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ORIGINAL RESEARCH PAPER

Sensitivity analysis of parameters affecting carbon footprint of fossil fuel power plants based on life cycle assessment scenarios

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ABSTRACT: In this study a pseudo comprehensive carbon footprint model for fossil fuel power plants is presented. Parameters which their effects are considered in this study include: plant type, fuel type, fuel transmission type, internal consumption of the plant, degradation, site ambient condition, transmission and distribution losses. Investigating internal consumption, degradation and site ambient condition effect on carbon footprint assessment of fossil fuel power plant is the specific feature of the proposed model. To evaluate the model, a sensitivity analysis is performed under different scenarios covering all possible choices for investigated parameters. The results show that carbon footprint of fossil fuel electrical energy that is produced, transmitted and distributed, varies from 321 g CO_2 eq/kWh to 980 g CO_2 equivalent /kWh. Carbon footprint of combined cycle with natural gas as main fuel is the minimum carbon footprint. Other factors can also cause indicative variation. Fuel type causes a variation of 28%. Ambient condition may change the result up to 13%. Transmission makes the carbon footprint larger by 4%. Internal consumption and degradation influence the result by 2 and 2.5%, respectively. Therefore, to minimize the carbon footprint of fossil fuel electricity, it is recommended to construct natural gas ignited combined cycles in low lands where the temperature is low and relative humidity is high. And the internal consumption is as least as possible and the maintenance and overhaul is as regular as possible.

KEYWORDS: *Carbon footprint; Life cycle assessment (LCA); Modeling; Power plant; Sensitivity*

INTRODUCTION

Electricity directly or indirectly has been linked to every action. In the year 2013, around 25,000 TWh of electricity has been produced in the world and around 13.5 Gt equivalent CO_2 has been emitted consequently (Van der Hoeven, 2014). CO_2 emission has been distinguished to be the main contributor to climate change and global warming, and electricity sector is responsible for two third of the emission. The decarbonization policies and processes mostly depend on using renewable energies instead of fossil fuels. Substituting current fossil fuels power plants with renewable energy can be a long term strategy. Therefore, power generation does not be independent of fossil fuels (emitting CO_2, CH_4, and N_2O) and fossil fuel power plants are constructed all over the world. However, by controlling some effective parameters, carbon footprint of the fossil fuel electricity is decreased. In industries other than power industry, many studies have studied carbon footprinting from different aspects manufacturing process. Hong *et al*. (2007) have investigated the effect of consumed energy in carbon footprint of commerce in china. Food and agriculture industries have been also pioneers in studies on carbon footprinting. Niccolocci *et al.*, (2008) have studied on two different brands of wine in Italy. Agriculture sectors have also been reviewed for

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wheat production in China by Gan *et al.* (2011). Cheng *et al.,* (2011) have examined the carbon footprint of china's crop production. Transport industry has also been analyzed by different researchers such as Johnson (2008).Carbon footprint biodiesel, LPG and heating oil have also studied by Johnson (2012) and Raymond *et al.,* (2009). Weber and Clavin (2012) have looked over the carbon footprint of gas oil produced by shale sand and CTL. They have recognized that even using gas oil from fuel farm cannot also reduce the carbon footprints of such a fuel. Szabo *et al.,* (2014) have investigated the carbon footprint of bio gas power plant and have deducted that carbon footprint reduction of such plant has been impossible because of the N_2O emission while using artificial fertilizer in fuel preparation infrastructure. Power industry like the above mentioned instances has been a good target for researchers. Many researchers have been studied the assessment of GHGs emission for different electricity generation technologies. Most of them have studied Life cycle environmental impacts of electricity generation in national scale. Among them Borizmohun *et al.* (2015), Treyer and Bauer (2016), Ozcan (2016), Atilgan and Azpagic (2016), Georgakellos (2012), Olkkonen and Syri (2016) have worked on a national scale for Turkey, Mauritius, Greece, UK, Finland and UAE. Some researchers have preferred to work on different technologies behind the national scale, such as Turconi *et al.,* (2013). They have investigated 167 case studies involving the life cycle assessment (LCA) of electricity generation based on hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, solar photovoltaic (PV) and wind. Results of this study have identified ranges of emission data for GHG, NO_x and SO_2 related to individual technologies. Their emission data have been evaluated with respect to three life cycle phases (fuel provision, plant operation, and infrastructure). They have omitted the effect of delivering the electricity to the end users. Bonamente *et al.,* (2015) and Abbaspour *et al.,* (2011) also have addressed the same issues for an integrated renewable and nuclear power plant. Other researchers have concentrated on the type of fuel such as studies of Takunaga and Konan, (2014) and Weldemichael and Assefa (2016) on biofuels, Raj *et al.,* (2016) on shell gas, Turner *et al.* (2014) on waste water, Silva *et al.* (2014) on sugarcane and bagasse and Shafie *et al.,* (2012) on rice husk, Rashidi *et al.*, (2012) on waste leachate. Li (2014) has also investigated on carbon emission reduction in electric power sector and his study has leaded to the conclusion that by using coal pretreatment system a 17% carbon reduction has been noticed.

The previous studies have one aspect in common which is the LCA assessment of Green House Gases (GHGs) emission and environmental impact of electricity from existing case studies (power plants). Up to the knowledge of the authors, no carbon footprint model has been developed yet that can be used to estimate the carbon footprint of a power plant in feasibility study and operational phase with good agreement.

This paper proposes a tank (storage area of the fuel) to wire carbon footprint model for fossil fuel power plants and calculate the carbon footprint of the power plant considering parameters viz. plant type, fuel type, fuel transmission type, internal consumption of the plant, degradation, site ambient condition, transmission and distribution losses. However, previous literatures have considered one or two of the mentioned parameters together without counting the effect of internal consumption and degradation (aging). For instance Turconi *et al.,* (2013) have investigated the effect of plant type. Atilgan and Azpagic (2016) have considered the influence of the fuel type. Raj *et al.* (2016) have studied the influence of fuel transmission type. Site ambient condition has also been studied by Kehlhofer *et al.,* 2009. They have studied the effect of site ambient condition on the output power of the plant, not directly on carbon footprint. Kim and Holme (2015) have worked on transmission and distribution losses. Considering the effect of degradation, internal consumption and site ambient condition are the distinguished features of the proposed model. After introducing the model, a sensitivity analysis is performed to indicate the importance of each parameter on carbon footprint calculation. For sensitivity analysis a baseline scenario is developed. The baseline scenario consists of two power plants with considering the emission of natural gas combustion and the other parameters assumed to be zero. To evaluate the dependency of carbon footprint on investigated parameters five groups of scenarios namely; emission group scenario, ambient condition group scenario, internal consumption group scenario, degradation group scenario and transmission and distribution group scenario are developed. This study has been carried out in Tehran, Iran during the year 2016. Data collection has been taken for 15 months.

MATERIALS AND METHODS

In this paper, a life cycle assessment approach is used to estimate carbon footprint of power sector, following the LCA methodology described in ISO 14067. To precise the model, emission of CH_4 and N_2O are also included. The emissions are converted to carbon dioxide equivalents based on 100-year global warming potential factors reported by the IPCC's Fifth Assessment Report, 2014. Carbon footprint is the science of calculating the amount of CO_2 eq (equivalent) emitted during the producing phases of unit of product Eq. 1 is considered for calculation of carbon footprint: Eq. 1 is converted to Eq. 2 to calculate carbon footprint of power plants:

$$\text{Carbon Footprint(CF)} = \frac{\text{total equivalent } CO_2 \text{ emission}}{number\ of\ unit\ product} \qquad (1)$$

$$\text{Carbon Footprint(CF)} = \frac{\text{total equivalent } CO_2 \text{ emission}}{\acute{P}OH} \qquad (2)$$

Where P' is the modified power of the plant (the net capacity of the plant) in MW and *OH* is the operating hours in an arbitrary time span.

Parameters affecting the carbon footprint of power plants

Type of power plant as mentioned in the previous researches (Torconi *et al.,* 2013) is the most important parameter in GHGs emission. The type of the power plant is the differentiation point for heat rate, efficiency and fuel consumption. The next parameter which influences the result is the fuel type. The differences of fuels are reflected in emission factor for each type of them (IPCC, 2006). Fossil fuels used in power plants are coal, oil and natural gas. Iran has very limited reserves of coal which are not high in quality. Fuels are used in power generation in Iran is mostly natural gas, fuel oil and mazut.

The other essential parameter is the distance of which fuel is transmitted (Raj *et al.,* 2016). Fuel is delivered to the power generation stations by means of pipelines, railway truck or road trucks. Natural gas is delivered via pipeline, while liquid fuels are delivered differently case by case. For example, mazut and fuel oil are delivered to Shazand power plant via pipeline, but fuel oil is transmitted to Genaveh power plant by road tankers. For quantifying the effect of fuel traveled distance on carbon footprint, the vehicle fuel consumption and pipe line leakage are important. As the assessment is applying the assumption of tank to wire, the fuel processing and fuel extraction are also considered. The forthcoming parameter affects the carbon footprint by altering the electrical energy. These parameters include site ambient condition (climate), internal consumption, degradation, transmission and distribution losses. Site ambient condition parameters are site ambient temperature, relative humidity and pressure. Site ambient pressure is related directly to the site elevation (Kelhofer *et al.*, 2009). Internal consumption is the electricity consumed for the electricity requirement in power plants for motors and other equipment. The amount of internal consumption is generally observed to be about 7.35% for (steam power plants) conventional thermal stations, 0.75% for simple cycle power plant (Brayton cycle power plant) and 1.8% for combined cycle station. Degradation is also an issue that influences the results. Degradation decreases the output power of plant about 3% in the entire life of the power plant. In fact, degradation is a function of operating hours. Transmission and distribution losses are also influential factors in carbon footprint of the electricity which is delivered to the consumers. Transmission and distribution losses depend on the age of infrastructure, voltage, load of the lines and number of consumers (Kim and Holme, 2015).

Modeling the carbon footprint of power plant

In order to calculate the carbon footprint of electricity, emission and net electrical energy which is delivered to end users are considered. For a comprehensive view, Fig. 1 shows the block diagram of the calculation process and presented graphical state of emission and electrical losses. The scope of work and the boundaries are also depicted in Fig.1. The losses continue further in other phases of life cycle of product which are mainly contributed to transmission and distribution. The system boundary is set after processed fuel is ready for transmission until the electricity is delivered to the end users. Fuel processing emission and consumption efficiency of end users are not in the scope of this study.

Emission calculations

To achieve precision in model estimations, in addition to CO_2, emission of N_2O and CH_4 are also considered. Moreover, emission of power plant in all phases of its life span has two components. These components are expressed in Eq. 3.

$$tc = ec + et \qquad (3)$$

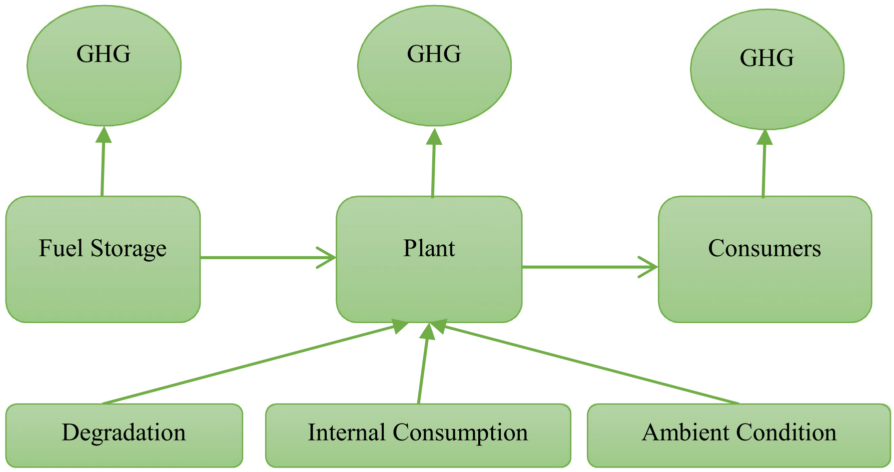

Fig. 1: Life cycle phase block diagram of the process

Where, *tc* indicates Total emission in kg, *ec* shows fuel combustion emission in kg and is fuel transfer emission in kg. Fuel transfer emission is the emission which is released because of the fuel transmission to power plant, and fuel combustion emission refers to the emission of the plant during operation. In the following sections the emission part of the model is explained completely.

Emission of fuel combustion

Emission of fuel combustion depends on the amount and type of consumed fuel. Actually, the heat content of the fuel and consequently the related emission factors play essential role in final calculation. Eq. 4 shows the combustion emission of a mixture of natural gas (NG), fuel oil (FO) and mazut (M) (IPCC, 2006).

$$ec = \sum_i a_i ef_i V_i \tag{4}$$

The coefficients α_i and ef_i are calculated by Eqs. 5 and 6.

$$\alpha_i = 10^{-9} \rho_i LHV_i \tag{5}$$

$$ef_i = ef_{CO_2 i} + 21 ef_{CH_4 i} + 276 ef_{N_2O i} \tag{6}$$

Where *i* is the fuel type index and switches to NG, FO and M, *ec* indicates emission of combustion in kg, ρ shows density of fuel in kg/m^3, *LHV* stands for Low Heating Value in kJ/kg, *V* is volume of consumed fuel in m^3, *ef* is Emission factor in kg/TJ. Emission factors are excerpted from IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Emissions of fuel transfer

Fuel transfer is a cause of indirect emission. Fuels are transferred to the plant via pipeline, rail and road trucks. Natural gas is always transmitted via pipeline in Iran. Fuel oil and mazut are sometimes transmitted via pipeline like Shazand and Sahand Power Plant. If fuels transmitted by the means of pipeline, the emission is estimated by Eq. 7 (IPCC, 2006).

$$et = \sum_i 10^{-12} V_i ef_i \tag{7}$$

i is fuel type index and switches to NG, FO and M, *et* shows emission of fuel transfer in kg, *Vi* indicates Volume of consumed fuel in m^3. If the liquid fuels are transmitted to power plant within road or rail freight transit, the decisive parameters are the distance of fuel transfer and the vehicle fuel consumption. The mentioned parameters are formulated to estimate the emissions in Eq. 8 (IPCC, 2006).

$$et = \sum_{i,j} fc_j . d_{ij} (v_i p_i) \beta_i ef \tag{8}$$

The coefficients and are calculated by Eqs. 9 and 10.

$$\beta = 10^{-15} LHV_{DO} \rho_{DO} \tag{9}$$

$$ef = ef_{CO_2} + 21 ef_{CH_4} + 276 ef_{N_2O} \tag{10}$$

Where, *i* is fuel index switches to NG, FO, and M, *j* is the means of transport index switches to rail and road tankers, *et* shows emission of fuel transfer in kg, f_c indicates fuel consumption rate of vehicles in l/ton.km, ρ shows Density of fuel in kg/m^3, *LHV* stands for low heating value in kJ/kg, *V* is volume of fuel consumed in m^3, *ef* is emission factor in kg/TJ, *d* is distance of transferred fuel in km. In Iran, the fuel consumption of road and rail freight is respectively 0.0051 and 0.036 l/ton.km.

Net electrical energy production

Net electrical energy which is received by consumers is almost less than what is produced and delivered to the substation of the plant. This concept happens because of the distance between location of power plant and location of consumption. Three other factors influence the net produced energy which one of them is related to site location and its ambient condition. Two others include degradation and internal consumption. These parameters are formulated in Eqs. 11 to 17. The net electrical energy for carbon footprint is estimated by Eq. 11.

$$E = \acute{P}.OH \qquad (11)$$

Where, P' shows Modified power in MW, and *OH* stands for Operating Hours. Modified power is the actual produced power and is estimated from the nominal power in ISO condition due to degradation, internal consumption, ambient condition, transmission and distribution. ISO condition is a standard condition for ambient condition which nominal power and actual power are the same. This condition is as follow: Temperature: 15°C, Pressure: 1.013 bar, and 60% relative humidity (RH). Modified power is calculated by Eq. 12.

$$\acute{P} = P.f \qquad (12)$$

Where, P' shows Nominal power in MW, *f* is Power factor. Power factor which is a representative of power reduction coefficient has five components. They are demonstrated in Eq. 13.

$$f = f_{degradation} f_{own\ consumption} f_{ambient\ condition} f_{transmission} f_{distribution} \qquad (13)$$

The above cited parameters are calculated by Eqs.14-16, where *L* stands for coefficient loss .

$$f_{transmission} = 1 - L_{transmission} \qquad (14)$$

$$f_{distribution} = 1 - L_{distribution} \qquad (15)$$

$$f_{own\ consumption} = 1 - L_{own\ consumption} \qquad (16)$$

Degradation

Degradation is the power plant loss due to fouling which is recoverable and aging which is non-recoverable unless parts are replaced (Kelhofer *et al.*, 2009). The simplified average non recoverable degradation is modeled and functionalized with Eq. 17. The coefficients are different for steam, gas and combined cycle power plants. Eq. 17 is derived by curve fitting from gas and steam turbine power plants book (Kelhofer *et al.*, 2009).

$$f_{degradation} = \frac{1}{a + bLn(OH) + cLn(OH^3)} \qquad (17)$$

Ambient Condition

The ambient condition function is dependent upon average ambient temperature (in degree C), the atmospheric pressure as reflected in average altitude h (in meters above sea level) and the average percentage relative humidity *RH*. The effect of the total ambient condition is the multiply of the each of three parameters function. This reflects in Eq. 18 (Kelhofer *et al.*, 2009).

$$f_{ambient\ \ condition} = f(h)f(\theta)f(RH) \qquad (18)$$

Elevation from sea level is influenced on the air density. Increasing the altitude reduces the density of the air and consequently reduces the air mass flow into the compressor and power output. In Iran the highest altitude on which plant establishment can be seen is 3000 meters above sea level. When altitude varies from sea level to 3000 meter above it, the ambient pressure decreases linearly with altitude (Kelhofer *et al.*, 2009). Thus, the power factor varies linearly with altitude and represented by Eq. 19.

$$f(h) = 1 - 0.00011(h) \qquad (19)$$

Average ambient temperature also has great effect on power output. Increasing the ambient temperature reduces the density of the air and consequently reduces the air mass flow into the compressor as constant volume engine. This is the main reason for changes in the simple cycle power output. Books were published as practice for gas turbine cycles produced power factor graph for average ambient temperature; the data fitted into Ratkowsky model (Kelhofer *et al.*, 2009). Eqs. 20 and 21 represent the effect of average ambient temperature on simple cycle and combined cycle plants, respectively.

$$f(\theta) = \frac{1.798}{1 + \text{eq}(-0.15 + 0.015\theta)} \quad (20)$$

$$f(\theta) = 1.0482\, e^{-0.0032\theta} \quad (21)$$

Comparison of Eq. 20 and 21shows the effect of ambient temperature on simple cycle and combined cycle together. The reduction of power factor with temperature is slower in combined cycle than simple cycle. Simple cycle and combined cycle power plant output will increase if the relative humidity of the ambient air increases, while other conditions remain constant. This occurs because at higher relative humidity, there is higher water content in the working medium of gas cycle, resulting in a better simple cycle enthalpy drop and more exhaust gas energy entering the heat recovery steam generator (HRSG). The effect of ambient relative humidity on power factor is considerably small. Eq. 22 is used to quantify the effect (Kelhofer *et al*., 2009).

$$f(RH) = 0.994 + 0.0045(RH) \quad (22)$$

For steam plant, ambient condition has no influence on the produced electricity because steam plants uses a closed cycle and the working medium is water. Therefore, power factor function equals one, i.e. $f_{ambient\ condition}=1$.

Transmission and Distribution

Transmission and distribution result in considerable losses in national grids. According to statistics released on year 2013, Iranian national grid has a loss of 3.45% in transmission and 14.9% in distribution. For the purpose of reducing the complexity of the grid, specific transmission electrical loss for each voltage level is introduced and has been calculated as follows. Losses are assumed to be the function of voltage level and circuit length of each voltage level. In this regard, total loss of transmission separated for 3 different voltage level including: 400, 230 and 132 kV. In the next step, the calculated loss for each voltage level has been divided into the length of its circuit. As a result, average loss for each specified voltage level per km is calculated. This method is also applied for the distribution loss. Transmission is modeled with cascade voltage reduction from 400 kV to 132 kV. For quantifying the effect of losses, losses are considered to be the function distance that the grid traveled. Eqs. 23 and 24 show the transmission power factor and Eq. 25 and 26 calculate this factor for distribution losses.

$$TL = \frac{GL}{kl} \quad (23)$$

Where *TL* is transmission loss per kilometer in %/km, *GL* shows total loss of a country or region in % and *kl* indicates total kilometer of the transmission grid in km

$$f_{transmission} = 1 - TL.l \quad (24)$$

Where *l* stands for distance of electricity traveled in grid in km.

$$DL = \frac{GL}{kl} \quad (25)$$

Where *DL* shows distribution loss per kilometer in %/km, *GL* is Total loss of in a specified region in % and *kl* is total kilometer of the distribution grid in km.

$$f_{distribution} = 1 - DL.\acute{l} \quad (26)$$

Where l' indicates distance of electricity traveled in Grid in km

Internal consumption of the plant

Internal consumption of the plant should also be subtracted from the power generated while the consumption makes the footprint larger. Internal consumption varies in a wide range because of the diversity of equipment and their manufactures. It is interesting that for each type of plants the average is almost constant. The average internal consumption is calculated. The average internal consumption is 7.35% for steam power plants, 0.75 % for simple cycle, 1.8% for combined cycle power plants. The average is calculated from all power plants in Iran. It means that the values are calculated from the average 20 steam power plants, 48 simple cycle and 19 combined cycle power plants of Iran.

Sensitivity analysis

To find the effectiveness of each investigated parameters on carbon footprint of the power plant, a sensitivity analysis is performed. The purpose of the analysis is to investigate and measure the effectiveness of parameters and the variability of carbon footprint due to the varying the parameters. One-factor-at-a-time (OAT/OFAT) model is applied for the assessment (Saltelli *et al*., 2008). For this purpose, one baseline scenario and five groups of scenarios are developed. The baseline scenarios compare the effect of types of power plants. First group of scenarios investigates the influence of fuel type and fuel transfer vehicle. The second group of scenarios inspects the effect of internal consumption. The third group of scenarios reviews the influence of site ambient condition on carbon footprint. The fourth group of scenarios investigates the influence of consumption location for the transmission and distribution losses and the fifth (final) group of scenarios addresses the issue of degradation. The baseline scenario consists of two types power plants. One is steam plant (SP) with the capacity of 1780 MW and the other is a combined cycle (CC) with the capacity of 486 MW. The fuel of both is assumed to be natural gas which is delivered via pipeline. No internal consumption is imagined and the other streams of emission are omitted. First scenario evaluates the emphasis of parameters affecting the emission. The scenario consists of eight sub scenarios and assesses the emission and its variability due to plant type, fuel type and fuel means of transfer. Table 1 shows the description of scenarios mentioned in this group.

This evaluation is also performed for internal consumption of the plant. Internal consumption of each type of plant is almost constant after the plant would be constructed. Analysis of detail load list to estimate the internal consumption of the power plant is not the purpose of this study; thus, three scenarios are developed for each type of power plant. The scenarios explain the minimum, avenge and maximum of internal consumption. The values are from in Tavanir statistics as presented in Table 2.

As described in the previous section, climate with site condition parameters are the subject of third group scenarios. This group consists of nine sub scenarios. In these sub scenarios effective parameters; altitude, mean ambient temperature and mean relative humidity as simulated by the towns of Iran, are considered. The specifications of scenarios are presented in Table 3. Each scenario explains the climatic condition of an

Table 1: Plant type, fuel type and fuel transfer scenarios description

No	Scenarios	Fuel combination	Transfer means	Plant type
1	A (Baseline)	Natural gas	Pipeline	SP+CC
2	B1	Mazut	Freight train	SP
3	B2	Mazut	Road tanker	SP
4	C1	Fuel oil	Freight train	CC
5	C2	Fuel oil	Road tanker	CC
6	D1	Natural gas + fuel oil	Pipe line + freight train	CC
7	D2	Natural gas + fuel oil	Pipe line + road tankers	CC
8	E1	Natural gas + mazut	Pipe line + freight train	SP
9	E2	Natural gas + mazut	Pipe line + road tankers	SP

Table 2: Plant internal consumption scenarios description

Plant type	Least internal consumption (%)	Average internal consumption (%)	Most internal consumption (%)
Steam plant	3	7.35	10.5
Combined cycle plant	1.2	1.8	2.3

Table 3: Site condition scenarios description

Scenarios	Altitude (m)	Θ (ºC)	RH (%)
A (ISO Condition)	0	15	60
B	-20	17.9	78
C	1361	12.6	53
D	37.2	18.6	65
E	22.5	25.4	64
F	9.8	27	64
G	1975	9	51
H	1484	17.8	41
I	899	18.8	40
J	2049	11.7	46

existing city in Iran. They are candidate to investigate firstly the effect of altitude, secondly the effect of temperature and thirdly the effect of relative humidity. Scenario B is representative of Anzali and scenario J is for Shahrekord.

The next scenario emphasizes the influence of transmission and distribution losses. The scenario consists of 6 sub scenarios. This group references six location of consumption in Iran. For each location the losses of transmission by estimating the grid length and voltage are calculated. The connections among neighbors are also extracted from the national maps of transmission (Alavipour *et al*., 2016). The first one is the location where plants are situated in Mazandaran. The surplus of the production is assumed to be consumed in other regional companies such Tehran, Semnan and both together. Two other scenarios are developed. One considers the consumption in all the neighboring companies and one is the consumption of the electricity totally on grid. The mentioned scenarios are described tabular in Table 4.

The next parameter to be added in the analysis is degradation of the plants. The rate of degradation is not the same in all plant type. However this parameter is the same in a specified plant in a specified time interval. To measure the response of the carbon footprint to degradation of power plants, final group of scenario is developed. The group has three scenarios, baseline scenario is assumed after the synchronization of the plant and grid in the first year of plant operation. The scenario 10^{th} is the scenario in which power plants are assumed to be in operation for 10 years. The 20^{th} scenario assumes the plant in the 20^{th} year of operation, and the last one is considered in 30^{th} year. Hence the plant operation hours is considered to be 262,800 hours. The power factor for all scenarios are calculated and presented in Table 5.

Table 4: Consumption location (Transmission and distribution losses) scenarios description

No.	Scenario tag No.	Consumption location
1	B	Mazandaran
2	C	Tehran
3	D	Semnan
4	E	Tehran and Semnan
5	F	Tehran-Semnan-Gilan-Khorasan
6	G	Totally on Grid

RESULTS AND DISCUSSION

For each scenario, emission of combustion, emission of fuel transfer and the amount of electricity generated are calculated. The results of first group of scenarios are presented in Table 6.

The influence of the final consumption location to specify the transmission and distribution losses are investigated by second group of scenarios. The carbon footprint of each scenario in the fourth group is displayed in Table 7.

Table 8 shows the effect of site ambient condition parameters on carbon footprint of consumed electricity. This table shows the effect of mentioned parameters just on carbon footprint of combined cycle power plants with regard to baseline scenario. As mentioned before in the modeling section, steam plants have not been influenced by site ambient condition.

Internal consumption influences the carbon footprint of power plants by delivering less energy to

Table 5: Degradation scenarios description

Plant type and degradation power factor	Baseline	Tenth year	Twentieth year	Thirtieth year
Steam plant	1	0.987	0.986	0.985
Combined cycle plant	1	0.982	0.979	0.977

Table 6: First group of scenarios investigating plant type, fuel type, fuel transfer means on carbon footprint

Scenarios	CF-combustion (g CO_2 eq /kWh)	CF-total (g CO_2 eq /kWh)
A(Baseline)	505.5	581.25
B1	700	753.78
B2	706	761.28
E1	637.7	698.81
E2	641.7	704.38
A(Baseline)	321	369.07
C1	444	484.41
C2	448	489.91
D1	404.6	448.78
D2	405.6	448.53

Table 7: Second group of scenarios investigating transmission and distribution losses on carbon footprint

No.	Scenario tag No.	Consumption location	CF steam plant (g CO_2eq /kWh)	CF CC plant (g CO_2 eq /kWh)
1	B	Mazandaran	506	321
2	C	Tehran	512	325
3	D	Semnan	517	333
4	E	Tehran and Semnan	510	329
5	F	Tehran-Semnan-Gilan-Khorasan	520	330
6	G	Totally on Grid	527	334

Table 8: Third group of scenarios investigating site condition on carbon footprint

	Altitude (m)	θ (ºC)	RH (%)	CF CC plant (g CO_2 eq /kWh)
A (ISO Condition)	0	15	60	321
B	-20	17.9	78	325
C	1361	12.6	53	352
D	37.2	18.6	65	327
E	22.5	25.4	64	339
F	9.8	27	64	342
G	1975	9	51	365
H	1484	17.8	41	365.5
I	899	18.8	40	351
J	2049	11.7	46	372

Table 9: Third group of Scenarios investigating internal consumption on Carbon Footprint

Plant type	Base line scenario CF (kg/kWh)	Least internal consumption CF (kg/kWh)	Average internal consumption CF (kg/kWh)	Most internal consumption CF (kg/kWh)
Steam plant	505.5	521.20	545.97	564.88
Combined cycle plant	321	324.73	326.71	328.39

Table 10: The final group of scenarios investigating degradation on carbon footprint

Plant type and year of operation	First year	Tenth year	Twentieth year	Thirtieth year
Steam plant	505.5	512.2	512.6	513.2
Combined cycle plant	321	326.9	328	328.6

grid meanwhile the fuel is consumed for producing of the amount of electricity. The pressure of the internal consumption on the carbon footprint of the generated power is shown in Table 9. The influence of degradation is shown in Table 10.

Steam power plant

The steam plant has a capacity of 1780 MW with availability of 62.1%. According to Tables 1 and 6, the energy is produced with different combination of fuels; natural gas, natural gas plus mazut and mazut. Mazut transfer is also assumed in two different ways; road tankers and rail tankers. Road tankers consume six times more fuel than rail tankers. Results show that carbon footprint of the mentioned steam plant varies in a range of 505.5 of baseline scenario to 761 g CO_2 eq/kWh in B2 scenario. Fuel transportation influences the results and causes a variation of 6 g CO_2 eq/kWh for mazut. If the mazut combined with natural gas for fuel portfolio, the share of transportation in emission is 4 g CO_2 eq/kWh. Fig. 2 shows the percentage of variation of carbon footprint to the baseline scenario. B2 scenario causes almost 40% variations in carbon footprint of steam plant. Fig. 3 shows the carbon footprint sensitivity to transmission and distribution losses. If the electricity is distributed in total Iranian national grid, carbon footprint increases by 21% comparing to the baseline scenario. From Fig. 3, it is obvious that localization of grid can help to reduce the carbon footprint, although the transmission of the produced energy on total grid has been done in very special cases for stabilizing the grid frequency.

Fig. 4 cited the effect of internal consumption of the steam plant. The internal consumption varies from 3% to almost 12%. Minimizing internal consumption leads to a reduction about 9% of carbon footprint. This fact can also lead to more electricity for sale. The surplus of sold energy can fulfil the investment finances. Fig. 5 illustrates the effect of degradation on the carbon footprint of steam plants. Degradation is an inevitable process for any kind of equipment. Maintenance and overall can slow the rate of degradation. However, the amount is about 1.45% in thirty years of operation and can be neglected considering the other factors.

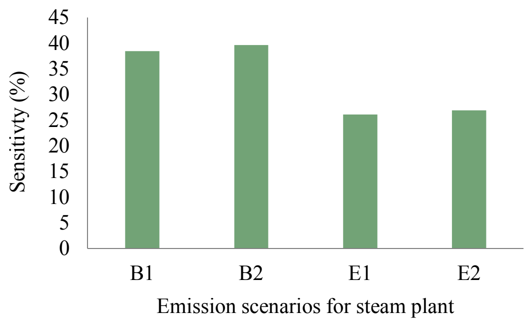

Fig. 2: Sensitivity of carbon footprint to group 1 scenario for steam plant

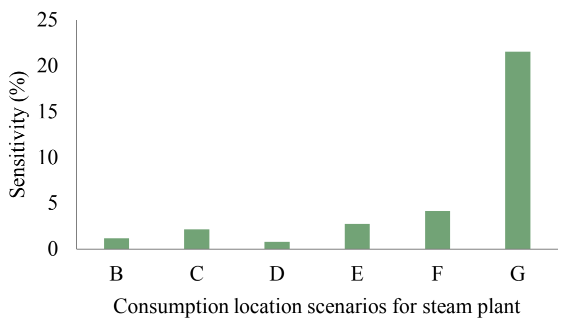

Fig. 3: Sensitivity of carbon footprint to group 2 scenario for steam plant

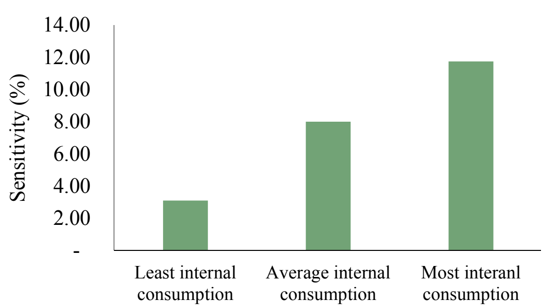

Fig. 4: Scenarios for internal consumption of the steam power plant

Combined cycle plant

Combined cycle plant with a capacity of 435 MW and availability of 56.7% produces 1,711, 681.32 MWh. By reviewing Table 5, the fuel combination is the same as steam plant. The only difference is the replacement of mazut with fuel oil. The results of different scenarios show that minimum of the plant carbon footprint is 321 and the maximum is 489.9 g CO_2 eq/kWh. The influence of fuel transfer is 4 g CO_2 eq/kWh for difference of road and rail transit of fuels for C category scenarios and 1 g CO_2 eq/kWh for D category scenarios. This fact is presented in Fig. 6. Transmission and distribution losses have the same result as the steam plant. The percentage of variation is cited in Fig.7.

Combined cycle is also sensitive to site ambient condition. Fig. 8 shows the variability of carbon footprint to site ambient condition. Baseline scenario is considered in ISO condition. A variation of almost 16% is calculated for J scenario as the altitude of the plant increases. The low altitude land with high relative humidity and low temperature is the best place to construct a combined cycle power plant.

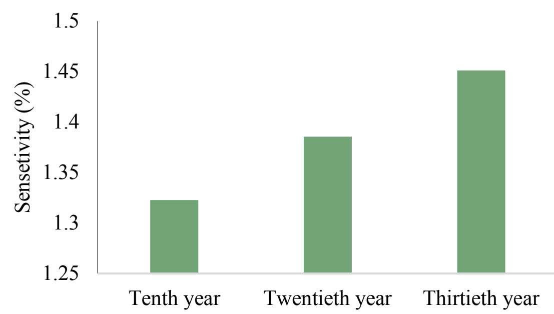

Fig. 5: Sensitivity of carbon footprint of steam power plant to degradation

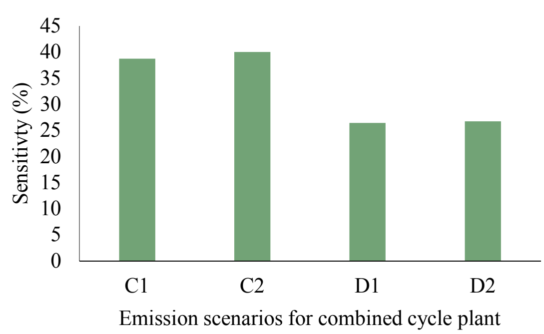

Fig. 6: Sensitivity of carbon footprint to group 1 scenario for combined cycle plant

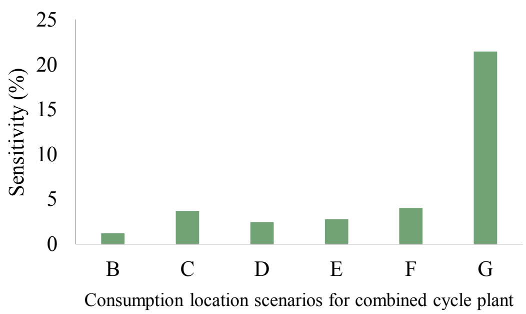

Fig. 7: Sensitivity of carbon footprint to group 2 scenarios for combined cycle Plant

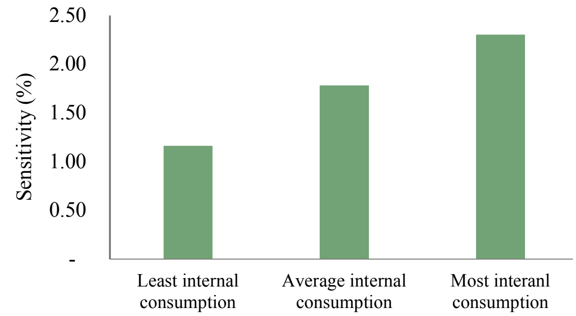

Fig. 9: Scenarios for internal consumption of the combined cycle power plant

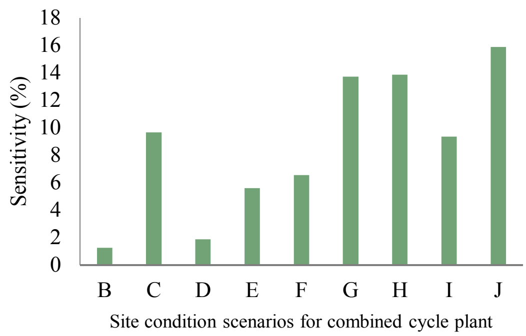

Fig. 8: Sensitivity of carbon footprint to group 3 scenarios for combined cycle plant

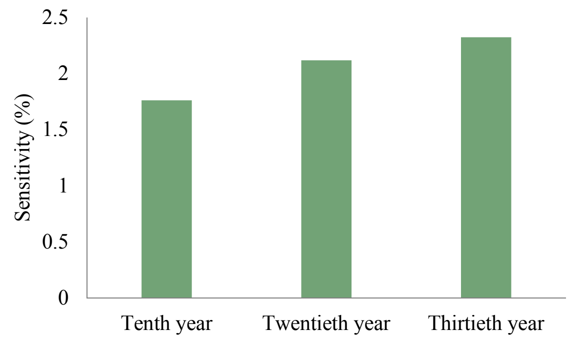

Fig. 10: Influence of degradation scenarios on carbon footprint of CC plants

Internal consumption effect which is pictured in Fig. 9 leads to the conclusion that combined cycle plants has almost low rate of internal consumption. Comparing Figs. 9 and 10 shows the degradation effect on carbon footprint of combined cycle power plant is in the same scale of internal consumption effect.

CONCLUSION

This study has proposed a carbon footprint model for fossil fuel power plants based on LCA standards. Plant type, fuel type, fuel transfer emission, site ambient condition, distribution and transmission losses, degradation and internal consumption are investigated as parameters affecting the carbon footprint of the power plant. The model has been evaluated by sensitivity analyses according to OAT/OFAT model with the purpose of informing electricity suppliers and policy makers on the current impacts and GHGs emission hotspots in the electricity sector. In Iran, capacity of simple cycle power plants is 26594 MW which has produced 73340 GWh of electrical energy accounts for 26.7 % of the total need of electrical energy in Iran. Capacity of Combined cycle power plants is 18978 MW which has produced 946823 GWh electrical energy accounts for the 35.3 % of total Iran network demand. The steam plants installed capacity is 15829 MW which producing 85624 GWh of energy that accounts for the 31.2 % of the required energy. Hydro power plants have a share of almost 5 %. The other types of power plants are responsible of nearly 2% of Iran network need. The total amount fuel consumed in the relevant period of time is 50172 million cubic meter of natural gas which equals 71.8 % of the total fuel consumption. The share of diesel oil is 8872 million liter which equals 12.6% of the total consumption fuel in power sector. Residual oil with the amount of 10273million liter has a share of 15% in the reference year. Being a rapidly developing country, energy demand in Iran is also growing, in particular its electricity consumption; which increased sharply in the period from 2001 to

2012. Iran electrical sector owns old infrastructures including power plants, substations and national grids. Hence vast variation and investment vision will be soon programmed for this fundamental sector. The actual implementation of the Joint Comprehensive Plan Of Action (JCPOA) on January 16, 2016, lifted crippling international sanctions against Iran which gives Iran the opportunity for stepping up the hunt for overseas investment in its energy infrastructure after talks with Siemens and Rolls-Royce. The new outlook for electricity sector has attracted the attention of academia to investigate the environmental impacts of the new vision. The outcomes of this study which can help the ministry for low registration are listed below:

- The carbon footprint of the total electricity sector is on average 491 g CO_2 eq/kWh. It is obvious that the mentioned quantity is not as high as the other developing countries which are dependent on fossil fuel because of the share of natural gas in Iran electricity sector. Fuel oil and mazut are backup fuel for winter when the natural gas pressure of the Gas Grid will be decreased in cold days due to residential consumption of natural gas for space heating.
- Carbon footprint of electricity at the last phase of life cycle (end user) varies from 312 to 980 g CO_2 eq/kWh. fuel type causes a variation of 28%. Ambient condition may change the result up to 13%. Transmission makes the carbon footprint larger by 4%. Internal consumption and degradation influence the result by 2 and 2.5%, respectively.
- Combined cycle power plants are the best choice for Iran electricity sector. Combined cycles recover the flue gas heat and produce more energy with consuming less water than steam power plants. They are not as expensive as steam power plants and not as sophisticated as them. If the total 26.5 GW of simple cycles evolves to combined cycles, the average carbon footprint of sector will be reduced to 404.5 g CO_2 eq/kWh.
- Degradation should be controlled by regular maintenance and overhaul. This factor can increase the carbon footprint of fossil fueled power plant by almost 5% during the plant life cycle. Substituting essential parts like turbine blades and HRSG harps and avoiding use of fuel and water with impurities can accelerate the process of aging.
- Internal consumption reduction by substituting the state of the art technology of electrical motors, using hybrid lighting systems, and building management systems for energy consumption of buildings in power plant can reduce the carbon footprint of the power plants. This reduction is 7% in steam, 1.8% in combined cycle and 0.7% in simple cycle plants. As in many other industries, the biggest consumption points in a power station are typically the motors that operate pumps, mills, fans and auxiliary systems. Older motors are often inefficient by today's standards, and in addition many systems are still controlled by throttling. This means the motor driving a pump or a fan runs at constant power regardless of load requirements. The flow of water or air is controlled with bypasses, resulting in significant energy waste. An integrated solution that combines variable speed drives with high efficiency motors can easily stem the energy waste. Today's motors and drive combinations can save 30 to 60 percent of the energy used by throttle valves and guide vanes to adjust air and water flow, and these energy savers are a mere fraction of the plant's total investment. By implementing such measures, electricity that was previously wasted can be sold to the grid, or the fuel wasted generating it can be saved. Depending on the application and local energy prices, the payback time of such an investment is typically under two years, and in some cases, just a few months.
- The reduced internal consumption can be provided by integrating renewable energy into the auxiliary power generation system. It seems necessary to count the emissions for producing the integrated renewable energy system. However, the operational carbon footprint such systems are zero.
- Site ambient condition is an essential factor for finding a suitable place for power plant construction. Site ambient condition includes three factors viz. altitude of the site, ambient temperature and ambient relative humidity. The effect of altitude is larger than ambient temperature, but ambient relative humidity is negligible.
- The distance which fuel is traveled is also important because it makes a source of indirect emission.

The proposed scenarios are also design to apply for finding an optimal location for constructing a power plant from global warming point of view. To find the place where the carbon footprint of the power plant is minimized, three spatial parameters viz.

altitude of construction location, distance of fuel traveling and distance between location of electrical energy consumption and location of power plant construction are important.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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