Fuel and GHG Emission Reduction Potentials by Fuel Switching and Technology Improvement in the Iranian Electricity Generation Sector

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ABSTRACT

In this paper, methodology to estimate GHG emissions of electricity generation sector was first explained. Then different scenarios to reduce GHG emissions by fuel switching and adoption of advanced power generation systems (based solely on fossil fuels) were evaluated.

The GHG calculation results for the Iranian power plants showed that in 2005 average GHG intensity for all thermal power plants was 610 gCO_2eq/kWh. However, the average GHG intensity in electricity generation sector between 1995 and 2005 experienced a 13% reduction. The results demonstrated that there were great potentials for GHG emission reduction in this industry.

These potentials were evaluated by introducing six different scenarios. In the first scenario, existing power stations' fuel was switched to natural gas. Existing power plants were replaced by natural gas combined cycle (NGCC), solid oxide fuel cell (SOFC), and hybrid SOFC plants in scenario numbers 2 to 4, respectively. In the last two scenarios, CO_2 capture systems were installed in the existing power plants and the second scenario, respectively.

Keywords: Greenhouse gases, GHG emission reduction potentials, Electricity generation sector, Iran, Fuel switching, NGCC, SOFC, Hybrid cycles, CO_2 capture.

1. INTRODUCTION

Although natural emission of greenhouse gases (GHGs) is essential to maintain life on earth, many human activities emit additional GHGs to the atmosphere. It has been shown that there is a direct link between increasing concentration of GHGs in the atmosphere and the global climate deterioration [1, 2].

In 1992, countries and governments around the world met in Rio de Janeiro to address the climate change challenge by taking action to reduce GHGs. As a result, the United Nations Conference on Environment and Development (UNCED) prepared an international environmental treaty known as United Nations Framework Convention on Climate Change (UNFCCC or FCCC). Again, in 1997, more than 160 countries met in Kyoto, Japan, to find a practical procedure to reduce GHG emissions. They agreed to reduce GHG emissions according to the Kyoto Protocol that set out targets and options available to achieve those targets [3].

The objective of Kyoto Protocol is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [3]. In this Protocol, countries are divided into two categories: Annex I Parties and Non-Annex I Parties. Annex I countries are committed to decrease their GHG emissions to the target levels below their GHG emissions levels in 1990. For instance, Canada's target is to reduce its GHG emissions to 6 percent below 1990 GHG emissions level by the period between 2008 and 2012. The reduction percentages are varied from 8% for the European Union and some other countries to 7% for the USA, 6% for Japan, 0% for Russia, and allowed increases of 8% for Australia and 10% for Iceland [4]. The Annex I parties are mostly developed countries and contribute most of the GHG emissions in the world. Also, the Annex I Parties are required to submit an annual national greenhouse gases inventory report according to UNFCCC reporting guidelines. A GHG inventory report is an annual national accounting of GHG emissions and removals in each country.

The Kyoto Protocol became formally binding on February 16, 2005, after it was ratified by more than 55 countries, covering more than 55 percent of the GHG emissions addressed by the Protocol. As of May 13, 2008, the total percentage of Annex I Parties GHG emissions was 63.7% and 181 countries and 1 regional economic integration organization (European Union) approved the Protocol [5].

Since most of the developing countries, including Iran, are among Non-Annex I Parties, they are not required to submit annual GHGs inventory report and they have no GHG emission reduction obligations. However, it is necessary to prepare such a report, at least unofficially, to anticipate future reduction obligation. That is why in the first part of this paper, methodology to prepare GHGs inventory report for electricity generation sector is briefly explained and the method is implemented to estimate GHG emissions in Iranian electricity generation industry.

According to the Kyoto Protocol, developing countries can join Annex I Parties as soon as they believe they are sufficiently developed. Therefore, eventually all countries will be required to submit such report and accept GHG emission reduction obligations. Thus, it is essential for these countries to be ready for that time and reduce their GHG emissions. Also, more importantly, the global climate change is a worldwide phenomenon so all countries in the world should be involved to face this challenge. Moreover, this report can be used as an indication of performance of the electricity generation sector in terms of their environmental impacts. This approach will lead to a more sustainable society which means enough resources for everybody at anytime.

Furthermore, meeting reduction target could have financial benefits for developing countries due to "flexible mechanisms" in the Kyoto Protocol. These mechanisms are developed to permit Annex I countries to buy GHG emission reductions from elsewhere. This means Non-Annex I countries have no GHG emissions limitation. However, they can implement GHG emission reduction project (which is called a GHG Project) and receive Carbon Credit for the project. Then, Annex I countries can purchase credit to meet their GHG reduction obligations. The purpose of these mechanisms is to encourage Non-Annex I parties to reduce their emissions since it is now economically viable [4]. Therefore, for Non-Annex I countries reducing GHG emissions are beneficial both environmentally and economically.

The objectives of this paper are to evaluate the current status of GHG emissions in fossil fuel-fired electricity generation industry and then to introduce and evaluate several scenarios to reduce these emissions from fossil fuel-fired power generation. In order to achieve these objectives, first, methodology to estimate GHG emissions to prepare annual greenhouse gases inventory report using UNFCCC reporting guidelines and Iran as an example will be explained. Then, different scenarios to reduce GHG emissions by fuel switching and adoption of advanced power generation systems will be evaluated.

2. CAUSES OF THE GREENHOUSE EFFECT

The earth absorbs energy from the sun and emits energy in the form of radiation. Since the earth temperature is much lower than the sun temperature, its radiation has much longer wavelengths. Greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O), are transparent for short wave radiant energy but they absorb some of longer wavelengths before they are lost to the space. This phenomenon results in increase in the atmospheric temperature which in turn causes atmosphere to emit long wave radiation both upward and downward to space and surface, respectively. The downward part of this radiation is the greenhouse effect.

Although the detailed causes of global warming is unknown and is, in fact, an active field of research, the scientific consensus considers increase in atmospheric GHG level as the primary cause of the recent global warming. One of the reports of the Intergovernmental Panel on Climate Change (IPCC Working Group I) concluded that [6]: "our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitudes and patterns of long-term variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests that there is a discernable human influence on global climate".

The major natural greenhouse gases are water vapor, carbon dioxide, methane, ozone, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons, perfluorocarbons and chlorofluorocarbons. It should be noted that since the influences of the various gases are not additive, it is not possible to state that how these gases contribute to the greenhouse effect. Carbon dioxide, methane, nitrous oxide and three groups of fluorinated gases are the subject of the Kyoto Protocol.

3. CURRENT STATUS OF GHG EMISSIONS IN POWER GENERATION INDUSTRY

In this section, current and expected future status of electricity generation sector and its contribution to GHG emissions in the world and Iran will be investigated.

According to the World Energy Outlook published by the International Energy Agency (IEA), the world's total net electricity consumption will increase dramatically in near future. The world electricity generation was 14,781 billion kWh in 2003 and will increase to 21,699 and 30,116 billion kWh in 2015 and 2030, respectively, which means a 2.7% average annual increase rate [7].

The same report predicted that the share of fossil fuels as energy supplies for electricity generation would remain constant at nearly 65%. Also, GHG emissions from energy industry will increase by 55% between 2004 and 2030. During this period, coal and oil are leading contributor to global energy-related CO_2 emission, respectively [7].

Figure 1 shows CO_2 emission of large point sources by industry. As the chart illustrates, power production industry is responsible for 54% of the industrial CO_2 emissions [8, 9].

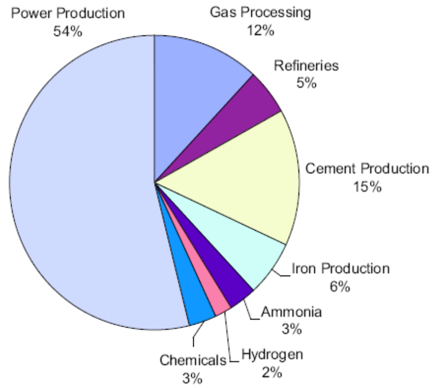

FIGURE 1: Industrial CO_2 emission of large point sources [8, 9]

Iran's electricity generation sector requires 54 GW of new power plants to increase its electricity generation from 153 TWh in 2003 to 359 TWh in 2030, growing at average rate of 3.2% per year over the period. This new capacity needs about $92 billion investment and is dominated by natural gas-fired, mostly combined cycle power plants (CCPP). In fact, more than 75% of electricity is generated in natural gas-fired power plants [10].

Table 1 reflects the status of Iranian electricity generation sector in terms of the sources and technologies [11]. The table shows the distribution of electricity generation capacity and generated electricity for different types of power stations and their contribution in Iranian electricity generation industry during the period of March 2005 to February 2006. As the table illustrates, more than 90% of generated electricity and 84% of electricity generation capacity are based on fossil fuel-fired power plants.

Type of Power Plant	Capacity (MW)	Percent (%)	Electricity Generation (GWh)	Percent (%)
Steam Cycle	15,554	37.9	93,383	52.4
Gas Turbine	12,050	29.4	32,128	18.0
Combined Cycle	6,832	16.7	36,194	20.3
Hydro-electric	6,037	14.7	16,085	9.0
Wind and Diesel	530	1.3	281	0.3

TABLE 1: Electricity generation capacity and generated electricity for different types of power stations in Iranian electricity generation sector during the period of March 2005 to February 2006 [11]

These statistics show that electricity generation sector is and will remain a major source of GHG emissions and it is essential to reduce these emissions.

4. GHG EMISSIONS SOURCES AND ELECTRICITY GENERATION SECTOR

The IPCC published a guideline for greenhouse gas inventory report preparation. The first guideline was issued in 1997 [12] titled "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories". The "2006 IPCC Guidelines for National Greenhouse Gas Inventories" provides methodologies for estimating national inventories of anthropogenic greenhouse gases emissions and removals by GHG sources and sinks. This guideline categorized GHG production sources into 5 categories [13]: energy; industrial processes and product use; agriculture, forestry and other land use; waste; and others.

Based on the 2006 IPCC Guidelines, electricity generation sector is considered to be in category 1-A-1-a-i. The definition of these categories is as follows [13]:

1- Energy: Comprises emissions from combustion and fugitive releases of fuels for energy uses. All GHG emissions from the non-energy consumption of fuels are commonly included under Industrial Processes and Product Use.

1 A - Fuel Combustion Activities: GHG emissions from the intentional oxidation of fuels within a device to generate either heat or mechanical work.

1 A 1 - Energy Industries: Sum of emissions from fuels consumption for power generation industries.

1 A 1 a - Main Activity, Electricity and Heat Production: All emissions from electricity generation, combined heat and power generation, and heat plants that their products are supplied the public. These plants can be in public or private ownership and include on-site use of fuel.

1 A 1 a i – Electricity Generation: GHG emissions from all fuel combustion to generate electricity excluding those from combined heat and power plants.

5. DIFFERENT METHODOLOGIES TO ESTIMATE GHG EMISSIONS

In this section different methods to estimate GHG emissions will be investigated and the estimation for Iranian electricity generation sector will be presented as a case study. In this paper the “2006 IPCC Guidelines for National Greenhouse Gas Inventories” [13] will be used for estimating GHG emissions for Category 1-A-1-a-i.

Generally, emission of each GHG is estimated by multiplying fuel consumption by the corresponding emission factor. There are three tiers presented in the 2006 IPCC Guidelines for estimating emissions from fossil fuel combustion for electricity generation. In these tiers fuel consumption and emission factors are considered as follows [13]:

Tier 1: fuel consumption from national energy statistics and default emission factors;
Tier 2: fuel consumption from national energy statistics and country-specific emission factors;
Tier 3: fuel consumption from national energy statistics for different electricity generation technologies and technology-specific emission factors.

All tiers use the fuel consumption as the activity data. Thus, this parameter will be defined and then the tiers will be explained.

Activity data

To estimate GHG emissions from stationary power generation, the activity data are typically the fuel consumption to generate electricity. As it will be elaborated later in this section, these data are sufficient for Tier 1 analysis. In higher tier approaches, additional data are required on fuel characteristics and the power generation technologies.

In most of national energy statistics used for GHG emissions estimation, fuels consumption is specified in physical units, such as in tonnes or cubic meters. But in above mentioned tiers, the energy content of consumed fuels is required to estimate GHG emissions. Therefore, the mass or volume units of fuel consumption should be first converted. The fuels energy content can be expressed by two definitions:

- net calorific values (NCV) or lower heating value (LHV),
- gross calorific values (GCV) or higher heating value (HHV).

The difference between NCV and GCV is the latent heat of vaporization of the water content of exhaust stream. Therefore, the NCV for coal and oil is about 5 percent and for natural gas about 10 percent less than the GCV. The IPCC Guidelines use NCV, expressed in SI units or multiples of SI units (for example TJ/Mg). As a result when statistical offices use GCV for national energy statistics, it should be converted to NCV. In this paper the net calorific values provided by Iran Power Generation, Transmission, Distribution, and Management Co. [11] will be used.

Tier 1 approach

Tier 1 approach is a fuel-based method to estimate GHG emissions. In this tier, the quantities of consumed fuel and average emission factors for all relevant direct greenhouse gases are used for GHG analysis. The Tier 1 emission factors are available in IPCC guidelines. Table 2 shows default emission factors and lower and upper limits of the 95% confidence intervals for three fuels (natural gas, diesel oil, residual oil) [13].

As the table signifies, CO_2 emissions can be estimated with high accuracy when these average emission factors are used. But use of default emission factors for methane and nitrous oxide introduce relatively high uncertainty to the estimation. The reason for this difference is stemmed from the fact that emission factors for carbon dioxide depend on the carbon content of the fuel and the combustion technology and operating conditions of the plants are relatively unimportant. But for CH_4 and N_2O, emission factors depend upon combustion conditions (both plants technology and operating conditions over time). Since in Tier 1 these combustion conditions are not considered, relatively high uncertainty can be seen in non-CO_2 averaged emission factors [13].

Fuel Type	CO_2			CH_4			N_2O		
	Default Emission Factor	Lower	Upper	Default Emission Factor	Lower	Upper	Default Emission Factor	Lower	Upper
Natural Gas	56,100	54,300	58,300	5	1.5	15	0.1	0.03	0.3
Diesel Oil	74,100	72,600	74,800	10	3	30	0.6	0.2	2
Residual Oil	77,400	75,500	78,800	10	3	30	0.6	0.2	2

TABLE 2: Default emission factors and lower and upper limits of the 95% confidence intervals used in the Tier 1 (kg of greenhouse gas per TJ on a net calorific basis) [13]

Tier 2 approach

In Tier 2 approach, similar to Tier 1, the quantities of consumed fuel from fuel statistics are used to estimate GHG emissions. But instead of the Tier 1 default emission factors, country specific emission factors are used. In order to develop country specific emission factors, information such as fuels carbon contents, fuel quality, and the state of technological development (particularly for non-CO_2 emissions) for a given country should be taken into account. Other parameters to be considered are variation of emission factors over time, and the amount of carbon retained in the ash (for solid fuels). The data used in this tier are more applicable to a specific country's conditions. Therefore, it is expected that the results of applying this method is more accurate and the uncertainty range is smaller [13].

Tier 3 approach

Tier 1 and Tier 2 approaches of estimating GHG emissions described in the previous sections necessitate using an average emission factors, either default emission factors in Tier 1 or country specific emission factors in Tier 2. As noted earlier, in reality, GHG emissions depend upon the fuel type, combustion technology, operating conditions, control technology, quality of maintenance, and age of the equipments. In Tier 3 approach, these parameters are taken into account by using different emission factors for each case. As mentioned in Tier 1, emission of CO_2 highly depends on the carbon content of the fuel and not the combustion technology. Therefore, it is not required to use Tier 3 approach to estimate emissions of CO_2 and the CO_2 emission factors from Table 2 are sufficient [13].

Table 3 shows default emission factors for non-CO_2 emissions for three fuels (natural gas, diesel oil, residual oil) in Tier 3.

Fuel and Technology Type	Emission Factors (kg/TJ energy input)	
	CH_4	N_2O
Natural Gas		
Boilers	1	1
Gas-Fired Gas Turbines (>3 MW)	4	1
Combined Cycle	1	3
Gas/Diesel Oil		
Boilers	0.9	0.4
Residual Oil		
Residual Oil Normal Firing	0.8	0.3

TABLE 3 : Default emission factors used in the Tier 3 [13]

Global warming potential

Global Warming Potential (GWP) is the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas (carbon dioxide). By definition, “a GWP is the time-integrated change in radiative forcing due to the instantaneous release of 1 kg of the gas expressed relative to the radiative forcing from the release of 1 kg of CO_2” [14]. In other words, “a GWP is a relative measure of the warming effect that the emission of a radiative gas might have on the troposphere” [14]. In the estimation of GWP of a GHG, both the instantaneous and the lifetime of the gas are considered. The 100-year GWPs, recommended by the IPCC (shown in Table 4) and required for inventory reporting, are used in this paper. According to the IPCC the GWP of CH_4 and N_2O are 21 and 310, respectively. This means the contribution of 1 kg CH_4 and N_2O to the warming of the atmosphere are 21 and 310 times higher than 1 kg CO_2, respectively, for a 100-year time frame [14].

GHG	100-year GWP
CO_2	1
CH_4	21
N_2O	310

TABLE 4 : Global Warming Potentials [14]

Choose a tier for GHG emission estimation in power plants

Since country specific emission factors for Iran’s power plants do not exist, the Tier 2 approach cannot be used. On the other hand, due to the fact that fuel consumption for each technology is recorded, Tier 3 will be used for estimation of GHG emissions for 2004. However, for years before 2004, Tier 1 is more suitable. The activity data for GHG emission estimation is provided by the Iran Power Generation, Transmission, Distribution, and Management Co. [11].

6. RESULTS OF GHG EMISSION ESTIMATION

In this section, the aforementioned method will be used to estimate GHG emissions in Iranian electricity generation sector.

Table 5 shows the calculation results (electricity generation, fuel consumption, GHG emissions and GHG intensity) for electricity generation by fossil fuel-fired thermal power stations in Iran for the period of March 2005 to February 2006. In this table, greenhouse gas intensity is the ratio of greenhouse gas emissions to generated electricity. This parameter is used to evaluate the performance of electricity generation sector in terms of GHG emissions. Tier 3 approach has been used for this table with default emission factors from Table 2 and Table 3. As shown in the table, the greenhouse gas intensity for steam power plants, gas turbines and combined cycle power plants are 617, 773, and 462 gCO_2eq/kWh, respectively with the overall intensity of 610 gCO_2eq/kWh for all thermal power plants. It can be seen that combined cycle power plants emit 25% and 40% less GHG compared to steam power plants and gas turbines, respectively. This result is expected because combined cycle power plants have higher efficiency. In this case, the efficiency of steam power plants, gas turbines and combined cycle power plants are 36.5%, 27.8%, and 45.5%, respectively, during the same period. This means 25% and 64% higher efficiency for combined cycles in comparison to steam power plants and gas turbines, respectively.

Power Plant Type	Electricity Generation (GWh)	Fuel Consumption			GHG Emissions (kt/year)			GHG Intensity (gCO_2eq/kWh)
		NG (10^6 m^3)	Diesel (10^6 lit)	Residual Oil(10^6 lit)	NG	Diesel	Residual Oil	
Steam Cycle	89,574	17,211	43	6,329	35,074	123	20,104	617
Gas Turbine	29,023	8,444	1,819	0	17,227	5,220	0	773
Combined Cycle	36,194	7,204	660	0	14,841	1,894	0	462
Total/Ave	154,791	32,859	2,522	6,329	67,143	7,237	20,104	610

TABLE 5 : GHG emissions in Iran's thermal power plants from March 2005 to February 2006

Regarding average GHG intensity, it should be mentioned that the value shown in Table 5, 610 gCO_2eq/kWh, is just for thermal power plants. If whole electricity generation is considered (including hydro-electric power plants) this intensity will be reduced to 570 gCO_2eq/kWh.

Table 6 shows the GHG emissions and intensity of Iran's electricity generation sector from 1995 to 2005. According to this table, the average GHG intensity was reduced by 13% in this period. One of the reasons for this GHG emission reduction in Iranian electricity generation sector was that in recent years many combined cycle power plants were installed in the country. In fact, in 1999 there was no electricity generation using combined cycles, but in 2005, 20% of total electricity was generated by using these power plants. Moreover, fuel switching from diesel and residual oil to natural gas is another factor for the reduced GHG emissions.

Year	Electricity Generation (GWh)		GHG Emissions (kt)	GHG Intensity (gCO_2eq/kWh)	
	Thermal	Total		Thermal	Total
2005	157,181	173,547	98,991	630	570
2004	149,103	160,029	90,958	610	568
2003	135,574	146,988	79,631	587	542
2002	126,740	135,177	78,844	622	583
2001	118,890	124,306	75,099	632	604
2000	111,697	115,708	70,863	634	612
1999	101,845	105,187	65,137	640	619
1998	90,474	97,862	57,222	632	585
1997	84,926	92,310	57,470	677	623
1996	77,839	85,825	53,959	693	629
1995	72,046	80,044	52,299	726	653

TABLE 6: GHG emissions and intensity of Iran's electricity generation sector from 1995 to 2005

So far the results demonstrated that Iran's electricity generation sector did a reasonably good job in reducing the GHG intensity in the past 10 years. However, the detailed calculation proved that still there are power plants with extremely high GHG intensity. The detailed estimation of GHG for all Iran's major power plants (with annual electricity generation of more than 100,000 MWh in 2005) has been preformed [15]. The results showed that the GHG intensity for steam power plants was ranging from 515 to 1125 gCO_2eq/kWh. The range for gas turbines and combined cycles were 584-1346 and 428-513 gCO_2eq/kWh, respectively [16]. This indicated that there are great potentials for further GHG intensity reduction in the sector [17]. In the remainder of this paper some of these potentials will be discussed.

7. GHG EMISSION REDUCTION SCENARIOS

As mentioned, the electricity production industry has been responsible for a considerable portion of total GHG emissions. Therefore, in the remainder of this paper, GHG emission reduction potentials under different scenarios will be investigated.

These scenarios are based on fuel switching and the adoption of advanced power generation systems (based solely on fossil fuels) in electricity generation. Despite the problems associated with fossil fuel-fired power plants, fossil fuels are available on a mid and long-term basis and their continued large-scale and widespread applications in power generation industry are essential in order to maintain current economic growth in the world. The IEA has commented that "numerous technology solutions offer substantial CO_2 reduction potentials, including renewable energies, higher efficiency power generation, fossil-fuel use with CO_2 capture and storage, nuclear fission, fusion energy, hydrogen, biofuels, fuel cells and efficient energy end use. No single technology can meet this challenge by itself. Different regions and countries will require different combinations of technologies to best serve their needs and best exploit their indigenous resources. The energy systems of tomorrow will rely on a mix of different advanced, clean, efficient technologies for energy supply and use" [18]. Thus, both fossil and non-fossil forms of energy will be needed in the foreseeable future to meet global energy demands. It is, therefore, important that alternative technologies are commercialized to permit the consumption of fossil fuels with significantly reduced GHG emissions and other pollutants.

Based on this, different scenarios to reduce GHG emissions are defined as follows:

Scenario number 1: In this scenario, GHG emission reduction potentials by fuel switching will be investigated. Based on this scenario, all power plants will use natural gas as primary fuel instead of their original fuel. But technology of power stations will remain unchanged.

Scenario number 2: In the second scenario, there will be fuel switching as well as technology changes. In this scenario, all power stations will be replaced by natural gas combined cycle (NGCC). The size of the alternative NGCC power plant is 505 MW. The plant configuration consists of two gas turbines, a heat recovery steam generator, and a condensing reheat steam turbine. In this work the efficiency of the power plant is considered to be 49% (based on HHV) [19].

Scenario numbers 3 and 4: In order to implement these scenarios all existing power stations will be replaced by solid oxide fuel cell (SOFC) for the third scenario and hybrid SOFC power plants for the fourth scenario. In both cases power plants will be fueled by natural gas.

Fuel cells operation is based on direct and continuous conversion of fuel chemical energy into electrical energy in electrochemical process. Because of this direct energy conversion, their efficiencies are usually higher than conventional electricity generation technologies.

Fuel cells can be classified by their operating temperature and electrolyte compositions, which dictate their suitability for different applications. Solid oxide fuel cells have high operating temperature (between 600 °C-1000 °C) which makes them especially suited for stationary power generation. SOFCs can use natural gas, syngas from coal, and various biofuels directly due to this high operating temperature, which allow for internal reforming of these fuels within the cells. The SOFC operating temperature is also high enough to allow for integration with gas turbines and/or other bottoming cycles in hybrid power plants. A hybrid SOFC cycle could be any combination of SOFC and gas turbine, steam turbine or combined cycle.

There are numerous demonstrational and semi-commercial units of SOFCs installed around the world with different sizes and configurations [20, 21, 22, 23]. But so far, to the authors' best knowledge, there have been three proof-of-concept SOFC hybrid power plants installed in the world. Siemens claims that it has been successfully demonstrated its pressurized SOFC and gas turbine hybrid system and has two units; a 220 kW at the University of California, Irvine, and a 300 kW unit in Pittsburgh [24, 25]. Also, in 2006 Mitsubishi Heavy Industries, Ltd. (MHI), Japan, claimed that it succeeded in verification testing of a 75 kW SOFC and micro GT hybrid cycle [26].

As mentioned, these two technologies are in development phase and there is no commercial product in the market yet. Therefore, there are no universally accepted configurations for them. For SOFC power generation units, efficiency of 50% to 60% has been reported [27, 28, 29, 30]. In the case of the SOFC hybrid cycle, the efficiency is higher and its range is wider, from 57% to 75% [31, 32, 33, 34, 35, 36]. For this paper the average efficiencies of 55% for the third scenario and 65% for the fourth scenario are considered.

Scenario numbers 5 and 6: CO_2 capture and storage (CCS) systems are technologies that can be used to reduce CO_2 emission by different industries where combustion is part of the process. A major problem of CCS utilization is their high efficiency penalty in power plants. For different types of power plants fueled by oil, natural gas, and coal there are three main techniques that can be applied [37, 38]:

- CO_2 capture after combustion (post-combustion);
- CO_2 capture after concentration of flue gas by using pure oxygen in boilers and furnaces (oxyfuel power plants); and
- CO_2 capture before combustion (pre-combustion).

The first method is consisted of treating exhaust gases (most likely by chemical absorption) in order to remove, liquefy and store carbon dioxide. This technology is currently expensive and involves significant efficiency penalty. The oxyfuel process increases the CO_2 concentration in the plant's off-gas by combusting fuel with pure oxygen instead of air. In the last method, fuel is first gasified and then CO_2 is removed from hydrogen rich fuel. The product of this process is almost pure hydrogen which can be used as a fuel in power plants.

In the fifth scenario, CCS is installed in the existing power plants with current technologies. For the last scenario, all existing power plants will be replaced by NGCC plants equipped with CO_2 capture system. The CCS system in these scenarios is capable of removing 90% of CO_2 from flue gas. But because of consumption of more fuel to compensate plants efficiency reduction, overall, 87% of CO_2 can be captured. The output penalty of 10% is considered for both scenarios.

8. GHG EMISSION REDUCTION POTENTIALS IN IRAN

Table 7 shows the energy of consumed fuel, electricity generation, GHG emissions and intensity for existing power plants and six reference scenarios and reduction potentials in each scenario in Iran's electricity generation sector for the period of March 2005 to February 2006. Again, the focus of this paper is on GHG emission reduction on fossil fuel-fired thermal power plants and other power generation technologies are not considered.

Table 7 shows that how fuel consumption can be decreased in different scenarios. For instance, the energy of consumed fuel can be reduced in the fourth scenario from base case (existing case) of 1,543 TJ to 857 TJ, which means 44% reduction. This is due to higher efficiency of introduced scenarios in comparison to current conditions.

	Power Plant Type	Existing	Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5	Scenario #6
Energy of Consumed Fuel (TJ)	Steam PP	882	882	0	0	0	970	0
	GT	375	375	0	0	0	413	0
	CCPP	285	285	1,137	0	0	314	1,251
	SOFC	0	0	0	1,013	0	0	0
	Hybrid SOFC	0	0	0	0,0	857	0	0
	Total	1,543	1,543	1,137	1,013	857	1,697	1,251
Electricity Generation (GWh)	Steam PP	89,574	89,574	0	0	0	89,574	0
	GT	29,023	29,023	0	0	0	29,023	0
	CCPP	36,194	36,194	154,791	0	0	36,194	154,791
	SOFC	0	0	0	154,791	0	0	0
	Hybrid SOFC	0	0	0	0	154,791	0	0
	Total	154,791	154,791	154,791	154,791	154,791	154,791	154,791
GHG Emissions (kt/year)	Steam PP	55,300	49,804	0	0	0	7,908	0
	GT	22,447	21,199	0	0	0	3,210	0
	CCPP	16,736	16,297	64,354	0	0	2,393	9,203
	SOFC	0	0	0	57,333	0	0	0
	Hybrid SOFC	0	0	0	0	48,513	0	0
	Total	94,483	87,300	64,354	57,333	48,513	13,511	9,203
Reduction Potential (%)	Steam PP	-	9.9	-	-	-	86	-
	GT	-	5.6	-	-	-	86	-
	CCPP	-	2.6	31.9	-	-	86	90
	SOFC	-	-	-	39.3	-	-	-
	Hybrid SOFC	-	-	-	-	48.7	-	-
	Total	-	7.6	31.9	39.3	48.7	86	90
GHG Intensity (gCO_2eq/ kWh)	Total	610	564	416	370	313	87	59

TABLE 7 : Energy consumption, electricity generation and GHG emission reduction potentials in Iran's electricity generation sector for the period of March 2005 to February 2006

The following are the factors that directly affect the GHG reduction potentials in Iran's power plants:

- Most of Iranian thermal power plants are equipped with duel fuel burners and use natural gas most of the time. In fact 77% of energy consumption comes from natural gas.
- The efficiency of natural gas fired power plants especially NGCC is higher than diesel and residual oil fired power plants.

- In 2005, as mentioned, approximately 20% of total electricity generation in Iran was produced by CCPP.

In this section, in order to show the variety of possible analyses, timely variation of GHG emission reduction potentials will be presented for Iranian thermal power plants. Table 8 shows the GHG emissions and intensity for existing situation and six reference scenarios and reduction potentials for each scenario in Iran's electricity generation sector between 1995 and 2005. The table indicates that the GHG reduction potentials were decreased from 1995 to 2005. Again, one of the reasons for this reduction was that in recent years a lot of combined cycle power plants were installed in the country. Moreover, fuel switching from diesel and residual oil to natural gas was another factor that reduced GHG emission reduction potentials in Iran. It should be noted that, as shown in the table, the net amount of GHG emissions were increased. This is because of commissioning of new power stations and increasing electricity generation capacity.

Year	Existing		Scenario #1			Scenario #2			Scenario #3		
	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	Reduction Potential (%)	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	Reduction Potential (%)	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	Reduction Potential (%)
05	98,991	630	91,847	584	7.2	65,166	415	34.2	58,057	369	41.4
04	90,958	610	84,638	568	6.9	61,817	415	32.0	55,074	369	39.5
03	79,631	587	74,515	550	6.4	56,208	415	29.4	50,077	369	37.1
02	78,844	622	72,415	571	8.2	52,546	415	33.4	46,814	369	40.6
01	75,099	632	68,185	574	9.2	49,291	415	34.4	43,914	369	41.5
00	70,863	634	64,444	577	9.1	46,309	415	34.6	41,257	369	41.8
99	65,137	640	59,340	583	8.9	42,224	415	35.2	37,618	369	42.2
98	57,222	632	52,539	581	8.2	37,510	415	34.4	33,418	369	41.6
97	57,470	677	50,607	596	11.9	35,210	415	38.7	31,369	369	45.4
96	53,959	693	46,826	602	13.2	32,272	415	40.2	28,751	369	46.7
95	52,299	726	45,541	632	12.9	29,870	415	42.9	26,611	369	49.1

TABLE 8: GHG emissions and intensity of Iran's electricity generation sector for different scenarios from 1995 to 2005

Year	Scenario #4			Scenario #5			Scenario #6		
	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	Reduction Potential (%)	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	Reduction Potential (%)	GHG Emissions (kt/year)	Intensity (gCO_2eq/kWh)	Reduction Potential (%)
2005	49,125	313	50.4	14,156	90	85.7	9,319	59	85.7
2004	46,601	313	48.8	13,007	87	85.7	8,840	59	85.7
2003	42,372	313	46.8	11,387	84	85.7	8,035	59	85.7
2002	39,611	313	49.8	11,275	89	85.7	7,514	59	85.7
2001	37,158	313	50.5	10,739	90	85.7	7,049	59	85.7
2000	34,910	313	50.7	10,133	91	85.7	6,622	59	85.7
1999	31,831	313	51.1	9,315	92	85.7	6,038	59	85.7
1998	28,277	313	50.6	8,183	90	85.7	5,364	59	85.7
1997	26,543	313	53.8	8,218	97	85.7	5,035	59	85.7
1996	24,328	313	54.9	7,716	99	85.7	4,615	59	85.7
1995	22,517	313	56.9	7,479	104	85.7	4,271	59	85.7

TABLE 8: GHG emissions and intensity of Iran's electricity generation sector for different scenarios from 1995 to 2005 (Cont.)

9. CONCLUSION

The first part of this paper showed the importance of preparation of GHG inventory report for electricity generation sector. The results demonstrated that Iran's electricity generation sector did a reasonably good job in reducing the GHG intensity in the past 10 years, with 13% overall reduction. However, the detailed calculation pointed out that still there are power plants with extremely high GHG emission intensity. This indicated that there are great potentials for further GHG emission reduction in the sector.

In the remainder of the paper, the GHG emission reduction potentials were investigated through six scenarios. The results illustrated that there are considerable GHG emission reduction potentials in Iranian electricity generation sector. Implementation of the scenarios can help the country in sustainable development. Moreover, it could be economically beneficial due to the possibility of selling Carbon Credit to Annex I parties of the Kyoto Protocol.

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