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A system dynamics analysis of energy consumption and corrective policies in Iranian iron and steel industry

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ABSTRACT

Iron and steel industry is the most energy intensive industrial sector in Iran. Long time subsidized energy has led to low energy efficiency in this industry. The sudden subsidy reform of energy prices in Iran is expected to have a great impact on steel production and energy consumption. A system dynamics model is presented in this paper to analyze steel demand, production and energy consumption in an integrated framework. A co-flow structure is used to show how subsidy reform affects energy consumption in the long run. The main focus of this paper is on direct and indirect natural gas consumption in the steel industry. Scrap based Electric Arc Furnace technology has been evaluated as an energy efficient way for steel making. The energy consumption in steel industry is estimated under various steel production and export scenarios while taking into account new energy prices to see the outlook of possible energy demand in steel industry over next 20 years. For example it is shown that under reference production scenario, potential reduction in gas consumption forced by complete removal of energy subsidy and utilizing scrap could lead to 85 billion cubic meters of gas saving over the next 20 years.

1. Introduction

Iron and steel industries are the most energy intensive industry in Iran taking 18% of total energy consumption, 28% of gas consumption and the source of 10% of CO_2 emission in the industrial sector [1,2]. Natural gas and electricity are main energy carriers in this industry and due to high proportion of gas in electricity generation, steel production increases gas consumption from this channel too. Long time subsidized energy has led to low energy efficiency in this industry [1,3]. The sudden subsidy reform of energy prices in December 2010 is expected to have a great impact on steel production and energy consumption. This essential structural change will make future trend of energy consumption different from past in this industry.

Our motivation for this research is to study the impact of the subsidy removal policy on energy consumption in steel industry under various steel production and export scenarios and the government supporting policies on capacity expansion in the next 20 years. Higher energy prices force the industry to consider technology change in the long run. Currently two kinds of technology are used for steel production in the country, namely, blast furnace (BF) and electric arc furnace (EAF). The dominant technology used in Iran is EAF using sponge iron produced by a direct reduction process [4]. This production process is the main consumer of natural gas in steel manufacturing. Considerable energy saving can be achieved using an alternative technology, called scrap based EAF, which does not require the energy intensive iron ore reduction process [5]. It is intended in this study to evaluate the potential energy saving resulting from utilizing scrap based EAF technology over the next 20 years. In this paper, we present a system dynamics model to study energy demand dynamics and consumers' behavior in iron and steel industry over the long run. The model considers steel demand, production and energy consumption in an integrated framework.

Many researchers have analyzed energy consumption, CO_2 emission and energy efficient technologies in iron and steel industries [6–8]. Johansson et al. [9] presented some opportunities for utilizing energy resources efficiently and reducing CO_2 emission in Swedish iron and steel industry. Tongpool et al. [10] studied environmental impacts of steel production and solutions in Thailand. Weiet al. [11] investigated energy efficiency of the iron and steel sector in China using Malmquist index decomposition. Zhang et al. [12] used Cobb_Douglas type of production function to estimate the impact of energy saving technologies and innovation investment on the productive efficiency of Chinese iron and steel enterprises. Ruth et al. [13] investigated the impact of cost of carbon

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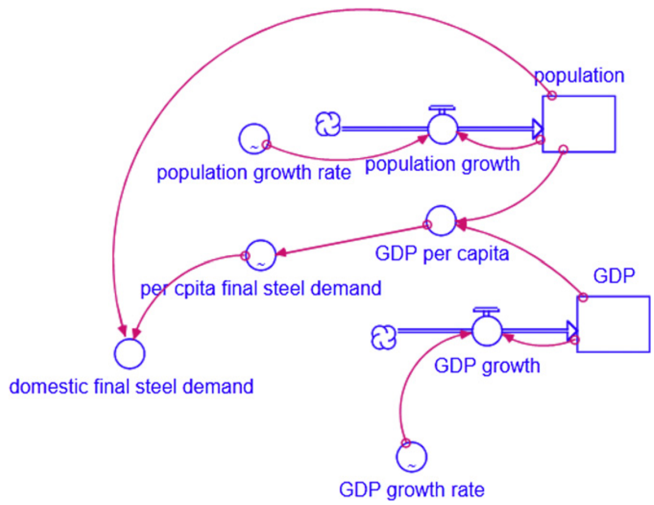

Fig. 1. Final steel products demand stock and flow diagram.

on energy use and carbon emission. Wang et al. [14] developed a model using LEAP software to generate different energy consumption and CO_2 emission scenarios for Chinese iron and steel industry from 2000 to 2030. Geilen et al. [5] developed a linear programming model for analyzing CO_2 emission reduction in Japanese iron and steel industry which could be used to analyze impact of CO_2 tax on technology selection, iron and steel trade and product demand. Soheili [3] used MEDEE model to estimate energy requirements of iron and steel industry in Iran up to 2025.

Estimating Energy demand in an industrial sector is a complex problem due to the presence of multiple decision makers, consumers' behaviors, technological limitations, feedback processes among subsystems, and various kinds of delays. System dynamics is a suitable approach to model such complexities. System dynamics (SD) approach, established by forester in 1961 [15], has been wildly used in socio-economic studies. In energy related subject, Nail [16] presented an SD model of gas industry dynamics in the united state. Other researchers developed SD energy models [17–20]. In industrial sectors, Anan et al. [21] used SD to estimate CO_2 emission in Indian cement industries. They presented policy options for stabilizing population growth, energy conservation and manufacturing processes for CO_2 mitigation. Li et al. [22] developed an SD model to forecast natural gas demand in china. Kiani et al. [23] 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 transportation sector, the SD model presented by Han [24] was used for policy assessment and CO_2 mitigation potential analysis. He pointed out that developing railways, slowing down highway expansion, and imposing fossil fuel tax would be the best policies to decrease energy demand.

The proposed SD model is composed of 3 main subsystems, steel demand module, production module considering capacity expansion and energy consumption module and includes the interactions among these subsystems in an integrated framework. Our analysis covers the following important issues which are elaborated in the proposed model:

1) the impacts of population and GDP growth on steel demand in future,
2) the structure of direct and indirect energy consumption under various production and export scenarios and new subsidy regime,
3) the impact of investment limitations and government supporting policies on capacity expansion,
4) analysis of potential energy saving achieved by feasible technology changes in the steel industry
5) Investigating the gas consumption and CO_2 emission of electricity generation needed by the steel industry.

A co-flow structure is used to show how subsidy reform would affect energy consumption in the long run. The model takes into account new capacity construction delay, investment limitations and share of different technology.

The rest of this paper is organized as follows. Three main modules of the proposed model are presented in Section 2.

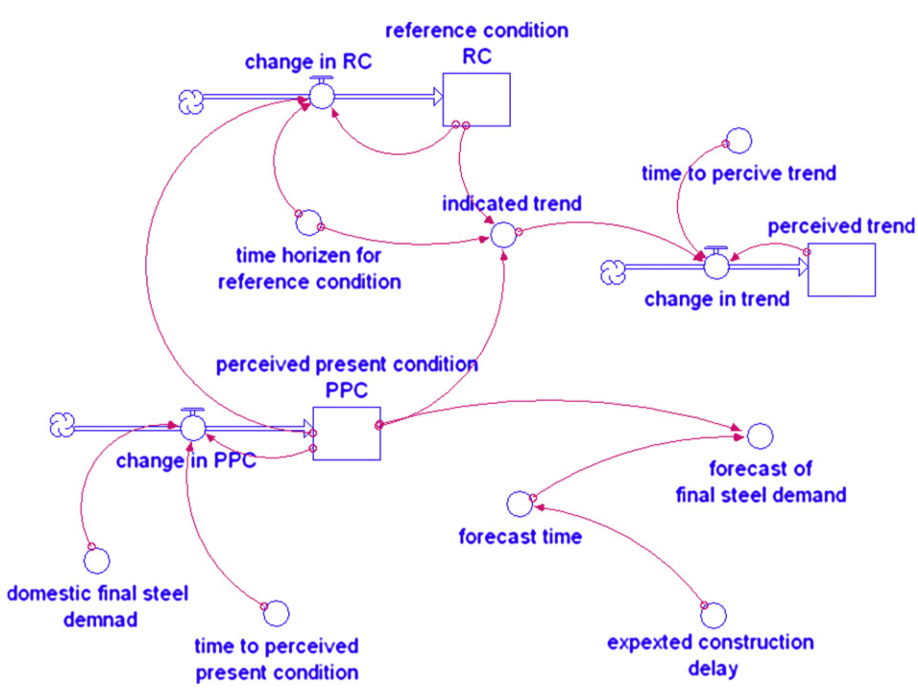

Fig. 2. Final steel demand forecasting stock and flow diagram.

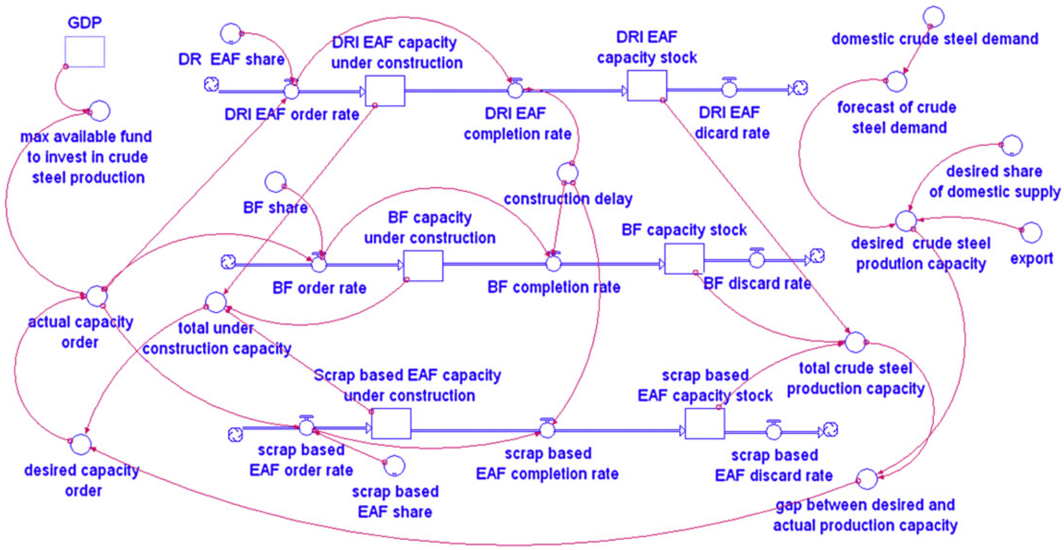

Fig. 3. Crude steel production capacity stock and flow diagram.

Simulation results and model validation are shown in Section 3. Section 4 represents different production and energy efficiency scenarios. Section 5 portrays future trend of energy consumption in the steel industry under various production scenarios and subsidy reform regime. Section 6 discusses the main conclusions.

2. The proposed system dynamics model for iron and steel industry

Three main subsystems of the model are explained in this section. In each subsystem, stock and flow diagram has been developed and feedbacks among subsystem are presented.

2.1. Steel demand

Final Steel demand increases with the growth of population and per capita steel demand. Per capita steel demand increases by per capita gross domestic product growth. The structure of steel demand is presented in Fig. 1. Crude steel demand is assumed to be equal to final steel demand.

2.2. Production capacity

The proposed SD model includes three kinds of technology: blast furnace (BF), electric arc furnace using scrap (scrap based EAF), and electric arc furnace using direct reduced iron ore (DRI-EAF). The production sub-model for each technology contains two stocks. The capacity under construction is converted to capacity stock using a delay function. The average construction delay is assumed to be 3 years. Producers, being aware of construction delay, make their decisions about capacity expansion based on the expected demand in future. In SD models, a trend function is often used to formalize human expectation [25] and is used to calculate the perceived fractional growth rate of steel demand. Then, the forecast of steel demand is calculated using Equation (1).

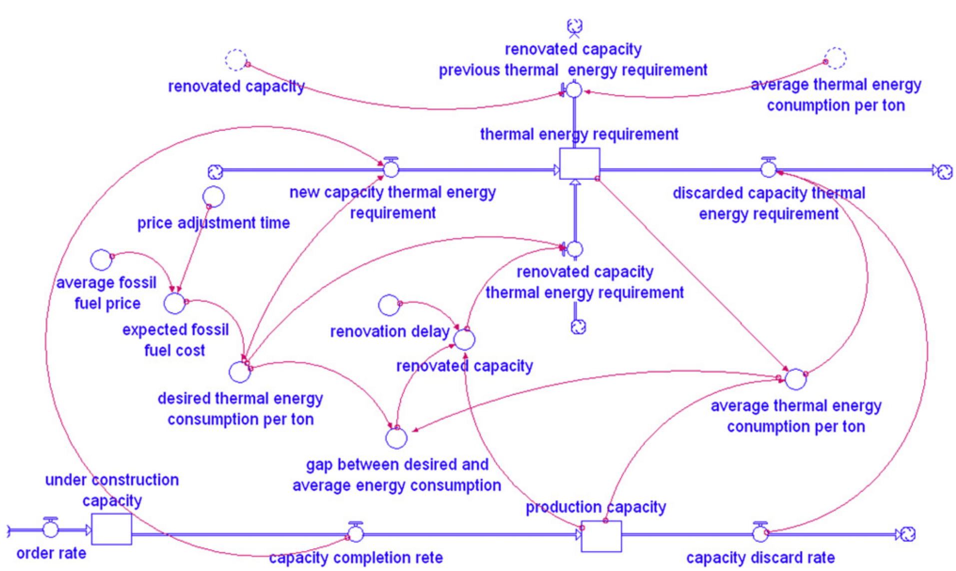

Fig. 4. Thermal energy requirement stock and flow diagram.

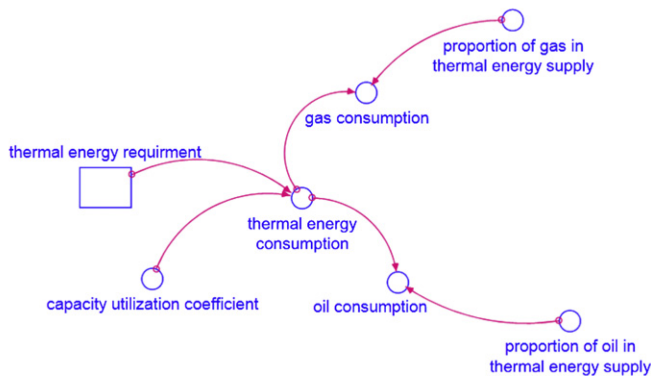

Fig. 5. Gas and oil consumption stock and flow diagram.

$$\text{Forecast of steel demand} = \text{perceived percent condition}*\exp(\text{perceived trend}*\text{expected construction delay})*(1+\text{perceived trend}*\text{time to perceived.present.condition}) \quad (1)$$

The stock and flow diagram for final steel demand forecasting is shown in Fig. 2. Final steel and crude steel desired production depends on forecast of domestic demand, desired share of domestic supply and desired amount of export. Desired share in domestic supply and desired export are determined exogenously. Steel production is highly under government control in Iran, accounting for 96% of crude steel production and 70% of final steel production [4]. Actual steel production depends on production capacity and capacity utilization. Model seeks to correct the gap between desired and actual production through ordering new capacity to be constructed which is not necessarily equal to desired capacity expansion. Financial limitation is another factor that impacts on production capacity order rate. In an ideal situation, the actual construction would be equal to the desired order rate. Maximum available fund to invest in steel industry depend on GDP. The split of each technology for crude steel production depends on the share of that technology in existing crude steel production capacity according to various production scenarios. The model structure for crude steel production capacity is shown in Fig. 3. The same model is used for final steel production capacity.

2.3. Energy consumption

2.3.1. Energy consumption in production process

Energy requirement is divided to three groups: thermal energy, electricity and natural gas required in direct reduction process.

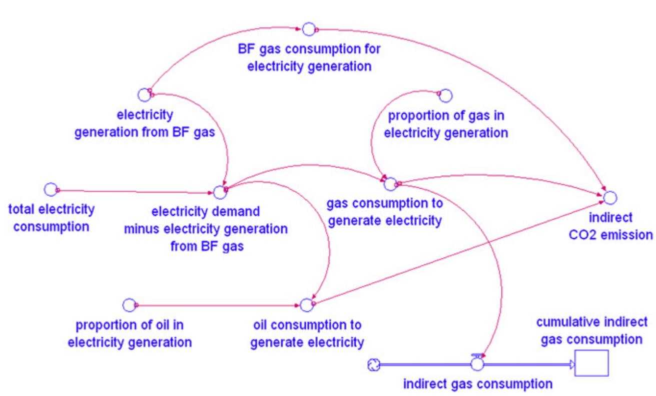

Fig. 6. Energy consumption and CO_2 emission to generate electricity stock and flow diagram.

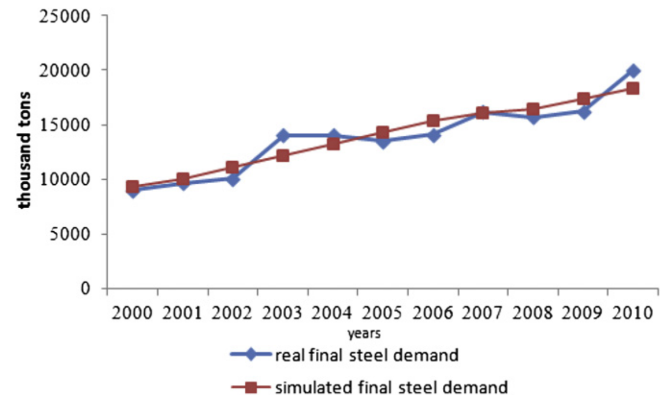

Fig. 7. Simulated final steel demand versus real data.

Production capacity stock in each technology contains different level of energy requirement and energy efficiency. To model such a situation, the modeler needs to keep track of the energy requirement for every capacity unit added and/or discarded. Co-flow structures are used herein to keep track of energy requirement of capacity expansion needed to respond to the demand. The stock and flow diagram for thermal energy requirement is shown in Fig. 4. Energy price is the key determinant of desired energy consumption. When energy price rises, investment in energy efficient technology will become profitable rather than paying more for energy cost. Energy requirement of new capacity is equal to the

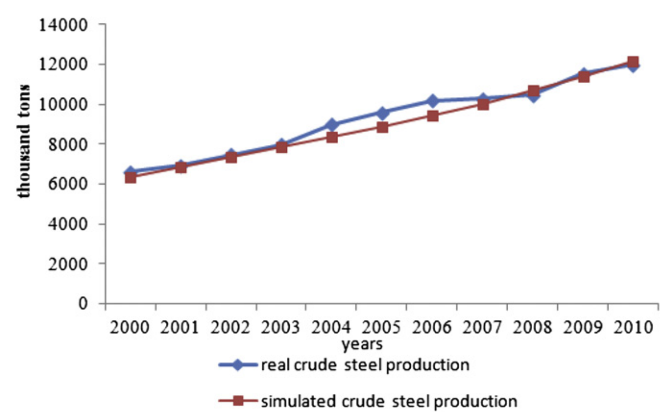

Fig. 8. Simulated crude steel production versus real data.

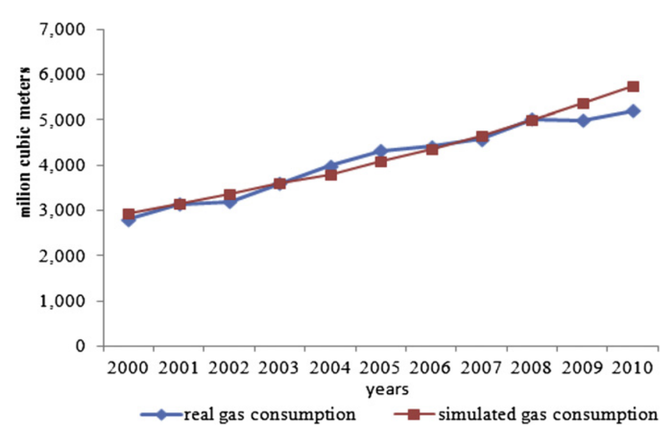

Fig. 9. Simulated gas consumption versus real data.

Table 1
Steel production scenarios.

Production scenarios	Desired share in domestic supply of steel demand	GDP growth rate		Desired export
	2011–2030	2011–2012	2013–2030	2011–2030
Low production & Import	75%	1.5%	3.5%	0
Base production & Domestic Supply	100%	4.5%	4.5%	0
High production & Export	100%	4.5%	7%	6 million tons

Table 2
Energy efficiency scenarios.

Energy efficiency scenarios	Description
Base energy efficiency	Continuation of previous trend of low energy efficiency
Moderate energy efficiency	Moderate increase in the desired efficiency due to subsidy reform
High energy efficiency	Higher desired efficiency due to using scrap based EAF technology

desired energy consumption. The same model is used for electricity and natural gas requirements in direct reduction process. In addition to new capacity construction, higher energy prices would encourage producers to renovate current machineries to correct the gap between the desired energy and current energy consumption.

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 should be multiply by capacity utilization coefficient. Gas and oil consumption depend on thermal energy consumption and the proportion of gas and oil in thermal energy supply as shown in Fig. 5.

2.3.2. Indirect energy consumption

Proportion of natural gas in Iran's net electricity supply is more than 80% [26]. Two big steel production companies, Mobarakeh and Zob-Ahan Esfahan, have their own power plants on their sites which supply a part of electricity requirements of these companies. Zob-Ahan Esfahan Company is the biggest blast furnace technology user in Iran and uses blast furnace gas (BF gas) to generate electricity. Stock and flow diagram of indirect energy consumption and CO_2 emission is shown in Fig. 6.

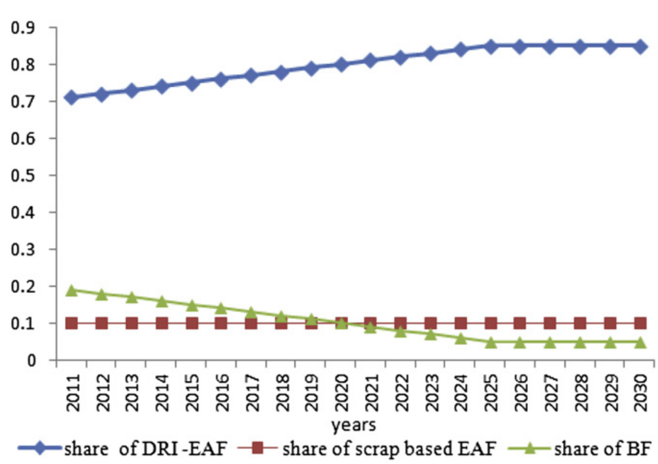

Fig. 10. Shares of different technologies in new investment in the base and moderate energy efficiency scenarios.

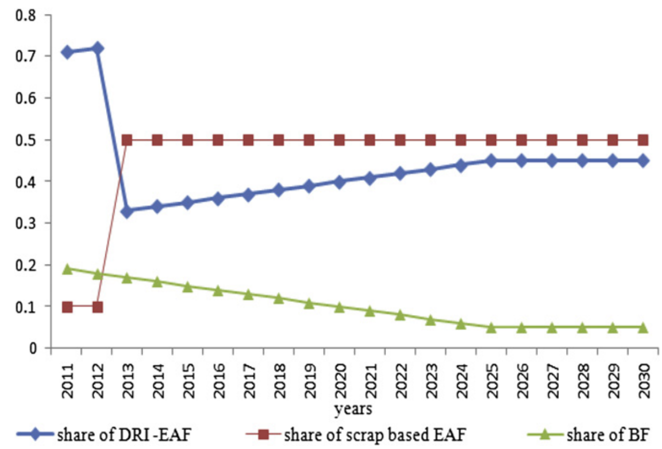

Fig. 11. Shares of different technologies in new investment in high energy efficiency scenario.

3. Model validation

The SD model explained in the previous section has been simulated using Ithink® 7.0.2 software for validation of results on final steel demand, crude steel production and total gas consumption. The simulation results show good conformity with historical trends as depicted in Figs. 7–9.

4. Production and energy efficiency scenarios

In this section, we introduce three production scenarios to be considered as possible trends of steel production in future. Then, we relate these production scenarios to energy efficiency scenarios resulting from the industry improvement plans and policies. The net population growth fractional rate is assumed to be 1.3% from 2010 to 2013, 1.1% from 2014 to 2017 and 1% beyond 2017 and the same in all scenarios according to [27].

4.1. Production scenarios

The three production scenarios, shown in Table 1, are described below.

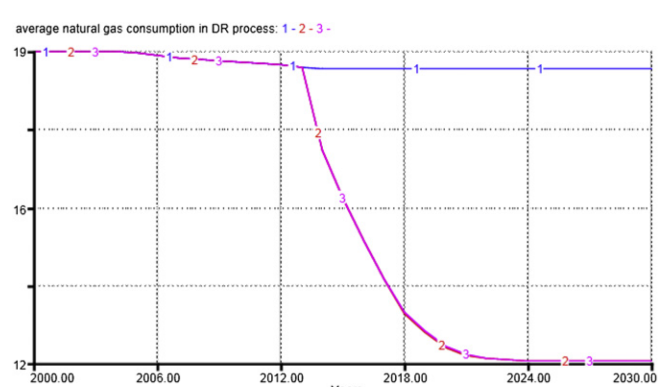

Fig. 12. Average natural gas consumption in direct reduction process (GJ/ton) 1-base 2-moderate and 3-high energy efficiency scenario.

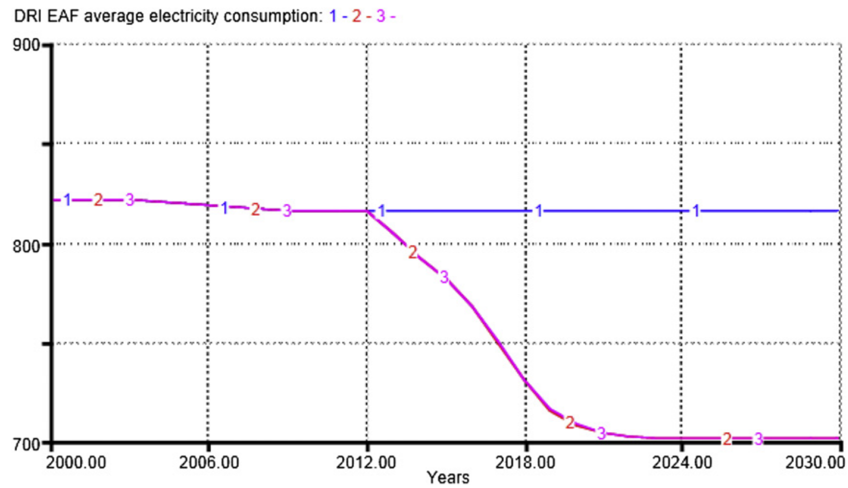

Fig. 13. Average electricity consumption per ton in DRI-EAF technology (KWH/ton) 1-base 2-moderate and 3-high energy efficiency scenario.

1) Low production and import scenario: Planning for capacity expansion is based on supplying 75% 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 assumed to be 1.5% for 2011 and 2012 and 3.5% beyond 2013.
2) Base production and domestic supply scenario: This scenario is the continuation of existing condition which aims at expanding manufacturing capacity to fully supply the country's demand.

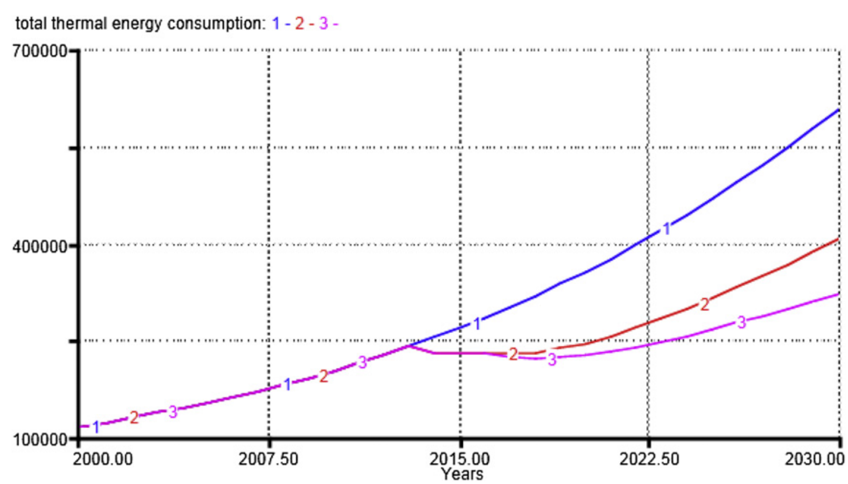

Fig. 14. Total thermal energy consumption (thousand Giga joules) 1-base 2-moderate and 3-high energy efficiency scenario.

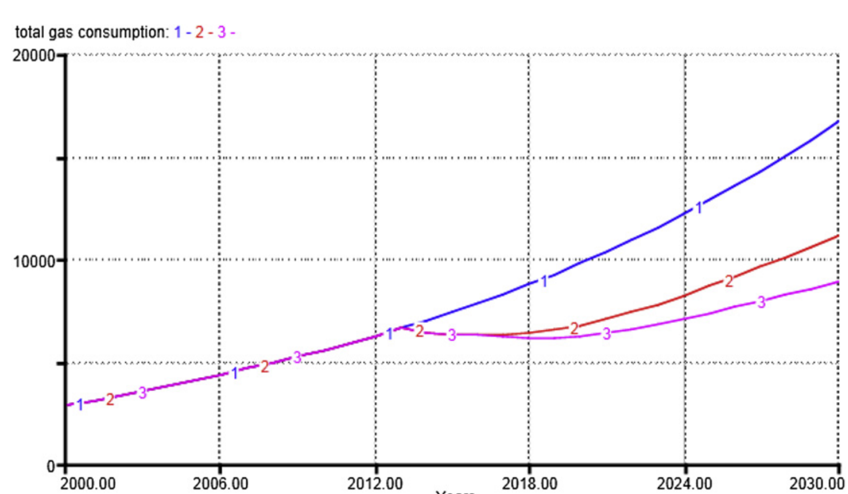

Fig. 15. Total gas consumption in the production process (million cubic meters) 1-base 2-moderate and 3-high energy efficiency scenario.

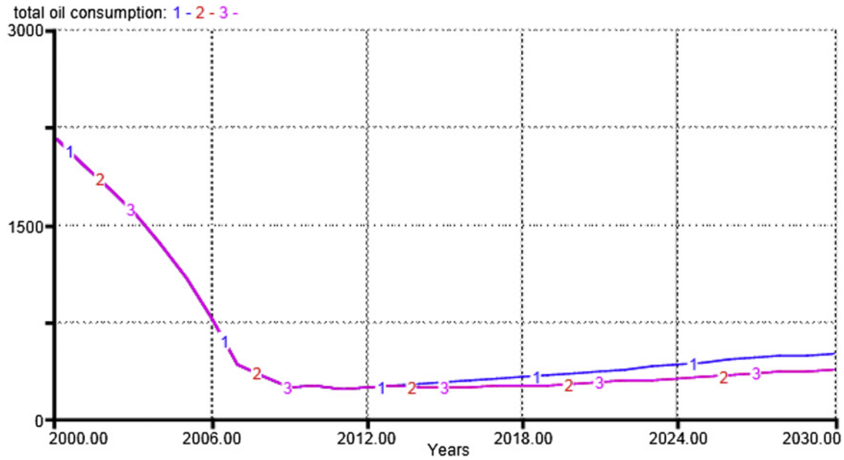

Fig. 16. Total oil consumption in the production process (thousand barrels) 1-base 2-moderate and 3-high energy efficiency scenario.

GDP growth rate is assumed to be 4.5% based on average GDP growth rate reported from 2006 to 2010 [26].

3) High production and export scenario: It is optimistically assumed that the GDP growth rate is 4.5% in 2011 and 2012 and 7% beyond 2013. It is further assumed that such GDP growth would allow the country to invest in steel industry capacity expansion so that it can fully respond to domestic demand and target 6 million tons export per year.

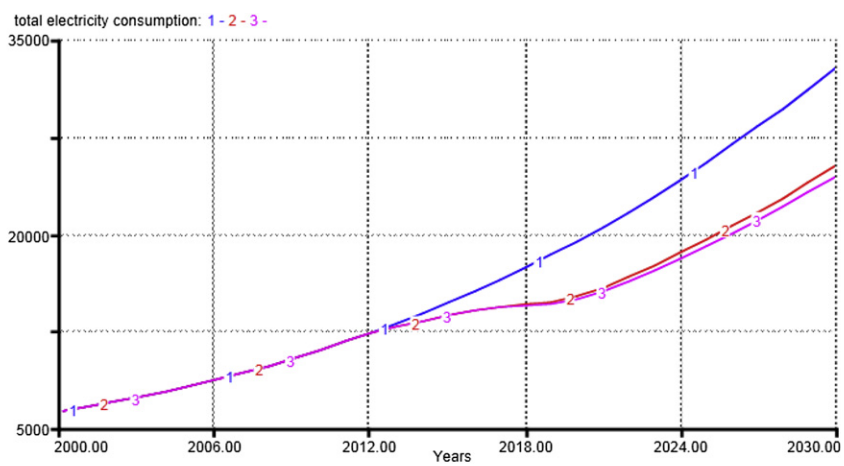

Fig. 17. Total electricity consumption in production process (million KWH) 1-base 2-moderate and 3-high energy efficiency scenario.

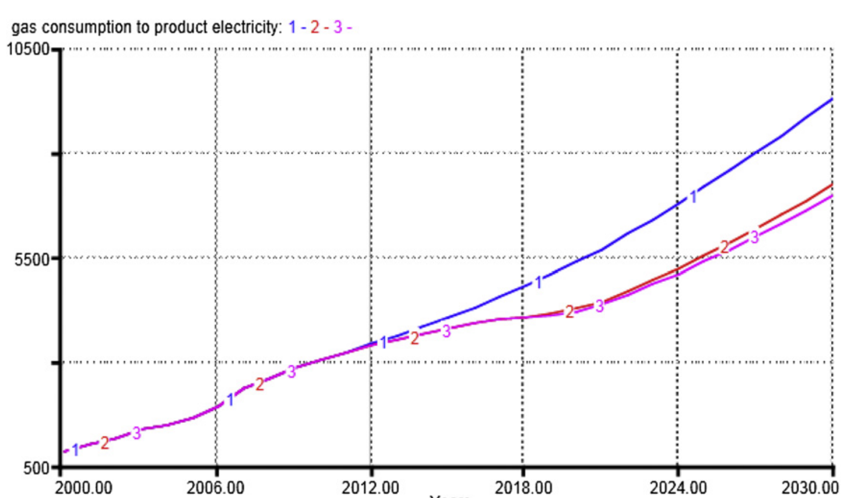

Fig. 18. Gas consumption to product electricity (million cubic meters) 1-base 2-moderate and 3-high energy efficiency scenario.

Table 3
Crude and final steel production and scrap tonnage used in EAF technology.

Production scenarios	Milestone year	Crude steel production (thousand tons)	Final steel production (thousand tons)	Share of scrap based		Scrap used in EAF steel production (thousand tons)	
				Base and moderate energy efficiency scenarios	High energy efficiency scenario	Base and moderate energy efficiency scenarios	High energy efficiency scenario
Low production & import	2015	15106	15539	10%	10%	1526	1526
	2020	16478	15968	10%	13%	1647	2200
	2025	20368	20067	10%	20%	2036	4144
	2030	23612	23275	10%	24%	2361	5765
Base production & Domestic Supply	2015	15598	18326	10%	10%	1560	1560
	2020	20452	24325	10%	18%	2045	3636
	2025	26459	31872	10%	25%	2567	6692
	2030	34072	38268	10%	31%	3424	10529
High production & Export	2015	15598	18,326	10%	10%	1500	1500
	2020	20536	24423	10%	18%	2053	3675
	2025	27421	32976	10%	26%	2746	7139
	2030	37184	45087	10%	32%	3727	12044

4.2. Energy efficiency scenarios

The three energy efficiency scenarios, as shown in Table 2, are described below.

Energy consumption of steel industry depends on energy efficiency and amount of production. Three scenarios for energy price and each technology proportion in new investment are presented to evaluate energy requirement. All three production scenarios are run under base moderate and high energy efficiency scenarios described below.

1) Base energy efficiency scenario: this scenario is 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. The investment in manufacturing technology is also assumed to follow the same existing trend of technology that is based on steel production mainly using DRI. Fig. 10 shows the expected share of each technology projected by the investment decision in the model.
2) Moderate energy efficiency scenario: Energy prices have suddenly jumped in 2011 due to a major subsidy reform policy [28,29]. Under the new subsidy regime, energy prices are expected to increase to reach world energy prices in 2016. This scenario assumes that such an increase in energy prices will lead to a better use of energy by the consumer gradually reaching to standard level of energy consumption. The expected share of each steel making technology is assumed to be the same as in scenario (1) shown in Fig. 10.
3) High energy efficiency scenario: The same trend of improvement in energy efficiency is assumed as in scenario 2. It is also assumed that higher efficiency is gained by utilizing scrap based EAF technology. Scrap sources and recycling will allow to increase scrap based EAF share in the new technology investment. The projected proportion of each technology under the assumption of this scenario is shown in Fig. 11.

5. Simulation results

The systems dynamics model has been run under every possible combination of production and energy efficiency scenarios using Ithink® 7.0.2 software on a personal computer with 2.4 GHz CPU speed and 6 mega bytes of RAM.

The results of three energy scenarios implementation under base production and domestic supply scenario are shown in Figs. 12–18. Lines 1,2 and 3 respectively represent the results of base, moderate and high energy efficiency scenarios. Figs. 12 and 13 show average gas consumption in direct reduction process and electricity consumption per tonnage of steel production using DRI-EAF technology. Fig. 12 shows a huge gap between the existing trend and standard energy consumption in the steel industry. We expect to catch up with standard level of energy consumption over time as the energy prices increase. Similar trends in energy consumption have been observed using other production technology that is not reported herein.

Figures 14 to18 show total thermal energy, total oil, gas and total electricity consumption in the iron and steel industry under base production and domestic supply scenario. The corresponding results for the other two production scenarios are reported in Table 4.

As Fig. 14 shows thermal energy consumption will reach to 606.7, 404.4, 319 million Giga joules in base, moderate and high energy efficiency scenario respectively, under base production and

Table 4
Direct gas and electricity consumption in steel production.

		Base energy efficiency scenario			Moderate energy efficiency scenario			High energy efficiency scenario		
		Oil (thousand barrels)	Gas (million cubic meters)	Electricity (million kwh)	Oil (thousand barrel)	Gas (million cubic meters)	Electricity (million kwh)	Oil (thousand barrel)	Gas (million cubic meters)	Electricity (million kwh)
Low production & Import	2015	229	6960	13786	202	5929	12864	202	5918	12843
	2020	237	7566	14914	179	5193	11785	179	4958	11692
	2025	286	9494	18674	212	6348	14422	212	5615	14053
	2030	321	11135	21841	238	7430	16903	238	6279	16378
Base production & Domestic Supply	2015	261	7332	14619	229	6236	13606	229	6236	13606
	2020	336	9732	19337	253	6689	15109	253	6171	14923
	2025	421	12826	25459	312	8604	19453	312	7305	18971
	2030	491	16606	32702	364	11094	25188	364	8805	24339
High production & Export	2015	261	7332	14619	229	6236	13606	229	6236	13606
	2020	337	9773	19457	254	6716	15170	254	6188	14980
	2025	435	13297	26383	323	8920	20163	323	7505	19638
	2030	562	18430	36404	417	12329	27929	417	9650	26935

Table 5
Cumulative direct gas consumption in steel production during 2000–2030 (billion cubic meters).

	Base energy efficiency scenario	Moderate energy efficiency scenario	High energy efficiency scenario
Low production & import	198	158.7	151.5
Base production & Domestic Supply	237	185.5	172.3
High production & Export	242	189	175

Table 7
Cumulative CO_2 produced by electricity power plants during 2000–2030 (million tons).

	Base energy efficiency scenario	Moderate energy efficiency scenario	High energy efficiency scenario
Low production & import	369	318	315
Base production & Domestic Supply	439	371	367
High production & Export	451	380	376

domestic supply scenario in 2030. To supply such thermal energy consumption by taking into account gas proportion in thermal energy supply, 16.6, 11, and 8.8 billion cubic meters of natural gas will be consumed in base, moderate and high energy efficiency scenarios as shown in Fig. 15.

Fig. 16 shows that oil consumption decreases rapidly because of government policy to substitute oil by gas in the domestic consumption.

As Fig. 17 shows electricity consumption will reach to 32,702, 25,188 and 24,339 million kW h in base, moderate and high energy efficiency scenarios respectively, under base production and domestic supply scenario in 2030. As Fig. 18 shows, if the current trend of gas turbine electricity generation continues, to supply such electricity demand, the indirect gas consumption will reach respectively to 9.2, 7.2, 6.9 billion cubic meters under base, moderate and high energy efficiency scenarios.

The amount of crude and final steel production under different production scenarios are shown in Table 3. The scrap used in EAF steel production and share of scrap based EAF in steel production under base, moderate and high energy efficiency scenarios are shown in Table 3 in order to project the future scrap demand. The share of scrap based EAF steel in crude steel production will reach respectively to 24%, 31% and 32% under low, base and high production scenarios by 2030. Crude steel production will reach respectively to 23.6, 34 and 37.1 million tons under low, base and high production scenarios by 2030. According to the forth national development plan, Iran aims to reach to 55 million tons of steel production by 2025 [30]. However, simulation results show that even in an optimistic high production scenario, crude steel production would reach to 37.1 million tons in 2030.

Table 4 shows direct gas, oil and electricity consumptions required for amount of steel production reported in Table 3 under various scenarios. The results show that there is 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 gas consumption gives more obvious figures of potential energy saving among various scenarios during simulation. Table 5 represents cumulative direct gas consumption from 2000 to 2030 under different scenarios. Looking at the base production scenario for example, it is seen that gas consumption under moderate energy efficiency scenario is 51.5 billion cubic meters less than that of base energy efficiency scenario in 2030. This deference reaches up to 64.7 billion cubic meters under high energy efficiency scenario. Tables 6 and 7 show the indirect gas consumption and CO_2 emission in the steel industry. This amount under moderate energy efficiency scenario is 19 billion cubic meters less than that of base energy efficiency scenario due to reduction in electricity consumption after subsidy reform which amounts to 68 million tons of CO_2 emission.

Table 6
Cumulative indirect gas consumption to generate electricity needed for steel production during 2000–2030 (billion cubic meters).

	Base energy efficiency scenario	Moderate energy efficiency scenario	High energy efficiency scenario
Low production & import	103.7	90	89
Base production & Domestic Supply	126.5	107.5	106
High production & Export	130	110	108

6. Conclusions

A system dynamics model is presented to analyze energy consumption in Iran's iron and steel industry. Gas, oil and electricity consumed in the steel industry have been projected under various steel production and export scenarios while taking into account new energy price regime. The model includes feedback loop structures for steel demand, production and investment in capacity expansion, as well as a co-flow structure to capture energy consumer behavior with respect to energy prices.

Direct and indirect gas consumption has been simulated under various steel production scenarios and energy efficiency scenarios. Our computational results show that in short term, the subsidy reform could lead to 15% and 7% reductions in gas and electricity consumption, respectively, due to a mild improvement in energy efficiency. In the long run, potential reductions are 33% in gas and 23% in electricity consumption resulting from deploying a full suite of energy saving plan and industry renovation. It is possible to further reduce the gas consumption between 10% and 15% by utilizing scrap based EAF technology.

Developing a scrap recycling system as well as increasing scrap import is highly recommended in order to supply sufficient scrap to the steel manufacturing industry. Our simulation results show that in the base production scenario, 34 million tons of crude steel plus 45 million tons of final steel will be produced comparing to the current production of 12 and 15 million tons, respectively. Consequently, total direct and indirect gas consumption in the steel industry will reach to 18.3 billion cubic meters per year by 2030 which is about 14% of total gas currently consumed in the country. Further socio-economical studies are needed to coordinate the country's gas export policy with future development plan for steel industry.

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