figures of potential energy saving among various scenarios during simulation. Table 10 represents cumulative direct natural gas consumption from 2000 to 2030 under different scenarios. Looking at the base production scenario for example, it is seen that natural gas consumption under moderate energy efficiency scenario is 15 billion cubic meters less than that of base energy efficiency scenario by 2030. This deference will reach up to 46 billion cubic meters under high energy efficiency scenario.

As Table 11 shows, under base production and domestic supply the indirect natural gas consumption in moderate energy efficiency scenario is 10 billion cubic meters less than that of base energy efficiency scenario due to a reduction in electricity consumption after subsidy reform. This difference will reach to 17 billion cubic meters in high energy efficiency scenario.

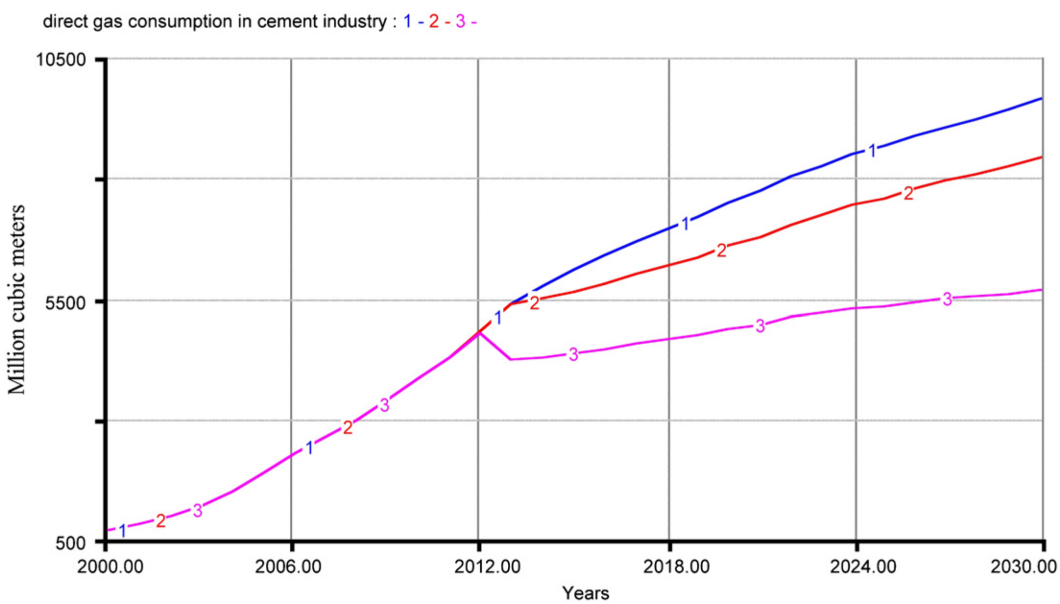

Fig. 11. Total natural gas consumption in the production process (million cubic meters) 1-base 2-moderate and 3-high energy efficiency scenario.

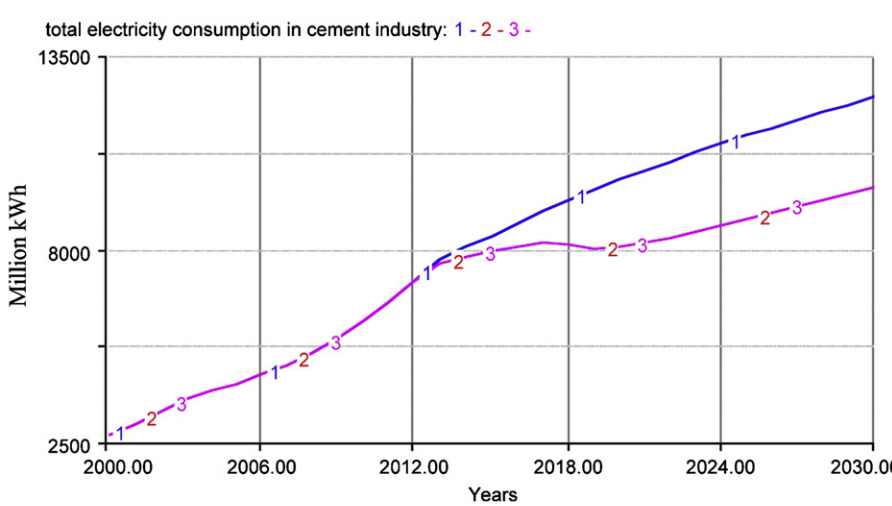

Fig. 12. Total electricity consumption in cement production process (million kW h) 1-base 2-moderate and 3-high energy efficiency scenario.

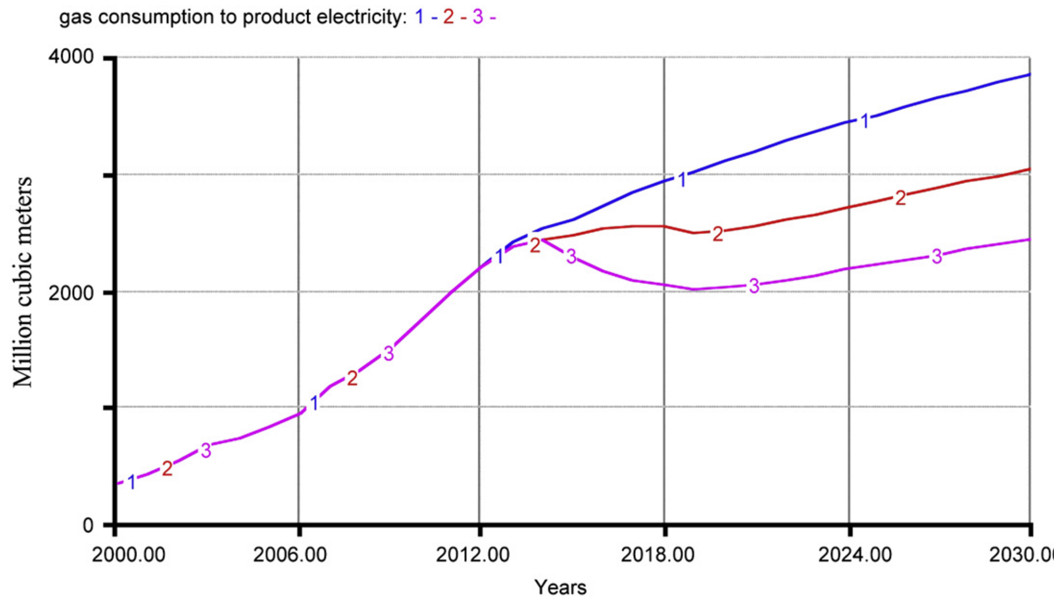

Fig. 13. Natural gas consumption to produce electricity (million cubic meters) 1-base 2-moderate and 3-high energy efficiency scenario.

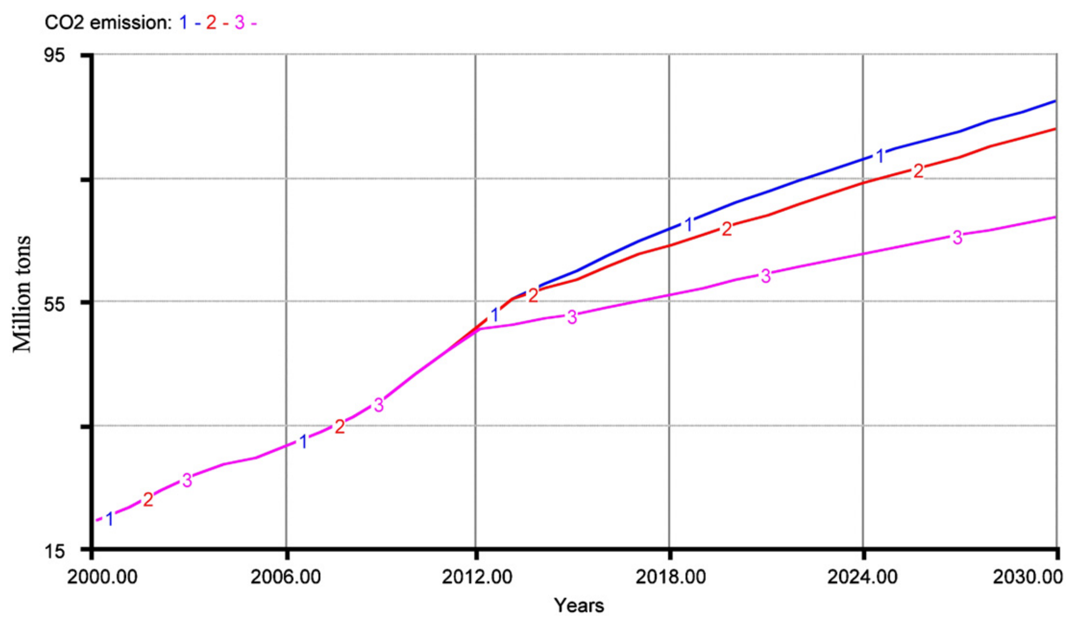

Fig. 14. total CO2 emission from cement production (million tons) 1-base 2-moderate and 3-high energy efficiency scenario.

Total CO_2 emission for cement production is shown in Table 12. Cumulative CO_2 emission under base production and domestic supply in moderate energy efficiency scenarios is 52 million ton less than base energy efficiency scenario. This deference reaches to 213 million ton in advanced energy efficiency scenario mainly because of a reduction in clinker production.

6. Conclusions

A system dynamics model is presented herein to analyze energy consumption and CO_2 emission in Iranian cement industry after implementing a subsidy reform policy. Natural gas, fuel oil and electricity consumed in the cement industry have been projected under various production and export scenarios while taking into account new energy price regime. The model includes feedback loop structures for demand, production and investment in capacity expansion. It also contains a co-flow structure to capture the consumers' behavior in the cement industry in reaction to energy price.

Direct and indirect natural gas consumptions have been simulated under various cement production and energy efficiency scenarios. Our computational results show that in the short run, the subsidy reform could lead to 7% reduction in direct natural gas usage and 5% reduction in electricity consumption due to a mild improvement in energy efficiency gained by higher energy price. In the long run, potential saving are more than 13% in direct natural gas and 21% in electricity consumption resulting from deploying a full suite of energy saving plan and equipment renovation. It is possible to further reduce the natural gas consumption by 29% under high energy efficiency scenario using blended cement production and waste material as an alternative fuel in the cement industry.

Table 9
Direct natural gas, electricity and fuel oil consumption in cement industry.

		Base energy efficiency scenario			Moderate energy efficiency scenario			High energy efficiency scenario		
		Fuel oil (thousand barrels)	Natural gas (million cubic meters)	Electricity (million kW h)	Fuel oil (thousand barrel)	Natural gas (million cubic meters)	Electricity (million kW h)	Fuel oil (thousand barrel)	Natural gas (million cubic meters)	Electricity (million kW h)
Low production and import	2015	3177	5276	7267	2950	4899	6875	2279	3784	6875
	2020	1941	5476	7267	1705	4811	5880	1258	3551	5880
	2025	1059	5621	7267	926	4919	5732	652	3461	5732
	2030	706	5679	7267	611	4969	5727	413	3325	5727
Base production and domestic supply	2015	3657	6073	8371	3389	5627	7908	2619	4349	7908
	2020	2659	7502	9971	2334	6586	8046	1723	4861	8046
	2025	1634	8676	11240	1429	7590	8854	1006	5340	8854
	2030	1197	9634	12357	1047	8426	9726	701	5639	9726
High production and export	2015	3999	6641	9159	3697	6139	8638	2859	4747	8638
	2020	3497	9868	13128	3068	8658	10570	2265	6391	10570
	2025	2325	12343	16007	2033	10795	12601	1430	7596	12601
	2030	1685	13560	17410	1474	11858	13696	976	7935	13696

Table10
Cumulative direct natural gas consumption in cement production during 2000 to 2030 (billion cubic meters).

	Base energy efficiency scenario	Moderate energy efficiency scenario	High energy efficiency scenario
Low production and export	124	114	92
Base production and domestic supply	161	146	115
High production and export	202	183	141

Table 11
Cumulative indirect natural gas consumption to generate electricity needed for cement production during 2000 to 2030 (billion cubic meters).

	Base energy efficiency scenario	Moderate energy efficiency scenario	High energy efficiency scenario
Low production and export	53	47	41
Base production and domestic supply	68	58	51
High production and export	85	72	62

Table 12
Cumulative CO_2 emission for cement production during 2000 to 2030 (million tons).

	Base energy efficiency scenario	Moderate energy efficiency scenario	High energy efficiency scenario
Low production and export	1307	1272	1195
Base production and domestic supply	1646	1594	1433
High production and xport	2027	1956	1699

Indirect natural gas consumption could be reduced by 21% due to saving in electricity usage in the long term. This reduction could amount to 37% by producing 20% of the required electricity from wasted heat recovery. In a moderate energy efficiency scenario, CO_2 emission could be cut by 5% in the long run due to saving in thermal energy and electricity consumptions. These reductions could amount to 22% under high energy efficiency scenario mainly due to producing more blended cement and less clinker production.

Our simulation results show that under the base production scenario, a total of 110 million tons of cement could be produced by 2030 comparing to the current production of 58 million tons. Consequently, total direct and indirect natural gas consumption in the cement industry under moderate energy efficiency scenario, which is the most probable scenario after subsidy reform, could reach to 8.5 billion cubic meters. That is about 6.5% of the total natural gas currently consumed per year in the country. The CO_2 emission could reach to 83 million tons which is 16% of the total CO_2 emission per year produced in the country. Other socio-economical factors may be included in the model in future studies.

This study recommends that some encouraging policy should be put in place for blended cement production as well as for using waste material as alternative fuel and wasted heat recovery for electricity generation. The projected gas consumption under the most probable scenario could also be used by natural gas provider as a basis for the future industry demand.

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