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Original Research Article

Environmental assessment of energy production from landfill gas plants by using Long-range Energy Alternative Planning (LEAP) and IPCC methane estimation methods: A case study of Tehran

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ABSTRACT

This study aims to analyze the electricity generation and its environmental aspects in Tehran city by using the LEAP model and developing two scenarios, including Business-As-Usual and Sustainable-Waste-Management (SWM). The base and final years of the planning are 2012 and 2035, respectively. It is attempted to integrate two models of IPCC (Intergovernmental Panel on Climate Change) for methane flow rate estimation and LEAP to estimate Tehran's energy and non-energy emissions. By linking these two models, the energy and environmental effects of the SWM scenario are estimated. To calculate the power production of the landfill gas (LFG) plants, the gas turbine model of GE10 is selected, and an Engineering-Equation-Solver (EES) code is developed based on methane flow rate and composition data obtained from the IPCC default method in the SWM scenario. The combination of EES codes and LEAP analysis shows that the LFG plants can supply 0.5 GW h power, which is 1.4% of the total demand in 2016, but it will raise to 0.9 GW h in 2035. Although utilization of LFG plants increases the cost of electricity production, the accumulated difference of 100 years global warming potential in the studied scenarios will be 81.2 Mt CO_2 equivalent from 2012 to 2035.

Introduction

Today, it is undeniable that the electricity generation of the industry throughout the world is significantly oil dependent, and substituting other energy resources for this black gold in a short term period is impossible. As a result, with respect to the intensive demand of energy, the environmental problems have become one of the most important concerns of the human beings. Thus the necessity to move away from or at least decrease the reliance of oil as soon as possible is essential.

It is known that oil resources are distributed unevenly around the world. Over 60% of oil reserves are found in Middle East [1]. Iran is one of the most hydrocarbon-rich areas in the world and Tehran, the biggest city of Iran, is one of the major consumers of oil and gas due to high electricity demand.

Given the importance of energy supply issue, all policymakers, politicians and stakeholders in the energy sector are concerned with finding solutions for the mentioned problems [2]. The first movements for planning energy resources was after the oil shock of 1973 so that the thoughts were focused on energy conservation and energy substitution [3]. Mounting the environmental concerns in 80s, modified the criteria of the decisions and dictated the importance of considering a combination of technical, environmental, political and economic factors for planning in this field to achieve sustainable development goals (SDGs) [4].

Several research papers have discussed the energy and electricity sectors planning based on different scenarios in the literature. For instance, Mulugetta et al. analyzed power sector scenarios till 2022 in Thailand [5]. Renewable energy resources have also been an important issue in these research projects. In Canada, a multi criteria study on renewable resources and choosing the best resource among five possible resources, regarding six factors has been performed [6]. In a similar research, Kowalski et al. designed regional and national scenarios to evaluate the renewable resources until 2020 in Austria [7].

The agenda of most of the scenarios in the research articles are investment on improving fossil fuel power plant efficiencies and establishing nuclear and/or renewable power plants. In Iran, for instance, a research study evaluated impacts of price change and energy efficiency programs on the consumption of energy carriers

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as well as greenhouse gas mitigation in the Iranian residential buildings sector by employing the Long-range Energy Alternative Planning (LEAP) model [8]. Considering the importance of less dependence on oil and gas and also mitigation of greenhouse gases and environmental pollutions, using renewable resources is a very intellectual solution. Using biomass, geothermal, solar and wind power systems and also landfill gas to produce electricity with respect to their different effects is highly noticeable. An illustration of these efforts is the analysis of environmental and economic impacts of using landfill gases (LFG) for electricity generation in Korea by utilizing the LEAP model. This study aimed to indicate the electricity generation by using LFG as an effective solution for CO_2 displacement over the medium term together with additional energy profits which would reduce the global warming potential by a maximum of 75% compared to spontaneous emissions of CH_4 [9]. Another research on substituting biomass with other energy carriers in Vietnam using the LEAP model showed that this fuel substitution led to a 10.83 million-tonnes reduction in greenhouse emissions [10]. LEAP was also employed to model wind energy usage in Panama's electricity sector [11] and development of solar and wind power in Ethiopia [12].

The energy potential from landfills has also been the subject of some research papers recently. For instance, Scarlat et al. [13] measured the energy potential of all waste generated in Africa and indicated if African governments decide to recover it and generate electricity, it can meet a considerable amount of demand. In addition, Ahmed et al. [14] estimated LFG capture and developed methods for the applying LFG as a renewable energy resource. They used the Intergovernmental Panel on Climate Change (IPCC) model and concluded that an average annual LFG amount of 17,200 tonnes obtained in Iskandar, Malaysia can be utilized as a fuel for efficient and economically justified power generation in the power plant.

As it can be seen, although many researchers have developed sustainable scenarios for long term energy generation in different regions of the world, a comprehensive long term study of the LFG potential for electricity generation in Tehran as the largest city of Iran has not been conducted yet. Moreover, although some papers in the literature have investigated landfill energy generation potential by different methods, no study has coupled the IPCC method with LEAP and developed a special coding for electricity generation by this method. This study can be used as a useful reference for energy planners in Iran for investment on LFG based power plants which will help to meet the electricity demand of the city as well as mitigating CO_2 emissions.

By assuming that Tehran should meet its own consuming electricity demand, the scope of this study is to analyze the electricity supply sector of Iran's largest and the most populated city from 2011 to 2035 in order to observe the changes in electricity production and distribution and also environmental issues when feasible Sustainable Waste Management scenarios are applied. Different from the studies in the literature, present study estimates the amount of methane production from the landfill gases by linking LEAP to the IPCC methane estimation method. Moreover, to forecast the potential of electricity generation by gas turbine power plant from the LFG, an EES coding is developed.

Methodology

Tehran is the capital of Iran with a population of about 8.3 million. It is also one of the largest cities in western Asia. With respect to population, a large amount of daily wastes for disposal in landfills is imaginable. In fact, about 7500 tons of wastes are taken from Tehran every day. Hence, significant effects of correct waste management on global warming, economics and energy supply of this city is obvious. For instance, by using biogas extracted from the landfills, policymakers can not only meet carbon reduction goals, but also plan for supplying more energy demands by adding an abundant and promising renewable energy source.

Landfill power production configuration

Landfill gas is created during the anaerobic decay of natural and wet substances in municipal solid waste (MSW). Based on the landfill design and its management and also waste composition, moisture and many other factors, landfills are accessible to accumulate and utilize this profitable renewable resource for power generation.

For a landfill restoration that prevents greenhouse gas emissions into the air, the emissions must be continuously taken out under the controlled conditions. Punctured tubes are buried into the landfill body and interconnected by a pipework system. By utilizing a blower, the gas is sucked from the landfill. A well planned gas gathering system will adaptably catch the landfill gas from different spots and handful high temperatures, leachate, condensates and air content along these lines, guarantee an expense proficient accumulation and in addition stable landfill gas quality. The main components of a typical landfill gas for energy system including separator, compressor, acid gas removal column and gas turbine generator are depicted in the Fig. 1.

Long-range Energy Alternative Planning (LEAP) model

In this research, energy and environmental modeling is carried out for Tehran. In many similar studies as cited in the introduction, LEAP has been employed as a tool for forecasting, planning and optimizing the future conditions of energy and environmental systems. LEAP software is used in this research obtaining all of the generation, transmission, distribution and consumption details to assess the scenarios which anticipates the environmental and technological behavior of the proposed system. LEAP is able to model both supply and demand sides and keeps economic aspects available for users. It can provide a widespread database of fuels, environmental effects and various technologies of energy systems (entailing: conversion, generation, transmission and distribution

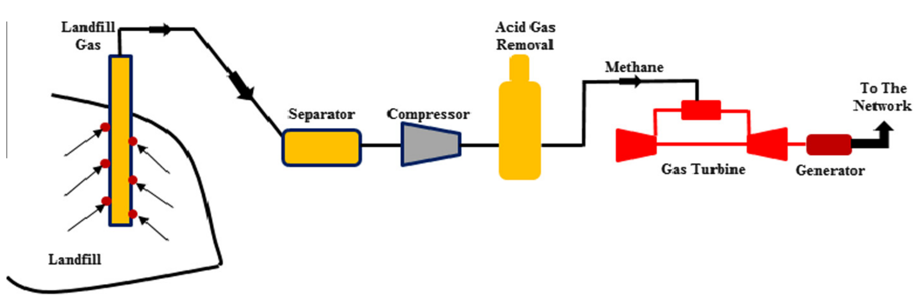

Fig. 1. Landfill power production configuration.

issues) and etc. Another useful characteristic of LEAP is simulating both energy and non-energy sector of greenhouse gases (GHGs) emission sources and sinks at regional, national and global scales [15].

Among regular energy system models, LEAP is one of the most adaptable and well known models, and is widely utilized for comprehensive energy planning and climate change assessments. More than 190 countries have used LEAP for different energy sectors [16]. In addition for analyzing the energy supply and GHG emissions, finding the mitigation possibilities of energy consumption and emissions for each demand sector, investigating different changes of emissions due to substituting power production structure or dispatching of generation technologies, analyzing economic feasibilities considering the cost variation of each scenario are other features of LEAP [17].

To get a better perception of how LEAP works, it is important to consider that, LEAP has a full energy system accounting framework, which involves both demand and supply-side technologies and accounts for total system impacts. By accessing to the environmental data base, LEAP can track the pollution resulting from each stage of the fuel chain, including the reduction in greenhouse gases emissions from extraction, processing, distribution, and combustion activities that might result from more efficient use of electricity or other fuels.

The structure of LEAP modeler is illustrated by Fig. 2.

The primary objective of this study is to investigate an approach for reducing Tehran's emissions. Using landfill's potential is an appropriate method to fulfill this aim which can be evaluated by the LEAP model.

Description of scenarios and assumptions

The present research includes two scenarios: Business-As-Usual (BAU) and Sustainable Waste Management (SWM). BAU scenario is based on the current data and it is assumed that the past trend is retained, however the demand growths are simulated in detail. In BAU scenario, it is also assumed that Tehran will not encounter abrupt changes or surprising conditions. In SWM scenario, environmentally-benign policies are considered for Tehran. The goal of SWM scenario is to decrease the emissions by implementing LFG, changing the combination of feed fuel of power plants and increasing the share of renewable energies in power generation.

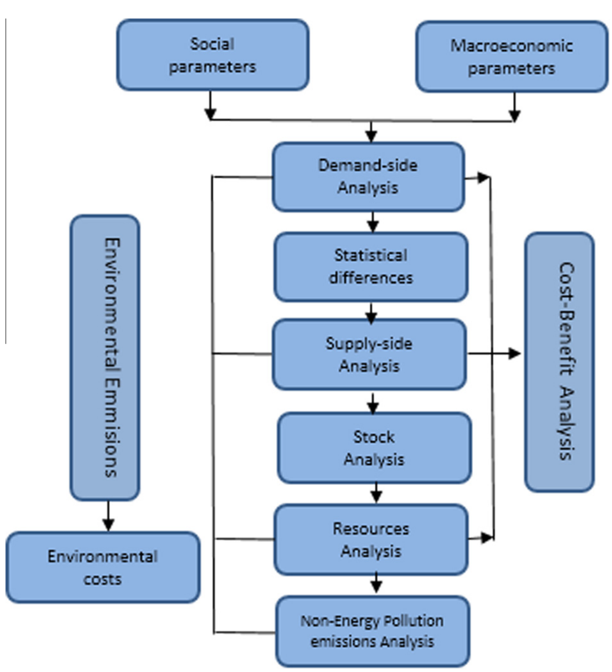

Fig. 2. Structure of LEAP model.

In this study, the last valid energy data for Tehran was presented by Iran's Ministry of Energy in 2012 is used. Accordingly, the base year of this work was determined 2012. In the first step, the base year information comprising: supply and demand sides of energies, fuel shares, efficiencies and other data were inputted based on the governmental report [18]. The demand energy sectors are as following: household, industrial, public, commercial, agricultural and lighting streets. The electricity demand of each sector in the base year is demonstrated in Table 1 [18]. The demand growth rate depends on the GDP and population. The growth rates of electricity for the mentioned sectors are obtained from Moshiri et al. research [19].

Distribution losses are depicted by Fig. 3. Total annual distribution system losses as a percentage of generation begins with 18.6% in 2012. For BAU, it will keep descending to 10.5% in 2035, but for SWM scenario based on improvements in power distribution lines and infrastructure which is presented by 5th developing plan in Iran energy sector [20], it is assumed that the losses will decrease to 9% of electricity generation by 2035. This amount is close to more developed countries like Portugal (8% losses), but not as much as top developed countries such as Japan (4% losses) [21].

It is worthy to note that, based on Iran's Ministry of Energy report, the annual growth rate of electricity production is 4.067% [20]. With respect to the elimination of restriction on the natural gas (NG) production in the final years of simulation, power plants can consume more NG [22]. Thus, SWM scenario assumes that the share of NG fuel for combined cycle, gas turbine and steam turbine power plants increases gradually, so that NG fraction would reach to 100% by 2035 and it would be the single fuel for these power plants on that time. The function of replacing NG with other fuels from 2012 to 2035 is linear.

In addition, in case of excess production, the surplus electricity is supposed to be exported to the other regions and if the shortfall happens, requirements will remain unmet. Tehran's export target is assumed to be as the same as Iran's objective. In fact, 2.87% of total gross electricity was exported in 2012. Based on Ministry of Energy targets [20], this value must increase up to 5.4% and 9.4% until 2014 and 2035 respectively, however, in order to make the sustainable scenario capable of meeting electrical demands by utilizing the sustainable technologies, the export target will remain constant (i.e. 2.87%). Thus, it is predictable that SWM scenario has enough profitability to compensate the additional costs of utilizing landfill power plants as renewable energy sources. Output price per unit of electricity produced is regarded 7 and 10 cents per kilowatt-hour for the years of 2017 and 2035 respectively [20]. These prices are based on the international and free markets while Iran's government supplies electricity cheaper in Iran due to the dedication of subsidies. The average price of electricity was 1.365 cents per kW h in 2012. Feedstock fuel prices are displayed in Table 2 for the base year [18]. In Tehran's energy system, all power plants consume three types of fuels; natural gas, gasoline and fuel oil. It is obvious that the renewable energy resources don't impose feedstock fuel expenditure to the energy system. In addition, it is assumed that the annual price growth will be 3% for fossil fuels [23].

The current committed production capacities are outlined in Table 3 [18]. Despite the BAU which pursues the past trend, the capacities of sustainable scenario are influenced by LFG plant. In fact, after the establishment of LFG plant, based on the availability of LFG production capacity, other technologies will provide the remaining electrical demand.

Fig. 4 depicts the load shape of Tehran's electrical system which is established on the annual requirements [20]. The planning

Table 1
The electricity demand of each sector and corresponding growth rates.

Sector name	Household	Industrial	Public	Commercial	Agricultural	Urban lighting
Electricity demand (GW h)	9132.6	4542.6	4128.8	5802.4	1504.0	394.0
Growth rate (%)	3.35	3.4	1.7	1.7	1.7	3.35

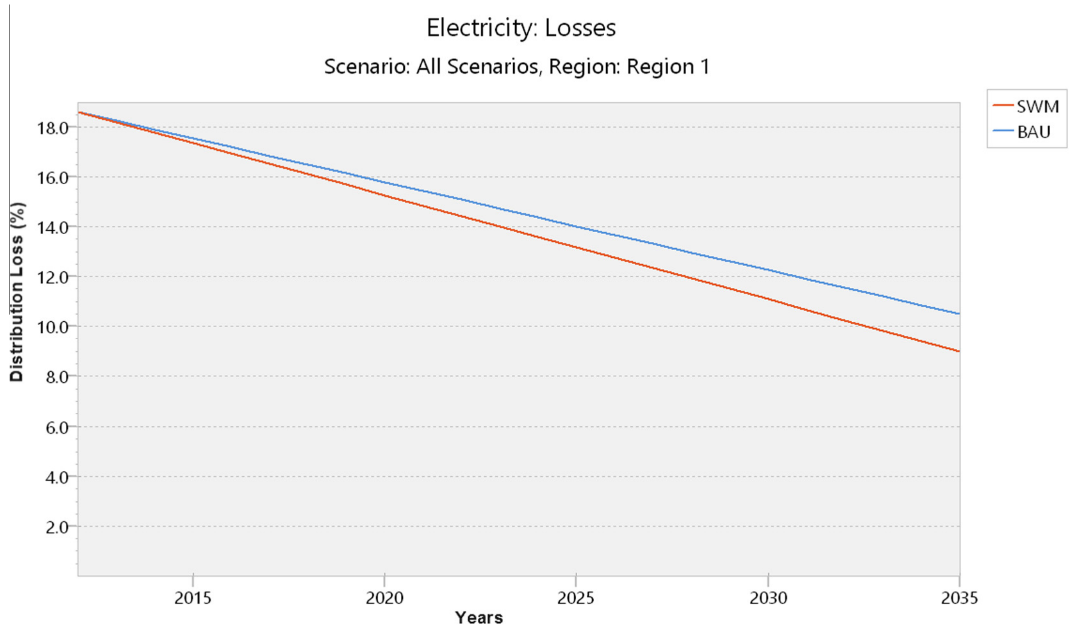

Fig. 3. Distribution losses based on studied scenarios in each year.

Table 2
Feedstock fuels prices and corresponding growth rates.

Fuel	Price	Unit	Annual growth rate (%)
Natural gas	0.42	US$/Cubic meter	3
Gasoline	97.00	US$/barrel	3
Fuel oil	14.55	US$/Gigajoule	3

Table 3
Committed production capacities.

Components	Committed capacity (MW)
Combined cycle	2868[a]
Hydro	315.3[a]
Steam turbine	297.5[a]
Gas turbine	2816.4[a]
Sludge plant	5.005[a]
LFG	61.1[b]

[a] Committed capacity for base year (2012).
[b] LFG plant will be applicable after 2016.

reserve margin is assumed to be 20% for BAU and 30% for SWM scenario.

Based on the related studies and the governmental reports [20,24] the expenditures and other related data of different power generation technologies are reported in Table 4. In this table, the maximum availability describes the percentage of the hours in a year (or in any particular time slice) when the process is available to be dispatched. In addition, the capacity credit refers to the amount of a producing unit's contribution to the reliability of the whole electrical supply system. It indicates how a generating unit will perform as a reliable source of peak energy. Furthermore, process efficiency is defined as the ratio of the energy output to the fuels input energy.

Modeling CH_4 emissions from landfills

An influential issue which affects the intensity of environmental impacts and also, the capacity of electricity or heat generation from landfill emissions, is estimation of biogas flow rates. The two main components of biogas are methane and carbon dioxide. Table 5 depicts the typical composition of biogas [25]. However, based on many factors, the percentage of some components may vary. It is notable that regarding the following three reasons, calculating the emissions of CO_2 is not necessary: (i) global warming potential (GWP) per mole of CH4 is 3.7 times higher than that of carbon dioxide [26], (ii) in the landfills, the concentration of CH_4 is greater than CO_2, and (iii) using methane for combustion is more practical. Moreover, in other researches, CO_2 emitted from both composting and landfill is not accounted for national net GHGs emission [27,28].

In order to develop a model for the mentioned biogas flow rates, IPCC Guidelines introduce the default method (Tier 1) and the First Order Decay (FOD) method (Tier 2) [29]. The FOD method is capable of producing a time-dependent emission profile which indicates the degradation trend over time. Under the optimum conditions, methane production begins within 2 years of MSW dump [29] and considering construction times, it is assumed that power extraction will be started after 2016. The usable biogas amount is considered for about 10–15 years [30]. Knowing that both methods evaluate emissions yearly and regarding the long-term viewpoint of this study (not over a few years), emission profile could be neglected and a constant emission trend with negligible changes for all inventory years is assumed.

Due to lack of information for Tehran and requirement of historical data for applying the FOD method, default method is more capable and effective.

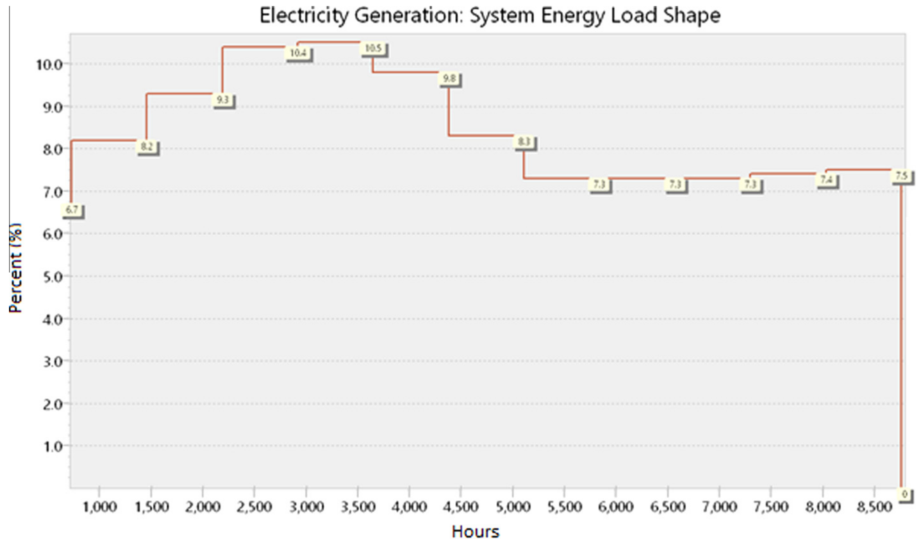

Fig. 4. The energy load shape of electrical system.

Table 4
Different power generation technologies characteristics.

Technology	Life time (year)	Maximum availability (%)	Capacity credit (%)	Process efficiency (%)	Capital cost (US$/MW)	Fixed O&M cost (US$/MW)	Variable O&M cost (US$/MW)
Combined cycle	30	82	100	43.9	0.86	0.004	0.0036
Hydro	30	35	100	100	1.36	0.0098	0.0
Steam turbine	30	78	100	33.8	1.0	0.0085	0.0042
Gas turbine	12	84	100	26.31	0.5	0.0041	0.0056
Sludge plant	20	95	100	30	3.28	0.186	0.13
LFG	20	95	100	30	1.34	0.038	0.13

Table 5
Typical composition of biogas [25].

Compound	Formula	%
Typical composition of biogas		
Methane	CH_4	50–75
Carbon dioxide	CO_2	25–50
Nitrogen	N_2	0–10
Hydrogen	H_2	0–1
Hydrogen sulphide	H_2S	0–3
Oxygen	O_2	0–0

The default method is represented by the following equation:

$$CH_4\ \text{emissions}(\text{Gg/yr}) = [(\text{MSWT} * \text{MSWF} * L_0) - R] * (1 - \text{OX}) \quad (1)$$

where MSWT is the total MSW generated (Gg/yr), MSWF is the fraction of MSW disposed at Solid Waste Disposal Sites (SWDS), L_0 indicates methane generation potential (Gg CH_4/Gg waste), R determines the recovered CH_4 (Gg/yr) and OX is the oxidation factor (fraction).

To calculate MSW generated in Tehran, MSW generation rate (0.84 kg/capita day) [31] should be multiplied by Tehran's population and 365 (days) for each year. It is necessary to remind that the MSW generation rate is varying and depends on urbanization, development, income, culture and other factors. The annual generation growth rate is assumed 2.055% [32]. For MSWF parameter, Hassanvand et al. reported that 83.6% of total MSW was disposed of in landfills [31]. Methane generation potential is accounted by Eq. (2) [29]:

$$L_0 = \text{MCF} * \text{DOC} * \text{DOCf} * F * 16/12 \quad (2)$$

where MCF is the methane correction factor (fraction), DOC indicates the degradable organic carbon [fraction (Gg C/Gg MSW)], DOCf is the fraction of DOC dissimilated, and F is the Fraction by volume of CH_4 in landfill gas. MCF indicates the effect of waste management on CH_4 emissions. Unmanaged SWDS dissipate less methane than a managed site for a given amount of waste, since a larger fraction of waste decomposes aerobically in the top layers of unmanaged SWDS [29]. For the base year, default value (i.e. 0.6) was accounted due to lack of accurate data collection. It is supposed that waste management will advance over the planning time in sustainable development scenario. The waste management will improve to 0.92 for 2022 and 1.0 for 2035. For 0.92 value, 80% of MSW will be disposed in the managed site and the remainder fraction is divided to two equal proportions which will be landfilled in other unmanaged sites (deep and shallow). For 2035, 100% of MSW will be collected in the managed sites. DOC is calculated by Eq. (3):

$$\text{DOC} = (0.4 * A) + (0.17 * B) + (0.15 * C) + (0.3 * D) \quad (3)$$

where A is the fraction of MSW that is paper and textiles, B is the fraction of MSW that is garden waste, park waste or other non-food organic putrescible, C indicates the fraction of MSW that is food waste and D is the fraction of MSW that is wood or straw. According to Eq. (3) and using MSW composition [31], DOC was estimated about 15.062%. DOCf is the decomposable fraction and it can be calculated by a theoretical model which is dependent only to the temperature 'T' in the anaerobic zone of a landfill and is given by Eq. (4) [28]. The temperature can be assumed to be constant about 35 °C. Thus, the value of 0.77 is estimated for DOCf fraction of carbon released as methane, 'F', may vary between 0.4 and 0.6 [33], but it is usually assumed 0.5 [29].

$$\text{DOCf} = (0.014 * T) + 0.28 \quad (4)$$

Table 6
LFG plant generated power calculated by EES coding for SWM scenario.

Characteristics	2016	2021	2027	2032	2035
No. of full load GT	5	6	8	9	10
Partial load	–	0.63%	–	13%	–
Gas flow (kg/s)	3.06	4.14	5	5.72	6.2
Total power(MW)	46.93	62.26	75	85.709	93.86
Gas generator (MW)	58.5	79.6	96	110	119.25

The methane recovery rate is supposed to be 75 and zero percent for SWM and BAU scenarios respectively and oxidization factor is zero (i.e. default value).

Power generation

For modeling the generated power from LFG plant, the gas turbine model of GE 10 is selected, and according to the reported data from the producer and thermodynamic governing equations, an EES code for calculating the generated power for SWM scenario is developed. It is notable that a fuel compressor is utilized to enhance the pressure of extracted methane of landfill plant from 6 to 25 bar. The required work of this compressor is calculated from the following equation:

$$W_{\text{compressor}} = P_1 Q_1 \frac{K}{K-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} - 1\right] \tag{5}$$

where P_1 and P_2 are the inlet and outlet pressures of the compressor, K is the exponential coefficient in adiabatic compression and for this fuel gas is equal to 1.28 and Q_1 is the volumetric flow rate of gas at suction conditions in cubic meters per second.

Considering each equipment as a control volume, generated power is calculated by writing basic thermodynamic equations as follows:

Mass rate balance equation:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \tag{6}$$

Applying the first law of thermodynamics, energy rate balance is obtained from:

$$\sum (\dot{m}h)_{\text{out}} - \sum (\dot{m}h)_{\text{in}} = \dot{Q}_{\text{cv}} - \dot{W}_{\text{cv}} \tag{7}$$

The desired results from this coding is reported in Table 6.

Results and discussion

Electrical aspect

Tehran has the largest power demand and growth rate of any city in Iran. As it can be seen in Fig. 5, the demand for electricity is expected to increase from 16371.8 GW h in 2012 to 27492.8 GW h in 2035. The highest growth of the electricity demand is observed in industrial section with 3.4% growth rate each year. While the growth rate for both household and urban lighting sections is 3.34%, and for the other sections is only 1.7%.

Based on the parameters described above, LEAP allocates the shares of generation to each plant type. This is illustrated in Fig. 6 for BAU scenario and in Fig. 7 for SWM one.

It is apparent that combined cycle plants serve the most share of demand in both scenarios, however, the percentage of generated power by this method is reducing slightly each year, beginning with 53.7% in 2012 and reaching to 51.6% and 49.3% in 2035 for BAU and SWM scenarios respectively. Share of gas turbine technology increases continuously each year from 36.8% in 2012 to 40.4% for BAU and 38.3% for SWM scenario. In addition, the share of hydro power plant and steam power plant will gradually change till 2035. Hydro power plant share will increase from 2.2% in 2012 up to 2.3% in 2035 for BAU scenario and 5.5% for SWM one. For steam power plant the share of power generation begins with 7.5% and decreases to 5.4% and 5.1% in BAU and SWM respectively.

A comparison between the scenarios for the annual energy contribution of each power generation technology in some selected years is presented in Table 7.

Although since 2012, the amount of LFG reaches to a level that is able to feed the selected gas turbine for a steady state operation, from 2016, LFG plants can take a more prominent role in providing a part of the Tehran power demand. 0.5 GW h (1.4% of the total demand in 2016) is served by LFG plants. This amount increases moderately each year and reaches to 0.9 GW h in 2035 which will be 1.77% of the total demand.

Environmental aspect

The annual amount of MSW production for Tehran is projected by the bar chart given in Fig. 8. The generation rate of MSW production begins with 0.8 in 2012, from 2013 to 2018 it is 0.9, then reaches to 1 for the last four years. Afterwards from 2023 to 2027 and from 2028 to 2031 it would be 1.1 and 1.2 respectively, and in the last three years it increases to 1.3. So that MSW amount is 2527.8 Giga Grams in 2012, it increases with mentioned growth

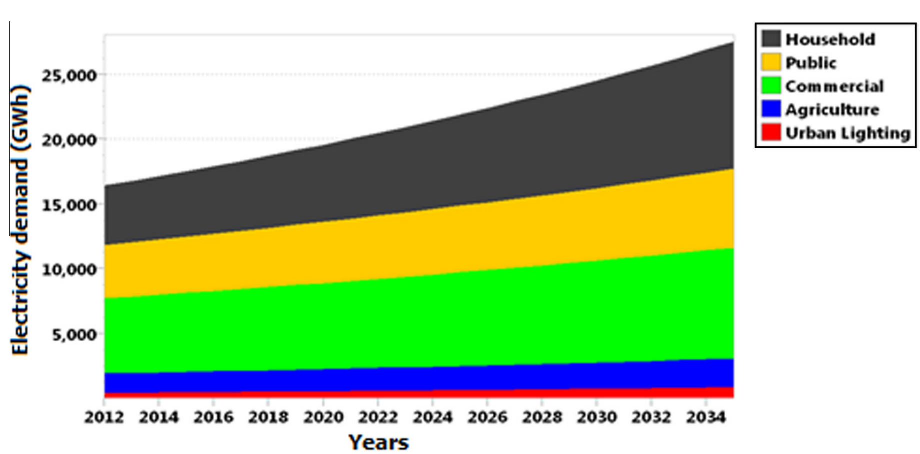

Fig. 5. Projected electricity demands by sector through 2035 for Tehran.

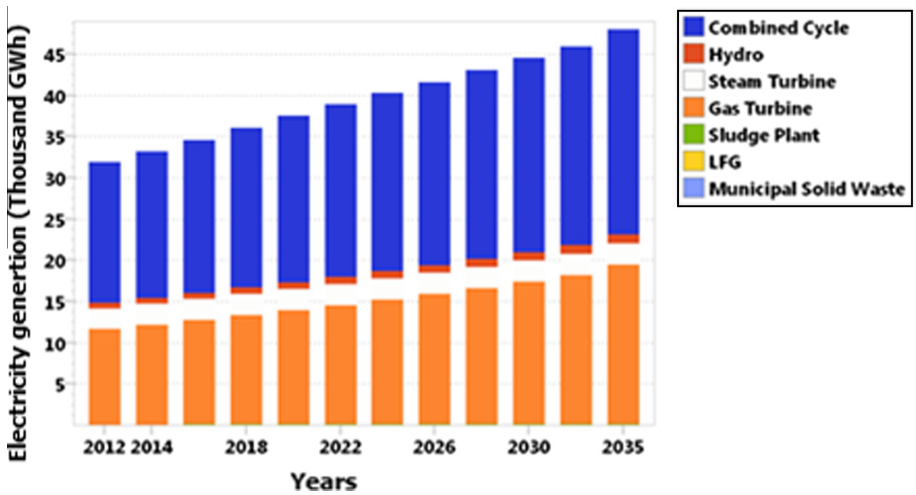

Fig. 6. Electricity dispatch for BAU scenario.

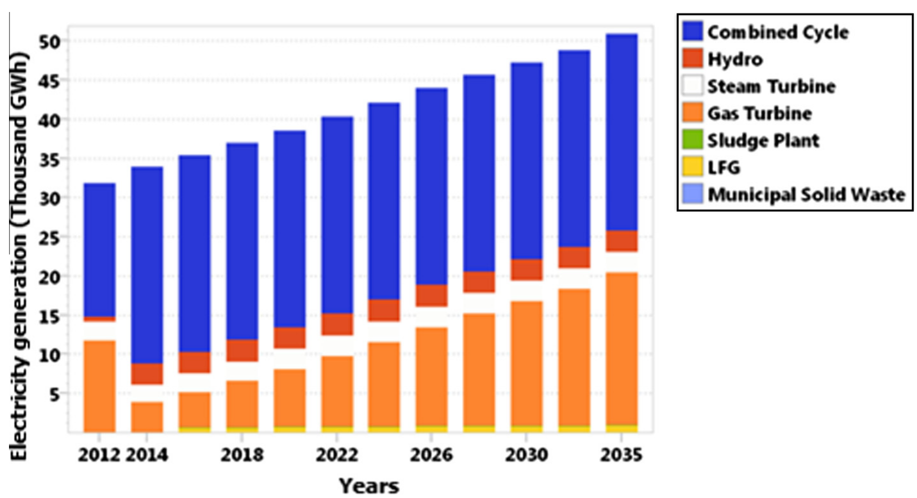

Fig. 7. Electricity dispatch for SWM scenario.

Table 7
Comparison of scenarios based on process shares in some selected years.

Process	2012 (-)	2018		2024		2030		2035	
		BAU	SWM	BAU	SWM	BAU	SWM	BAU	SWM
Combined cycle	17.1	19.4	25.1	21.6	25.1	23.5	25.1	24.8	25.1
Hydro	0.7	0.8	2.8	0.9	2.8	1	2.8	1.1	2.8
Steam turbine	2.4	2.6	2.5	2.6	2.6	2.6	2.6	2.6	2.6
Gas turbine	11.7	13.2	5.9	15.1	10.8	17.3	15.9	19.4	19.5
LFG	–	–	0.6	–	0.7	–	0.8	–	0.9
Total	31.8	36	36.9	40.2	42	44.5	47.3	48	50.9

rates each year and reaches to 4035.8 Giga Grams in 2035. 83.6% of the MSW is disposed each year.

Figs. 9 and 10 illustrate the amount of annual emitted methane for each scenario.

As it is expected by using LFG power plants in SWM scenario, a portion of emitted methane would be recovered and so the emitted methane will decrease compared to BAU in which no methane is recovered and the volume of the emitted methane will increase with more intensity. As it is apparent in these figures, from 2016, by utilizing LFG power plants in SWM scenario, the amount of emitted methane decreases significantly from 148.5 m^3 in 2012 to 161.1 m^3 for BAU and 48.9 m^3 for SWM. In 2035 these amounts are 237.1 m^3 and 98.8 m^3 respectively.

Moreover, from the GHG emissions point of view, SWM is more attractive than BAU scenario. One hundred years global warming potential diagram for each scenario is shown in Fig. 11.

According to the BAU and SWM scenarios, for the entire electricity sector, the global warming potential in 2012 is estimated to be 20.7 million metric tonnes of CO_2 equivalent, however, after 2012 for BAU scenario, the global warming potential is more than SWM in each year. In 2035 it reaches to 32 and 29.4 million metric tonnes of CO_2 equivalent for BAU and SWM respectively.

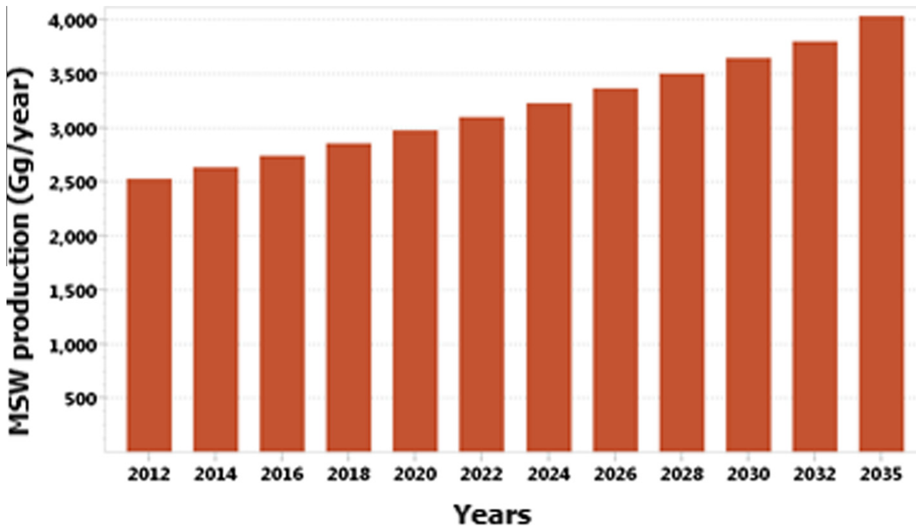

Fig. 8. Projection of annual MSW production in Tehran.

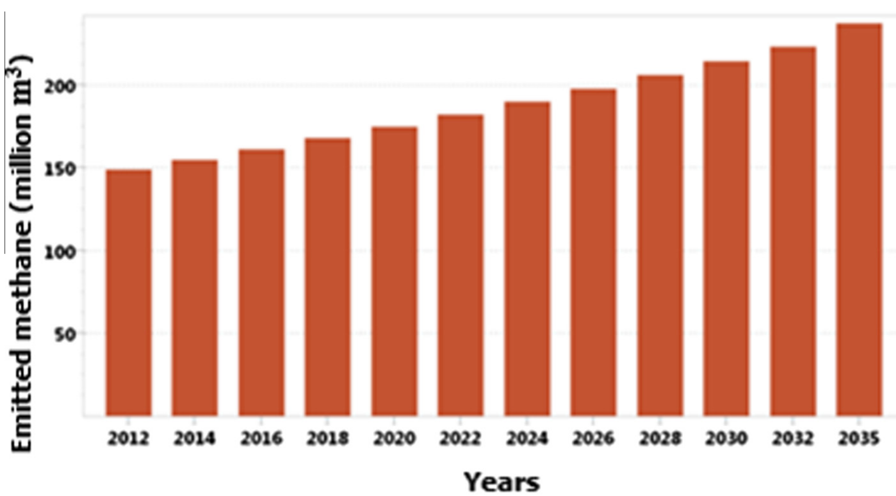

Fig. 9. The amount of emitted methane in BAU scenario each year.

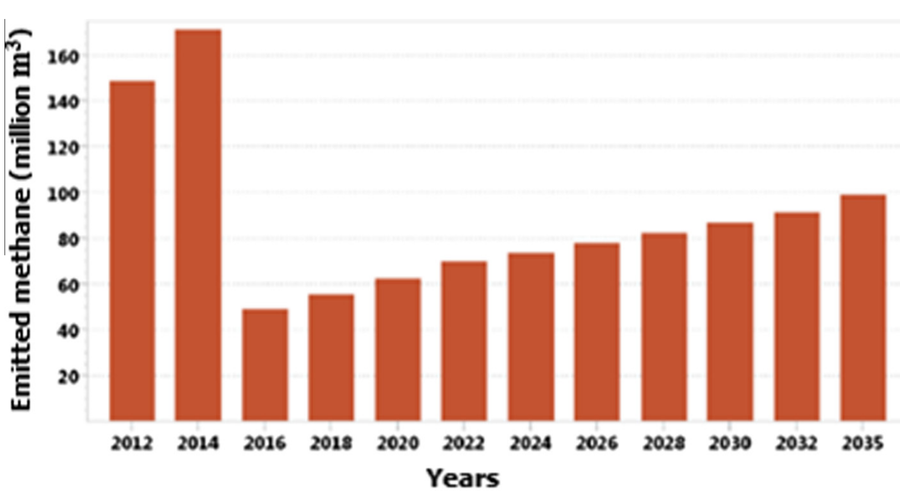

Fig. 10. The amount of emitted methane in SWM scenario each year.

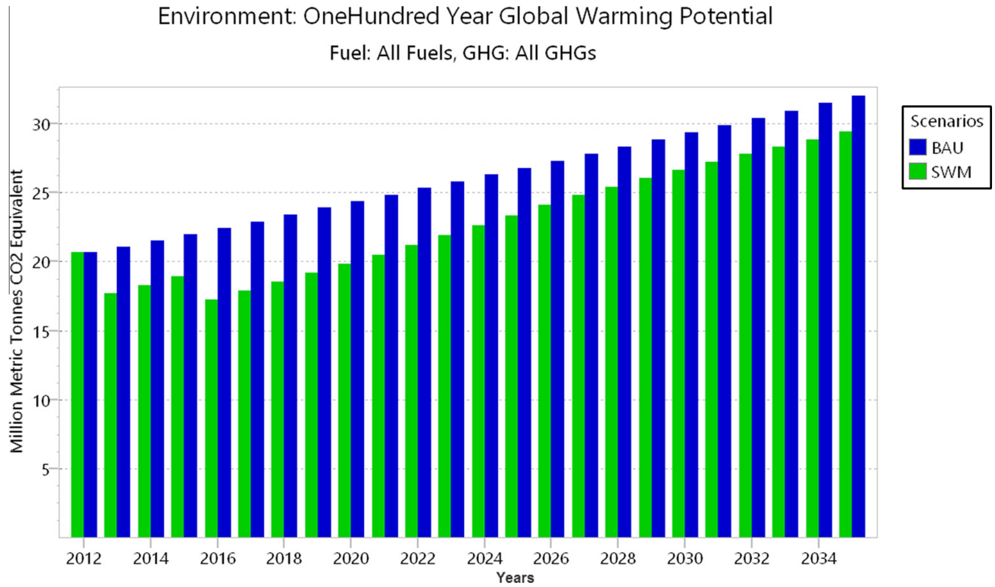

Fig. 11. One hundred year GWP of the scenarios.

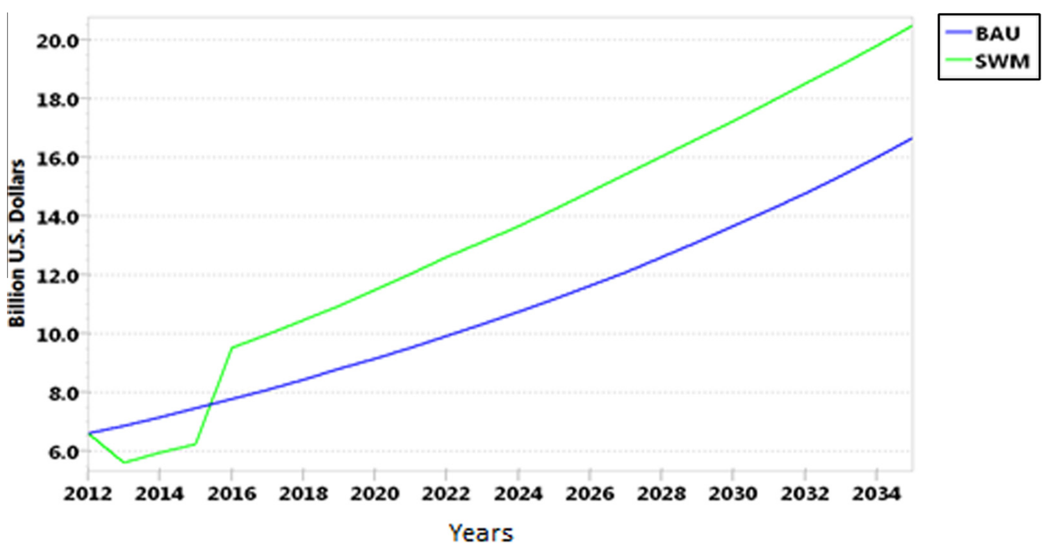

Fig. 12. Cost of production for each scenario.

Considering all 23 years of this study, a decrement of 81.2 million metric tonnes of CO_2 equivalent in SWM scenario compared to BAU, shows the superiority of SWM from environmental aspect.

Cost aspect

A cost comparison between the scenarios is depicted in Fig. 12. As it can be seen from 2016 by using LFG power plants the cost of electricity production for SWM is higher than BAU, however the generated electricity is greater and environmental problems are less in this scenario.

Conclusion

This research provided a comprehensive analysis on the environmental and energy effects of LFG plants on Tehran's energy system until 2035. Sustainable scenario altered the electricity dispatching situation in Tehran's energy system considerably by utilizing LFG power plants. Also, it mitigated GHGs emitted from municipal SWDSs noticeably. These type of renewable power plants supplied about 0.5 GW h which is 1.4% of the total demand in 2016 and an incremental trend continued, so that it reached to 0.9 GW h in 2035 which was 1.77% of the total demand. The results signify that populated cities such as Tehran, have exclusive potential to apply LFGs which helps countries to attain energy self-sufficiency especially for those with restrictions in energy resources. The LFG technology is classified as renewable. Thus, LFG allows policymakers to diminish the dependence on fossil fuels.

This study calculated Tehran's total MSW and annual disposed MSW, about 4035.8 and 3373.9 Giga Grams respectively in 2035. The Sustainable Waste Management recovered 146.6 and 296.4 million cubic meter methane annually in 2016 and 2035 correspondingly, while these values are zero for reference scenario. This comparison discloses the environmental impacts of methane recovery in landfills. For instance, Tehran's one hundred years global warming potential (GWP) was estimated 20.7 million metric tonnes CO_2 equivalent in 2012, however, in 2016 this amount is increased to 22.4 for BAU scenario and declined to 17.3 for SWM scenario by landfill gas electricity generation and other sustainable policies. The aggregated differences of GWP in the scenarios will be 81.2 million metric tonnes CO_2 equivalent during the planning period. Thus, considering the mitigation of GHG emissions, the electricity extraction from LFG is environmentally justified.

As it was predictable, utilization of LFG imposes an enhancement to the production cost of the system. The cost of production was about 6.5 billion U.S. dollars before establishment of the LFG power plants, but this value increased to 9.5 after adding LFG to the dispatching system. This situation continues so that it will reach to 20.5 and 16.7 billion US dollars for SWM and BAU in 2035 respectively. Although the BAU scenario has not applied LFG for electricity generation, these growths are due to meeting the requirements of the demand side.

The captured methane can be transported by pipelines to be burnt by other industries, but it is necessary to remind that the gross energy content of the landfill methane differs from the conventional natural gas. It is noticeable that the landfill must be implemented accurately to decline the risk of leachate which affects the groundwater and soil around the site.

Future studies can be concentrated on linking other biogas landfill estimation models to LEAP model.

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