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LCA Frameworks Integration in Carbon Footprint Modeling of Simple Cycle and Combined Cycle Power Plant for Sustainable Planning in Iran

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ABSTRACT: The present research introduces a pseudo comprehensive carbon footprint model for simple cycle and combined cycle power plants based on Life Cycle Assessment frameworks for sustainable planningin Iran. For this purpose, parameters which their effects are considered distinguishable have been investigated. The mentioned parameters include: plant type, fuel type, fueltransmission type, own consumption of the plant, degradation, site ambient condition, transmission and distribution losses. Investigating power plant operational phase and transmission and distribution effect on carbon footprint assessment of power plant is the specific feature of the proposed model. Afterward, a sensitivity analysis is performed under different cases covering all the possible choices for investigated parameters affecting the carbon footprint. The results show that carbon footprint of fossil fuel (simple and combined cycle) varies remarkably due to the parameters. Results of sensitivity analyses show that by controlling the effective parameters carbon footprint of power plants can be reduced by 142%.

Key words: Carbon footprint, Power plant, Electricity, Transmission, Distribution

INTRODUCTION

All electricity generation technologies produce carbon dioxide (CO2) and other greenhouse gas emissions. Many environmental problems can ascend as a consequence of these emissions such as acid rain, air pollution and global warming. Based on statistics of International Energy Agency in year 2013, about 25000 TWh of electricity has been produced in the world and consequently 13.5 Gt CO2eq (equivalent) has been emitted in atmosphere (IEA, 2013). Increasing rate of mean earth temperature which is consequence of increasing rate of GHG emission is an interesting issue for researcher, organization and governments to make some specific policies in order to control of global warming. To equate the effects of diverse technologies precisely, the total CO2 amounts emitted throughout a system's life must be considered. Both of direct - arising during operation of the power plant, and indirect - arising during other non-operational phases of the life cycle- have been considered in precise calculation. One of the m major source of GHG emission are Fossil fuelled technologies (coal, oil, gas) and as a results these technologies have the largest carbon footprints, because they burn these fuels during operation (IEA, 2016).

One of the most important subjects which emerged from ecological footprint concept is "Carbon footprints". Carbon footprint is a significant sign of human activities influence on the environment. In detail, carbon footprint (CF) is a measure of the total amount of greenhouse gasses, stated as carbon dioxide equivalents, that directly and indirectly outcome of an activity or that accumulate during the life steps of a project (Carbon Trust, 2007). Study on carbon footprints covers a various range of both large-scale and small-scale areas of interest. For instance, large-scale studies have considered at the carbon footprint of industrial production and agricultural activities, while small-scale studies have consists of topics such as the carbon footprint of specific industrial processes and carbon footprint of individual behavior. Calculation of carbon footprints for individual behavior have been investigated by many methods and models such as works of Rahman et al. (2011). Life cycle assessment (LCA) is one of the best method in different calculation approaches mostly consist of different procedures such as life cycle assessment which has been done by Brizmohun et al (2015), Treyer and Bauer (2016), Atilgan and Azpagic (2016, 2015), Ozcan (2016), Sengül et al (2016), Georgakellos (2012) on a national scale for Turkey, Mauritius, Greece and other countries. Some scientists have favored to study on different technolo-

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gies worldwide, such as Turconi et al. (2013). Other researches are focused on the fuel type such as study of Tokunaga and Konan (2014).

This paper proposes a carbon footprint model for fossil fuel power plants. In contrast to the previous studies which have addressed only total emission and the net electrical energy, this paper calculates the carbon footprint of the power plant considering nine parameters viz. plant type, fuel type, fuel transmission type, own consumption of the plant, degradation, site ambient condition, transmission and distribution losses. Investigating power plant operational phase and transmission and distribution effect on carbon footprint assessment of power plant is the specific feature of the proposed model. A sensitivity analysis to indicate the importance of each parameter on carbon footprint calculation is performed. Because Iran Government tends to renovate the total electrical network including power plants and transmission and distribution grid after Joint Comprehensive Plan of Action, the results of this study leads to provide specifications to optimize the power plant location to fulfil the sustainable planning for the 6th National Development Program.

MATERIALS & METHODS

Carbon footprint is the science of calculating the amount of CO2eq emitted during the producing phases of unit of product. Therefore, Eq. 1 is considered for calculation of carbon footprint:

$$\text{Carbon Footprint(CF)}=\frac{\text{total equivalent } CO_2 \text{ emission}}{\acute{P}OH} \quad (1)$$

Where P is the modified power of the plant (the net capacity of the plant) and OH is the operating hours in an arbitrary time span. For modeling the emission and electricity production life cycle assessment (LCA) approach has been used, following the LCA methodology described in ISO 14067. The equivalent emission of CH4 and N2O are also included for precise results. The emissions are converted to carbon dioxide equivalents based on the 100-year global warming potential factors reported by the IPCC's Fifth Assessment Report, 2013.

Emission of the plant in all phases of its life span has two components viz. emission of fuel combustion and fuel transportation. Emission of fuel combustion depends on the amount and type of fuel consumed (Li, 2014). Actually the heat content of the fuel and consequently the emission factors play essential role in final calculation. Eq. 2 shows the combustion emission of a mixture of natural gas (NG) and diesel oil (DO) (IPCC, 2006):

$$ec = \sum_i a_i ef_i V_i \quad (2)$$

Which α_i-i and ef*i* are calculated by Eqs. (3) and (4):

$$\alpha_i = 10^{-9} \rho_i LHV_i \quad (3)$$

$$ef_i = ef_{CO_2 i} + 21 ef_{CH_4 i} + 276 ef_{N_2O i} \quad (4)$$

Where *i* is fuel type index and switches to NG and DO, ec presents emission of combustion in kg, ?stands fordensity of fuel in kg/m3, LHVis Low Heating Value in kJ/kg, V indicates volume of fuel consumed in m3 andefis emission factor in kg/TJ. Emission factors are excerpted from IPCC Guidelines for National Greenhouse Gas Inventories. Fuel transportation is a cause of indirect emission. Fuels are transported to the plant via pipeline, rail and road trucks. Natural gas is always transmitted via pipeline in Iran. If Diesel oil is transported via pipeline, the emission is estimated by Eq. 5 (IPCC, 2006):

$$et = \sum_i 10^{-12} V_i ef_i \quad (5)$$

Where i is fuel type index and switches to NG and DO, etpresentsemission of fuel transportation in kg, Vstands forvolume of fuel consumed in m3 andefisemission factor in Gg/106 m3. If the liquid fuels transmitted to power plant within road or rail freight transit, the decisive parameters are the distance of fuel transfer and the vehicle fuel consumption (Raj et al., 2016). The mentioned parameters are formulated to estimate the emissions in Eq. 6 (IPCC, 2006):

$$et = \sum_{i,j} fc_j d_{ij} (v_i p_i) \beta_i ef \quad (6)$$

And β and *ef* are calculated by Eqs. 7 and 8.

$$\beta = 10^{-15} LHV_{DO} \rho_{DO} \quad (7)$$

$$ef = ef_{CO_2} + 21 ef_{CH_4} + 276 ef_{N_2O} \quad (8)$$

Where i isfuel index switches to NGand DO, j indicates the means of transport index switches to rail and road tankers,et stands foremission of fuel transportation in kg,f_cpresents fuel consumption rate of vehicles in l/ton.km, ?is density of fuel in kg/m3, LHVindicates Low Heating Value in kJ/kg, Visvolume of fuel consumed in m3, efpresentsemission factor in kg/TJ anddis distance of fuel transportationin km. In Iran average diesel oil consumed as the fuel of freight road and rail tankers. The fuel consumption of road and rail freight is respectively 0.0051 and 0.036 l/ton.km. Net electrical energy which is the power plant product is estimated by Eq. 9:

$$P' = P.f.OH \quad (9)$$

Where P is nominal power in MW andf indicates Power factor and OH is the operating hours. Power factor which is a representative of power reduction coefficient has five components which are mentioned in the previous paragraph and demonstrated in Eq. 10:

$$f = f_{degradation}\, f_{own\ consumption} f_{ambientcondition} f_{transmission} f_{distribution} \quad (10)$$

The above cited parameters are calculated by estimating the loss caused by the effective factors.This fact is formulated as Eq. 11:

$$f_i = 1 - L_i \quad (11)$$

Where L stands for loss coefficients. The first parameter is degradation is the power plant loss due to fouling which is recoverable and aging which is non-recoverable unless parts are replaced. The simplified average non recoverable degradation is modeled and functionalized with Eq. 12. The coefficients are different for simple and combined cycle power plant (Kelhofer et al., 2009).

$$f_{degradation} = \frac{1}{a + bLn(OH) + cLn(OH^3)} \quad (12)$$

The ambient condition 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. This reflects in Eq.13(Kelhofer et al., 2009):

$$f_{ambient\,condition} = f(h) f(\theta) f(RH) \quad (13)$$

Elevation from sea level (Air pressure) has an influence 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 attitude on which plant establishment can be seen is 3000 meters above sea level. In this order of attitude above sea level, the atmospheric pressure varies linearly with altitude (Kelhofer et al. 2009). Thus the power factor varies linearly with altitude and represented by Eq. 14:

$$f(h) = 1 - 0.00011(h) \quad (14)$$

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 gas turbine power output. Books were published as practice for gas turbines produced power factor graph for average ambient temperature; the data fitted into Ratkowsky model. Eq. 15 and Eq. 16 represent the effect of temperature on gas turbine and combined cycle plants respectively(Kelhofer et al., 2009):

$$f(\theta) = \frac{1.798}{1 + eq(-0.15 + 0.015\theta)} \quad (15)$$

$$f(\theta) = 1.0482\, e^{-0.0032\theta} \quad (16)$$

Simple cycle and combined cycle output will increase if the relative humidity of the ambient air increases, while other conditions remain constant. This is because at higher of relative humidity there will be a higher water content in the working medium of the gas cycle, resulting in a better gas turbine enthalpy drop and more exhaust gas energy entering the heat recovery simple cycle generator (HRSG). Eq. 17 is used to quantify the effect (Kelhofer et al, 2009):

$$f(RH) = 0.994 + 0.0045(RH) \quad (17)$$

Transmission and distribution result in considerable losses in National Grids. According to statistics released on year 2013, National Grid has a loss of 3.45% in transmission and 14.9% in distribution (Tavanir, 2013). 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 kilometer is calculated. This method is also applied for the distribution losses (World Bank, 2013).

Own consumption of the plant should also be subtracted from the power generated while the consumption makes the footprint larger. Own consumption has a wide range because of the variation of equipment and their manufactures. However for each type of plants the average is almost constant. The average own consumption is calculated and presented in Table 1 (Tavanir, 2013).

Table 1. Own consumption of the Plants

	Gas	Combined cycle
Own consumption (%)	0.75	1.85

To find the effectiveness of each investigated parameters on carbon footprint of the power plant, a sensitivity analysis has been performed. The purpose of the analysis is to investigate and measure the effectiveness of parameters and their variability of carbon footprint.The one-factor-at-a-time (OAT/OFAT) model is applied for assessment (Saltelli, 2008, Wolfram et al., 2016). For this purpose one baseline casehas been developed with least carbon footprint. In fact the baseline case compares the effect of types of power plants for a 486 MW gas turbine power plant and a 486 MW combined cycle. Table 2 shows various conditions that effect the emission of the power plant with the same amount of product.This evaluation is also performed for own consumption of the plant as described in Table 3. Site ambient condition has also affected the carbon footprint of both power plants. However, the effect is different to some extent when the effect of ambient temperature is considered. For quantifying the effect of site ambient condition, cases in with different condition considered. These cases are compatible with 10 cities in Iran and presented in Table 4.

The influence of transmission and distribution losses have also been studied with 6 different consumption locations in Iran. For each location, 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. The first is the location where plants are situated; Mazandaran. The surplus of the production is assumed to be consumed in other regions such as Tehran, Semnan and both together. Two other cases in this regard have also been investigated;one considers the consumption in all the neighboring companies and one is the consumption of the electricity totally on grid. The mentioned cases are described in Table 5.

The next parameter to be added in the analysis is degradation of the plants. The rate of degradation is different in different plant type. However this parameter is the same in a specified plant in a specified time interval. Carbon footprint of two plants are estimated in four time span, the first is in first year of operation, the second is in the year 10th and the third is in the rear 20th and the fourth one is considered in 30th year as explained in Table 6.

Table 2. Plant Type, Fuel type and Fuel Transport Effect

No	Fuel combination	Transfer means
1	Natural Gas	Pipeline
2	Diesel Oil	Freight Train
3	Diesel Oil	Road Tanker
4	Natural Gas + Diesel Oil	Pipe line + freight train
5	Natural Gas + Diesel Oil	Pipe line + Road Tankers

Table 3. Plant Own Consumption condition

Plant Type	Least Own Consumption (%)	Average Own Consumption (%)	Most Own Consumption (%)
Gas Turbine Plant	0.2	0.9	2.1
Combined Cycle Plant	1.2	1.8	2.3

Table 4. Site Ambient Condition Cases

	Altitude (m)	θ(°C)	*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

Table 5. Consumption Location Cases

Consumption Location
Mazandaran
Tehran
Semnan
Tehran and Semnan
Tehran-Semnan-Gilan-Khorasan
Totally on Grid

Table 6. Degradation Condition

Plant Type and degradation Power factor	First year	Tenth year	Twentieth year	Thirtieth year
Gas Turbine	1	0.977	0.971	0.968
Combined Cycle Plant	1	0.982	0.979	0.977

RESULTS & DISCUSSION

The simple cycle plant has a capacity of 486 MW with availability of 62.1%. According to Table 2, this amount of energy can be produced with different combination of fuels; natural gas, natural gas plus diesel oil. The diesel oil transportationhas also been discussed 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 simple cycle varies in a range of 481in minimum to 761 g CO2eq/kWh in maximum. Fuel transportation influences the results and causes a variation of 6 g CO2eq/kWh for diesel oil. If diesel oil combines with natural gas for fuel portfolio, the share of transportation in emission is 4 g CO2eq/kWh. Fig. 1 shows the carbon footprint of each cases. Considering the fuel change, carbon footprint can be reduced by 40%.Fig. 2 shows the carbon footprint of simple cycle with all parameters constant and justthe consumption location varies in 6 different locations. If the electricity distributed in total Iran national grid, carbon footprint increases by 21% comparing to minimum. From Fig. 2, it is obvious that localization of grid can help to reduce the carbon footprint, if the ambient condition would cause minor consequences. Fig. 3 indicates the effect of site ambient condition. This parameter can show a variation of almost 32%. Fig. 4 cited the effect of own consumption of the simple cycle plant. The own consumption can varies from 0.1% to almost 2.1%. Reduction of these amounts to least possible own consumption leads to a reduction about 2.5 % of carbon footprint. This fact can also leads to more electricity for sale. The surplus of energy sold can fulfil the investment finances. Fig. 5 illustrates the effect of degradation on the carbon footprint of simple cycle plants. Degradation is an inevitable process for any kind of equipment. Maintenance and overhauls can slow the rate of degradation. However, the amount is about 1.45% in thirty years of operation.

Combined cycle plant with a capacity of 486MW is considered. By a reviewing Table 4 one more, the fuel combination is the same as simple cycle plant. The results of different cases show that minimum of the plant CF is 321 and the maximum is 489.9 g CO2eq/kWh. The influence of fuel transportation is 4 g CO2eq/kWh for

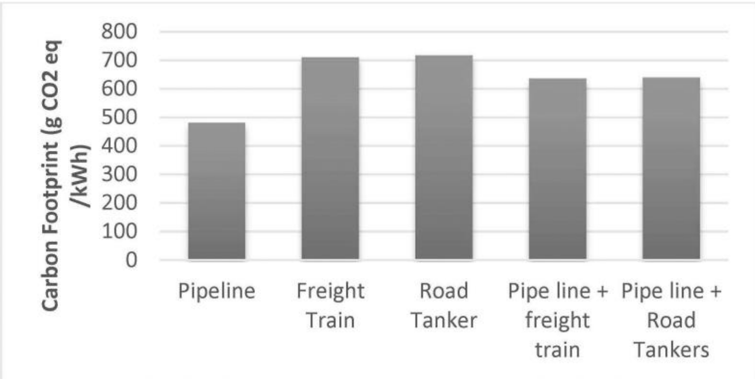

Fig.1. Carbon Footprint and emission cases for Simple Cycle plant

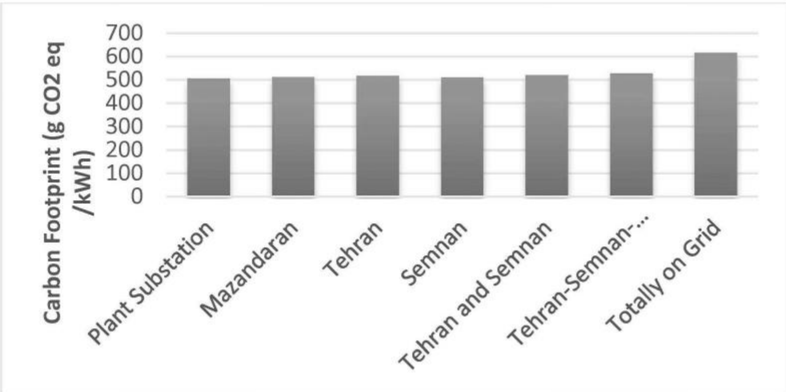

Fig. 2.Carbon Footprint and consumption location cases for Simple Cycle plant

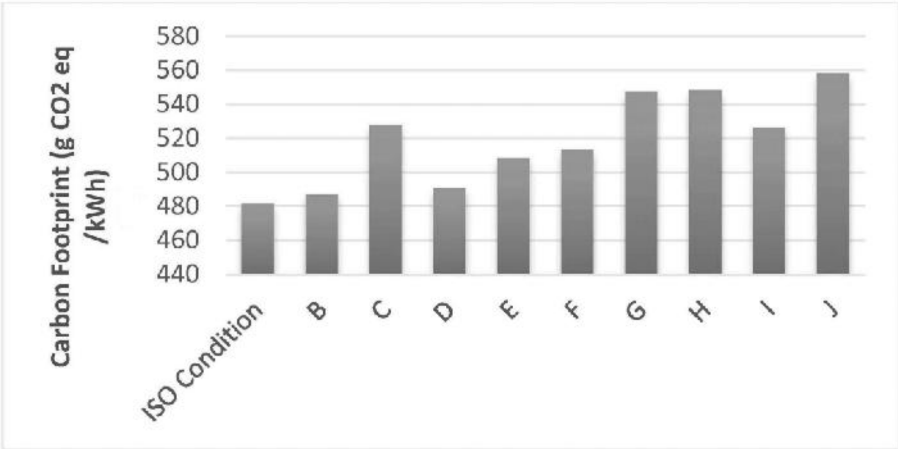

Fig. 3.Carbon Footprint and site ambient cases for Simple Cycle plant

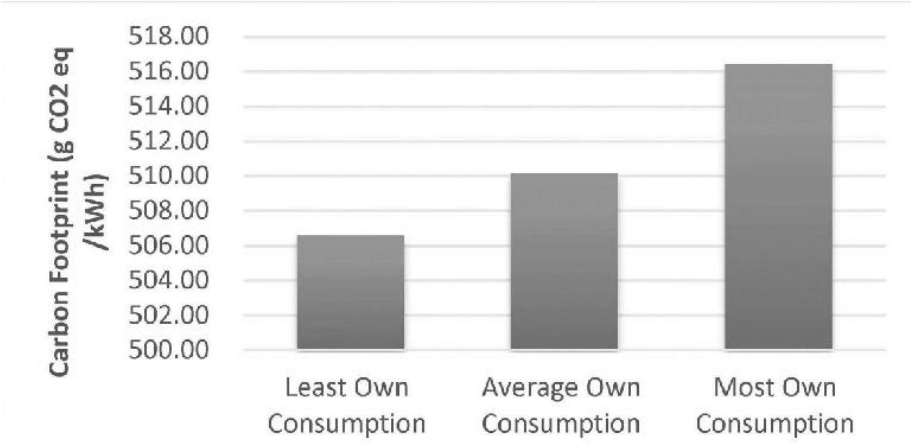

Fig. 4.Carbon Footprint and own consumption cases for Simple Cycle plant

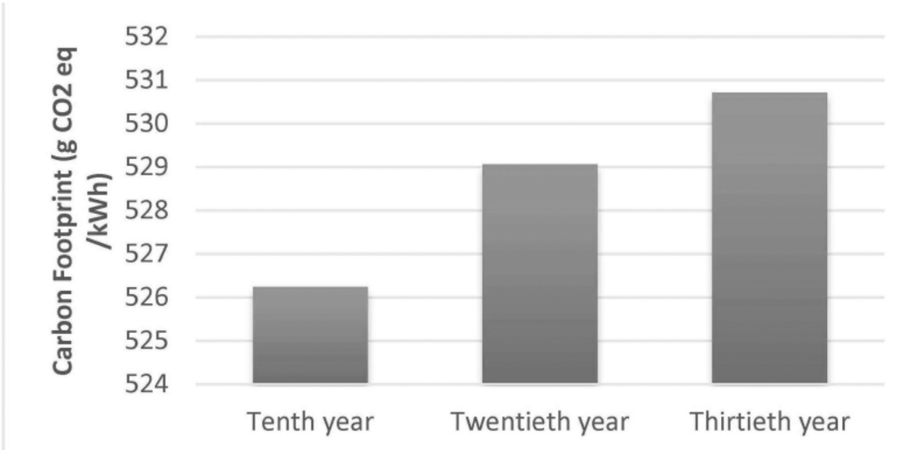

Fig. 5.Carbon Footprint and degradation cases for Simple Cycle plant

the difference of road and rail transit of fuels. This fact is presented in Fig. 6. Fig. 7 shows the effect of consumption location effect on carbon footprint and gives the conclusion that transmission and distribution losses have the same result as the simple cycle plant.Combined Cycle is also sensitive to site ambient condition. Fig. 8 shows the variability of carbon footprint to site condition. A variation of almost 16% is calculated for J city as the altitude of the plant increases. The low altitude land with high relative humidity and low temperature is the best

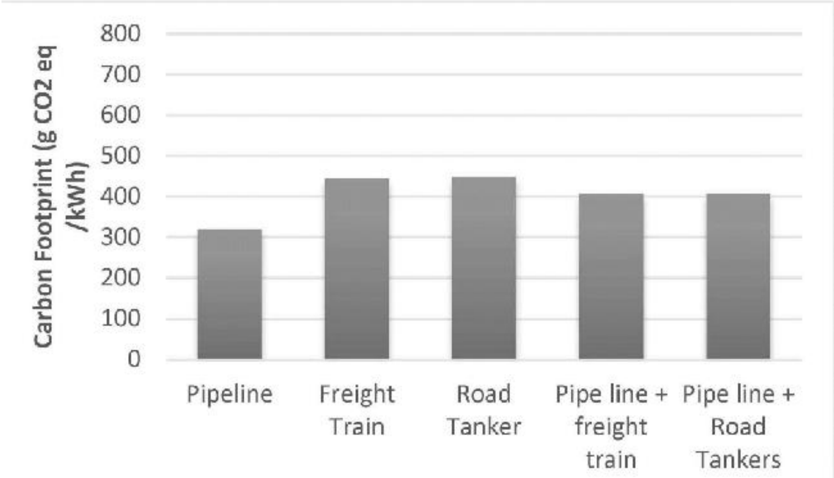

Fig. 6.Carbon Footprint and emission cases for Combined Cycle plant

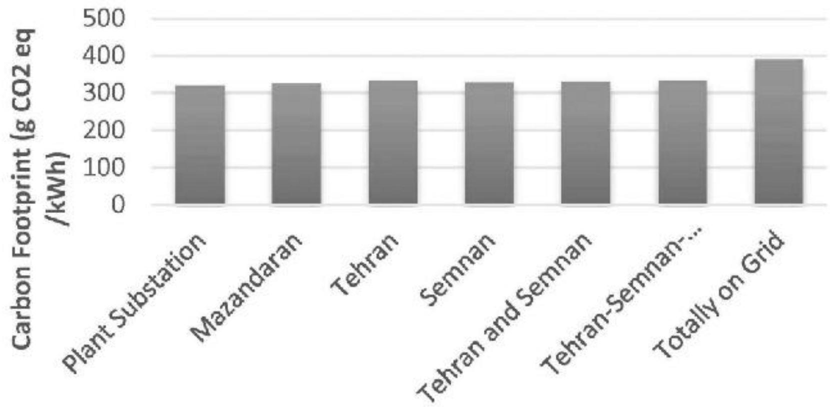

Fig. 7. Carbon Footprint and consumption location cases for Combined Cycle plant

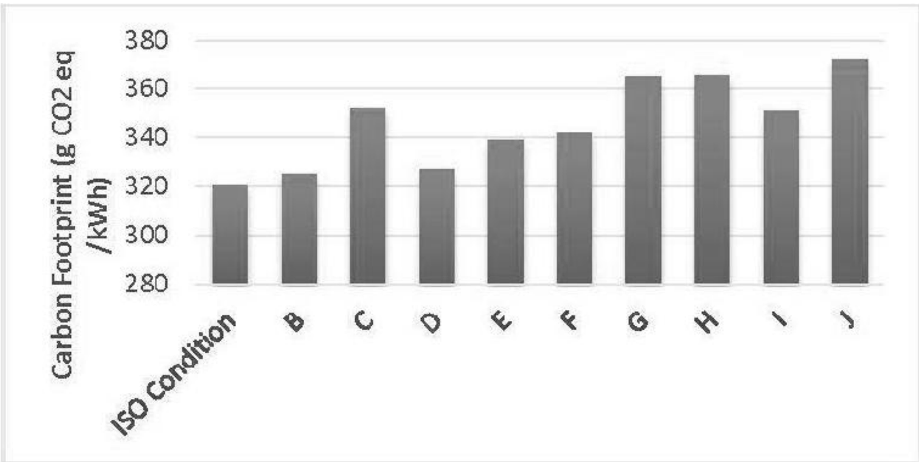

Fig. 8.Carbon Footprint and site ambient cases for Combined Cycle Plant

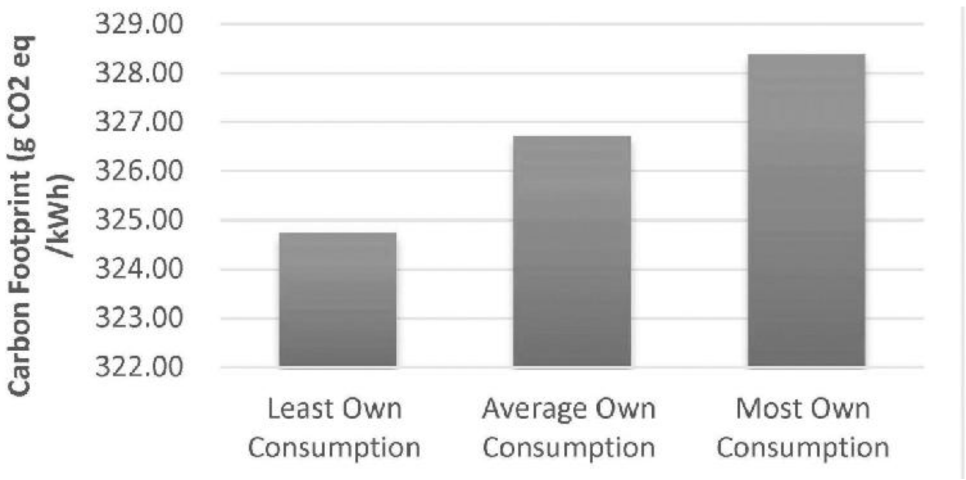

Fig. 9.Carbon Footprint and own consumption cases for Combined Cycle Power Plant

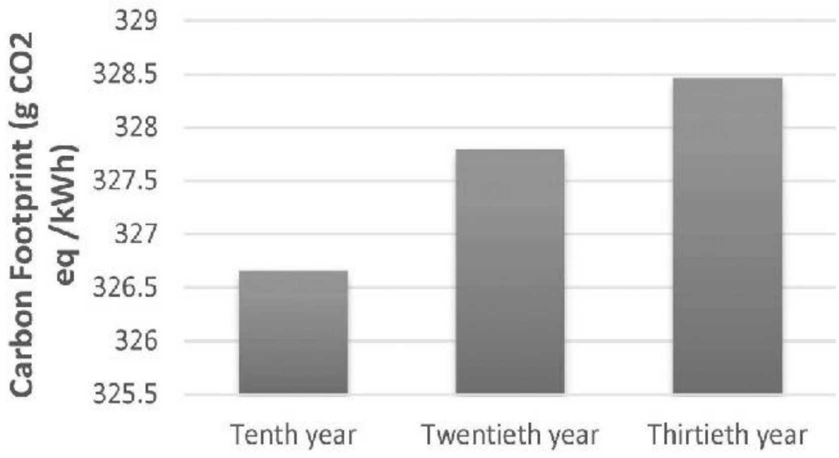

Fig. 10.Carbon Footprint and degradation cases for of Combined Cycle Plants

place to build a combined cycle power plant. Result of this study can create a specification for location optimization of power plants. The newly planned power generation stations then would be categorized as sustainable power plants.Own consumption effect which is pictured in Fig. 9 leads to the conclusion that combined cycle plants has almost low rate of own consumption. Comparing Fig. 9 and Fig. 10 shows the degradation effect on carbon footprint of combined cycle plant is in the same scale of own consumption effect.

CONCLUSIONS

This study has proposed a carbon footprint model and a sensitivity analysis by considering Iran as the case study. The main purpose of the study has been creating a tool for sustainable planning in Iran. Fossil fueled simple cycle and combined cycle power plants consume natural gas, diesel oil. The results show that the carbon footprint of electricity delivered to the final consumers varies in a range from 321 to almost 780 g CO2 eq/kWh when all negative parameters are considered in a special case.The amount shows 142% variation. From the global warming point of view combined cycles emits the least GHGs in comparison with other types of the fossil fuel power plants and can be the best choice for power infrastructures. If all 85 GW of gas turbine cycles evolve to combined cycles the average carbon footprint of grid can be reduced from 574 to 506 g CO2 eq/kWh.Fueltransportation via pipeline is agreed to be the best choice, when no pressure booster is required. This is possible when fuel preparation location is close to the power plants. Rail tankers have also preference to road tankers. Development of railway in Iran can reduce the fuel transportation emission by 75%.The next parameter affecting the carbon footprint of electricity is the site condition of the power plants. Site ambient condition is so effective on simple cycle. Combined cycles have been less touched by the site condition in comparison with simple cycle plants. The stated conclusion can be an input to optimize location of power plants. Own 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 1.8% in combined cycle and 0.7% in simple cycle plants. Transmission and distribution play an important role in carbon footprint of electricity for final consumers. If the electricity transmitted through the entire network of Iran, cause 15% more emission. As unsuitable site condition increase the carbon footprint of electricity up to 50%. It is suggested that before constructing a power plant, a carbon footprint study would be conducted. The comparison of site ambient condition carbon footprint and transmission and distribution carbon footprint is a good guide to choose an optimal location for the power plant. A better suggestion is the renovation of grid and after that localization of power generation and consumption leads to a lower carbon footprint of electricity. Based on the 6th Iranian Development Program, besides the cogency of diversity of electrical energy production portfolio, Optimization of production, increasing the efficiency of power plant, reducing the loss of transmission and distribution, 37000 MW of fossil fueled must be commissioned for the year 2025. While new power plant are about to constructed, result of this study can create a specification for location optimization of power plants. The newly planned power generation stations then would be categorized as sustainable power plants.

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