Demand side management for electricity in Iran: cost and emission analysis using LEAP modeling framework

Mina Masoomi[1] · Mostafa Panahi[1] · Reza Samadi[2]

Abstract

In recent years, escalating cost of generating electricity, substantial investments with the purpose of building power plants, and environmental pollution related to the power generation have underlined the importance of optimal power supply and demand management. Given that, by employing Long-range Energy Alternatives Planning (LEAP) software, the present study set out to optimize the energy system of Iran through two model capabilities, namely electric sector optimization and simulation. To do so, the energy system was initially evaluated by optimizing Iran's demand for electricity by the Demand Side Management (DSM) scenario. Then, Iran's electricity sector was optimized to generate electricity at the lowest cost by setting emission roof with different scenarios, especially the Optimized scenario. The social cost and GHG emission were evaluated in both steps. The prospective social costs of the electricity generation sector based on Optimized and DSM scenarios were calculated to be 5.1 and 4.8 Billion U.S. Dollars in 2035. Regarding the environmental results of the study, the emission rates of pollutants based on Optimized and DSM scenarios were reported to be144 and 429 $MtCO_2$ for the same year.

Keywords Energy system optimization · Electricity policies · Social cost · GHG emission reduction

1 Introduction

Energy efficiency increase, greenhouse gas (GHG) reduction, and energy cost decrease can be achieved by the energy management and standardization. Energy management lowers costs, carbon emissions, and the risks. It also raises efficient energy consumption by the help of activities, processes and techniques promoting higher efficient energy consumption (Ates, 2015). With the steady growth of the world population and the advent and popularization of energy hungry technologies in the past few decades, the need for such solutions

✉ Mostafa Panahi
   m.panahi@srbiau.ac.ir

[1] Department of Energy Engineering and Economics, Faculty of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran

[2] General Manager of the Social, Economic and Environmental Studies Office, SATBA - Ministry of Energy, Tehran, Iran

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and strategies to control the ever-increasing consumption of energy, particularly electricity has become more apparent (Statistical Review of World, BP global 2017).

In Iran, easy access to relatively cheap electricity has reduced the incentive for electricity conservation and energy efficiency. This unfortunate pattern of electricity consumption in Iran stresses the necessity of new policies to improve the situation. Given that, the present study examines the energy system of Iran between 2013 and 2035 in different optimization scenarios using Long-range Energy Alternatives Planning (LEAP) software. In the first part of the study, the electricity demand is optimized by DSM policies.

Because of the importance of electricity for the provision of all services to economic sectors, especially households, the electric power industry has always played a decisive role in the economic development of the countries. However, electric power industry is now struggling to handle preexisting challenges such as steady sharp growth of electricity consumption as well as emerging challenges such as environmental pollution and depletion of fossil fuel reserves (Schmidt et al., 2017).

IEA (2009) has reported that thermal power plants account for the greatest share of CO_2 emission, a share that is to grow even further by 2050 (Cai et al., 2013). According to IEA, in 2010, Iran was the ninth country with the highest CO_2 emission due to fuel combustion (IEA, 2011), a place which is by no measure proportional to Iran's economy, putting the Iranian government under increasing pressure to address the issue (Kachoee et al., 2018).

In recent years, the increased cost of electricity generation, underinvestment in new power plants, environmental pollution of power generation, and increased fuel prices have further highlighted the importance of power supply and demand optimization. In the second part of this study, Iran's electricity generation sector is optimized using the electric sector optimization capability of the LEAP software.

In 2013, Iran's total energy consumption was equivalent to 1229.7 Million Barrels of crude oil, which showed a 4.3% increase compared to the previous year. Meanwhile, Iran's per capita energy consumption was 3.2 times the global average in agriculture sector, 1.8 times the global average in the household, public, and commercial sectors, 1.6 times the global average in the transport sector, and 1.5 times the global average in the industry sector. In the same year, Iran's electric power industry consumed 6.36 Billion Cubic Meters of natural gas, 15.3 Billion Liters of fuel oil, 12.2 Billion Liters of gas oil, 2.3 Billion Cubic Meters of blast furnace gas, and 2.3 Million Cubic Meters of coke gas. In case of shortage of natural gas in the cold months of the year, Iranian engineers have to use alternative fuels such as gas oil in gas turbine and combined cycle power plants and fuel oil in steam power stations (Energy balance, 2013).

In the early years of energy supply modeling, it was typical to encounter models with total concentration on only one energy sector, energy system, or energy carrier and with complete emphasis either on environmental implications or on energy supply cost and security implications (Ouedraogo, 2017a).

LEAP software has the following features: The prediction tool; tools for analyzing energy policies, physical, economic and environmental effects of alternative energy programs; and providing optimization measures. Since the innovation of paper is to assess and evaluate both supply and demand sides of Iran's electricity in the long term, and as the present research aimed to perform the environmental assessment, energy and environmental modeling was one of the main reasons for selecting LEAP software. We also compared the optimization of power supply side with the DSM scenario for the first time in Iran. These discussions indicate the need to answer two questions:

Will the optimization of Iran's electricity supply and demand have positive economic effects?

What is the potential of reducing the GHG emission of the studied thermal power plants by optimizing Iran's electricity supply and demand management?

This study focuses on the analysis of GHG emission and social costs of Iranian thermal power plants in the coming years. In the course of the paper, efforts are made to determine the least-cost solution for electricity generation in the coming years, that is the best electricity generation technology to enhance energy efficiency at the lowest cost, evaluate the prospects of reducing power consumption in the Iranian economic sectors, and to identify the available pathways for optimizing the energy system in order to reduce GHG emissions.

To that end, we first use the LEAP software to simulate a DSM scenario, where we optimize the power demand due to consumption of different sectors as well as transmission and distribution losses. We then use the electric sector optimization capability of the LEAP software to determine the least-cost electricity generation solutions for the supply side (electric power sector). For a clearer understanding of the research design, the Table 3 is provided as Appendix.

Finally, the results of evaluating the parameters of both models of electricity supply and demand optimization are compared. The literature review section is one of the essential parts of the research. In the next section, the previous papers related to the title of the present paper will be reviewed. Also, the research innovation is fully expressed in the previous section according to the previous papers and the research gap.

2 Literature review

Due to the importance of sustainable development and according to the objectives of this paper, all parameters of environmental pollution emissions and reduction of social costs and energy demand side management are evaluated by optimizing both sectors (supply and demand) of electricity. Moreover, there are a great number of studies to assess energy policies including optimizing energy supply and demand as well as environmental policies around the world.

A review of previous papers indicates that most of the papers have examined the evaluated parameters separately, which are mentioned below. LEAP software provides features such as prediction tools as for analyzing energy policies, physical, economic, and environmental effects of alternative energy programs, investments, and optimization measures. Some papers have been conducted using LEAP software.

Rogan et al. (2014) introduced the first national model using Long-rang Energy Alternatives Planning software in order to integrate end-use and detailed analysis of the demand side by minimizing the cost for electricity generation sector modeling in Ireland.

Ouedraogo (2017b) used the long-range energy alternatives planning (LEAP) as a framework to give details of scenarios of developing the African power system.

Liu et al. (2021) evaluated carbon emissions in the long-term (LEAP)-Tourist model including energy alternatives planning system. They considered two scenarios and four sub-scenarios to assess and estimate the gas peaks of tourism greenhouse in China in 2017–2040. The findings show that under the integrated (INT) scenario, GHG emissions would peak at 1048.01 Mt CO_2eq in 2033. About the fact that the INT scenario has seen positive results in terms of energy savings and carbon mitigation, the tourist industry's peak year of 2033 is already later than China's projected peak year of 2030.

Yang et al. (2021) applied a long-term model including a Long-range Energy Alternatives Planning System (LEAP)-Zhang model to assess the environmental and

socio-economic impacts of developing renewable energy in Zhangjiakou through examining the energy consumption and greenhouse gas emissions in 2016–2050. The business as normal scenario (BAU) and the integrated scenario (INT) (which includes three sub-scenarios of renewable energy alternatives scenario (REA), industrial structure optimization scenario (ISO), and energy saving facility scenario (ESF)) have been developed.

Given the importance of reducing the emission of environmental pollutants, a number of previous research studies have evaluated the potential for reducing the emission of environmental pollutants.

Zhao et al. (2013) found major factors influencing the carbon emissions in electric power industry of china and found that the emissions were rapidly increased from 1980 to 2010.

In a study by Bautista (2012), Venezuela's power sector was analyzed to determine the total cost of energy generation and GHG emissions in four scenarios until 2050. This study found that given the abundance of resources in the studied area, sustainable development in the electricity generation sector can be achieved by several methods, but the easiest way to reduce GHG emission is to improve energy efficiency.

Ardebili (2020) evaluated bio-power generation potentials in Iran from agriculture and animal resources to estimate their availability. As a consequence, extracting energy from these wastes may be a viable strategy for reducing Iran's annual GHG emissions by about 0.6%.

Rehman et al. (2021) estimated the GHG emissions in Pakistan considering 5 central sectors, including energy, industrial, agriculture, waste, and land-use change and forestry. The government must take serious measures to reduce GHG emissions to reduce and regulate air pollution. The government should investigate the forms of GHG pollutants in these areas in addition to defining growth areas or regions for GHGs. To effectively mitigate pollution, new legislation and monitoring networks must be built.

Ikram et al. (2020) evaluated the correlation between ISO 14,001 certification, access to electricity, consumption of renewable energy, CO_2 emissions, and agriculture in the countries of the South Asian Association for Regional Cooperation (SAARC). The findings of this study will aid organizations and policymakers in making CO_2 mitigation decisions and investments while also strengthening environmental sustainability practices. The findings showed that adopting ISO 14,001 reduced CO_2 emissions significantly using clean energies. There are many other advantages to engaging in and improving environmental protection for this part of the world and beyond.

Solaymani (2020) predicted the sustainable energy security index (SES) in 2007–2015 for the energy demand subsystem in Iran. They compared the rural and urban SES index from the residential sector. They concluded that the rural SES index was lower than the rural SES index, which shows that lower pollution and low-cost energy in rural areas required executing certain policies.

Many other studies have been done on the optimization of energy systems given the importance of optimizing energy systems and reducing electricity generation costs. Chung et al. (2017) concluded that LNG is an undesirable source considering supply instability and economic competition through economic, environmental, and supply reliability.

Prina et al. (2019) have developed a long-term perfect foresight model with high time resolution by combining EnergyPLAN with a multi-objective optimization algorithm.

Lund et al. (2017) examined different types of energy system models and classified them based on the theoretical context. They looked at the statistical method, the role of policy, and the role of modelers and planners in comparing simulation and optimization methods at various stages.

Lyden et al. (2018) compared 13 community-scale tools focused on input data, supply technologies, architecture optimization, outputs, demand side management, storage, and realistic considerations.

Yue et al. (2018) reviewed various methods of uncertainty in modeling energy systems. To follow this scope, they established four separate methodologies, including stochastic programming, Monte Carlo analysis, robust optimization, and modeling to produce alternatives.

Farrokhifar et al. (2020) provided an inclusive review on recent literature regarding gas and electricity systems' coordinated planning. Initially, they evaluated the planning of energy systems. Then, they examined the planning power and gas grids, including dimensions, objectives, and constraints, and uncertainties. In the next stage, foreign perspectives were discussed to compare mathematical approaches to the planning of electricity and natural grids. Finally, there is a review of potential study possibilities as well as findings.

Lauer et al. (2020) investigated various extensions of operation modes in Germany's biogas plants in 2016–2035. This valuable study took into account the costs of flexibility and construction of new biogas facilities, as well as the costs gained by onshore wind turbines and other saved potential costs.

Since the increase in population and the development of industry in turn lead to an increase in electricity demand, some types of research have been conducted to manage energy demand. Ramanathan and Reddy (1995) developed a simple model for estimating potential cost saving or conservation potential in a variety of DSM programs. Their model was used as the case study for Maharashtra state electricity board (MSEB) that is an electric utility in Maharashtra State of India.

Basiri et al. (2020) showed that the availability of natural gas can be obtained using an adequate supply and effective energy usage, according to structural equation modeling.

Good (2019) investigated the effect of behavioral economics for demand response modeling. In the energy chain, there is a demand reaction. Individuals are often modeled as sensible and productive economic actors, whereas in fact, they are heavily affected by perceptions and desires. The findings suggest that expectations have an effect on demand response, making it critical to appeal to them while seeking demand response.

It should be noted that the energy system has been optimized with different models to reduce the emission of environmental pollutants in a number of previous research studies, and only one side of the energy system (supply or demand) has been examined. In general, there is no answer to the following question, "Will the simultaneous optimization of the country's energy supply and demand side by imposing a limit on the emission of environmental pollutants in power plants have positive economic and environmental effects?".

The innovation of this paper is in measuring and evaluating the forecast of both sides of Iran's electricity supply and demand in the long run. According to the purpose of the paper, this study is environmentally evaluated. One of the main reasons for choosing LEAP software is having energy and environmental modeling. Furthermore, the optimization of the electricity supply side is compared with the DSM scenario for the first time in Iran.

Following such an important scientific discovery, a scientific question was answered that such a comprehensive question has not been answered using the LEAP model so far according to previous papers. Leap is used to predict supply–demand to identify future models, detect potential for savings, assess environmental impacts, and energy policies. This feature is the main reason for choosing this software by optimizing and comparing supply and demand side policies according to the purpose and innovation of the present paper.

According to previous papers, the purpose of the optimizing energy systems is producing cheaper products and managing energy demand given the previous studies in several separate sections, including reducing the emission of environmental pollutants. The most obvious difference between this paper and the previous papers, which evaluates all parameters by optimizing both supply and demand of energy and limiting the emission of pollutants.

Due to the importance of reducing the parameters of environmental pollutant emissions and social costs in the electricity industry, which can have a significant impact on economic growth, there are a few papers on both parameters by LEAP software. As a result, the reduction in both social cost parameters and the emission of environmental pollutants from thermal power plants will lead us to sustainable development.

According to the research gap, the present paper deals with the simultaneous optimization of the supply and demand side of Iran's electricity system to fill the existing gaps in the direction of leading to sustainability of economic, social, and environmental aspects. Moreover, applying an important scenario, the emission limit of environmental pollutants, and generating cheaper electricity will give politicians and legislators a clear perspective for decision-making and planning in this area. The next part of the present paper deals with the methodology of both models, including simulation of the demand side and optimization of the supply side of the electricity industry.

3 Method

3.1 Modeling

In this study, we use two capabilities of the LEAP software to achieve the research goals. The procedure implemented in the LEAP software is shown in Fig. 1. This study is divided into two parts. The first part is devoted to the simulation of the entire energy system, which includes energy demand, energy transformation, and energy transmission and distribution losses. The second part describes the optimization performed in the LEAP software to determine least-cost power generation solutions with the help of OseMOSYS model. Using the software capabilities, simulations are performed in different scenarios defined in line with research objectives.

3.1.1 Simulation in LEAP

LEAP is a software program developed at the Stockholm Environment Institute (SEI) in Boston for fast and convenient analysis of energy utilization and GHG emission in different scenarios based on user-defined inputs with regard to current and future energy demands (Cai et al., 2008; Phdungsilp & Wuttipornpun, 2010). LEAP has gained a good reputation as an easy-to-use and flexible accounting tool for energy demand/supply modeling (Chontanawat et al., 2014; Letschert et al., 2013; Park et al., 2010; Pukšec et al., 2014).

This software also includes a technology-environment database (TED) which contains comprehensive data on technical characteristics, costs, and environmental impacts of different technologies provided by the Intergovernmental Panel on Climate Change, the US Department of Energy, the International Energy Agency and other reliable sources (McPherson & Karney, 2014).
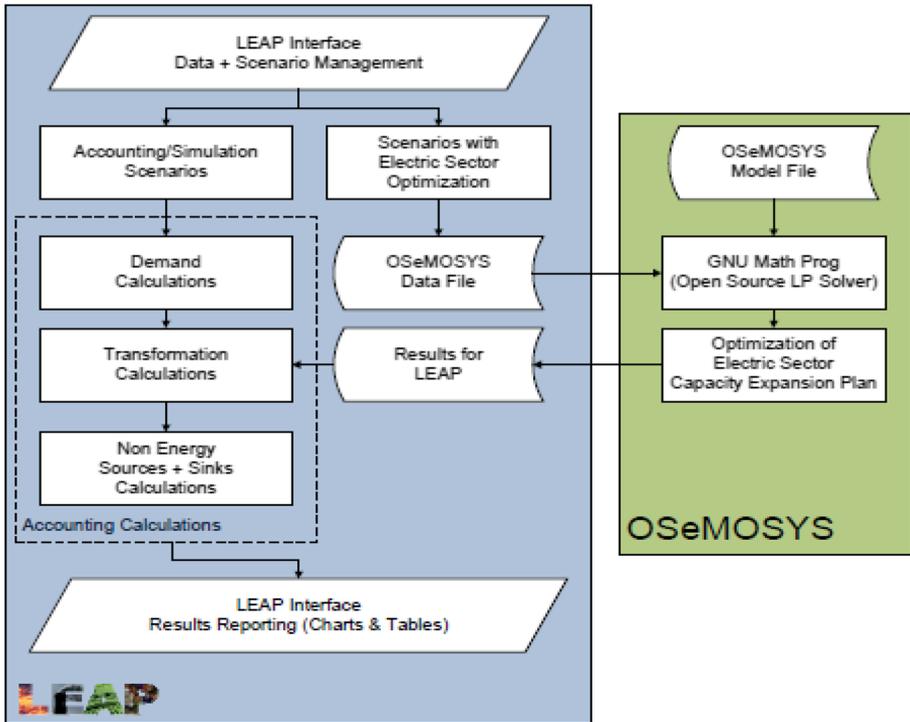
Fig. 1 Optimization and simulation procedure in LEAP

Due to the features of LEAP software, this software is considered a database (it enables users to predict the energy supply and demand on the planning horizon), a prediction tool (it enables users to predict the energy supply and demand on the planning horizon) and as a tool for analyzing energy policies, economic and environmental effects of energy alternative programs. Since it provides investment and optimization measures, this feature is the main rationale behind choosing this software given the purpose and innovation of the study (optimization and comparison of simultaneous supply and demand side policies in the electricity of Iran).

LEAP software can be used to predict the supply and demand for identification of future models, identification of saving potential, and assessment of environmental effects. It also helps decision-makers to test a wide range of projects (including the system development, changing the composition of carriers, and energy optimization in the final step), programs and technologies, as well as design and assessment of energy and environmental policies.

LEAP has the ability to model energy systems for trend analyses and short-term assessments without extensive historical macro-economic data, or based on the statistical data of the base year only (Ouedraogo, 2017b). Another desirable feature of LEAP is its flexibility in the sense that it can import data from other sources and export its results for other models and platforms (SEI 2006). Before modeling in the software, the tree structure of simulations was designed.

The tree structure considered for the simulation of Iranian energy system in the software consists of three categories: key assumptions, demand, and transformations. The integral

parameters of the model were put in the key assumptions category, the parameters related to energy consuming sectors were put in the demand category, and the parameters related to electricity generation sector were put in in supply category. Indicators influencing the trend of energy consumption and supply as independent variables form key assumptions.

The model also included three subcategories of macroeconomic indicators, demographic indicators, and social costs. Demographic indicators of interest were the population of Iran, the number of households in the country, and the household size (the average number of people in a household). The macroeconomic indicators of interest were GDP, household income, economic growth rate, and the share of industry, commercial, agriculture, and transportation sectors in GDP.

Environmental impacts were included in a folder named the Effects, where the externalities of each pollutant including GHGs were separately considered. The demand side included all energy consumers, i.e., household, commercial, transportation and industry sectors. The power plant production sector is evaluated as one of the main and most important economic sectors in the transformation sector. In this section, special branches called modules are used to model the energy supply in various parts of the transformation, including production, transmission, and processes.

In each module, the calculation and energy production processes of each technology related to different power plants are performed separately and their results are shown. Moreover, there is a module related to transmission and distribution loss assessment (T and D) in this section. Transmission and distribution losses in 2013 are listed in the loss sheet. These numbers are obtained from the sum of transmission losses and over-distribution and distribution in the energy balance of the Ministry of Energy. Information is available on steam power plants, gas turbine power plants, combined cycle power plants, and diesel power plants in designing the transformation sub-section to the power generation module (Masoomi et al., 2020).

The input data of the simulation model related to each type of power plants (efficiency of thermal power plants, total power generation, and nominal capacity of each power plant) are entered separately in the software related to each power plant for the base year (2013) (Table 1). Consumption fuels (natural gas, diesel and furnace oil) of each of the country's thermal power plants were received from the Ministry of Energy according to the type of power plant and were used as input data. In the next step, the pollution levels of each consumed fuel are determined by referring to the environmental database in the LEAP software based on IPCC coefficients. In the basic parameters section, the interest rate is set at 10%. An important part of the input data related to the base year (2013) has been extracted from the energy balance sheet and the Statistics and Information Center of the Central Bank of Iran and imported to the software (Masoomi et al., 2020).

3.1.2 Electric sector optimization in LEAP

The 2011 version of LEAP is equipped with a feature for automatic calculation of least cost capacity expansion and dispatch of supply-side transformation modules. This feature makes use of the OSeMOSYS modeling system. OSeMOSYS is an analytical toolbox developed in a collaboration of SEI, the International Atomic Energy Agency (IAEA), the United Nations Industrial Development Organization (UNIDO), the UK Energy Research Center, and the Royal Technical University (KTH) in Sweden in order to facilitate energy research and planning, especially in developing countries (SEI 2011).

Table 1 Input data of simulation and optimization models for 2013 as the base year

Optimization			Simulation			Models
Variable OM Cost (U.S. Dollars Per: Megawatt-Hour)	Fixed OM Cost (U.S. Dollars Per: Megawatt)	Capital Cost (U.S. Dollars Per: Megawatt)	Exogenous Capacity (Megawatt)	Efficiency (%)	Historical Production (Megawatt-hour)	Processes
1.48	9008.6	99094.6	14812.8	44.1	87135100	Combined cycle power plant
2.06	11711.2	189177	15314.4	36.8	89664000	Steam power plant
0.88	4504.3	108103.2	20049.9	30.9	66038800	Gas turbine power plant
0.79	4504.3	126120.4	283.8	34.4	71049	Diesel power plant

In this study, the feature discussed in 3.1.1 was employed to determine the optimal expansion and dispatch of power plants in the studied system. Here, optimality refers to the state where the net present value of the system's social costs over the studied period is the lowest.

Moreover, the tree structure designed in the energy supply optimization model of LEAP software is created in the unit (module) of demand only as a single branch, in which the country's electricity demand has started to grow from zero in the base year (2013) due to the development plan to increase electricity capacity and has reached 745.9 Thousand GWh in the 2035 modeling horizon. This energy demand is identical in all scenarios. All units in this model, except for the demand unit and the key assumptions unit, are all the same modules designed in the energy system simulation model.

In addition to the variables entered in the simulation model for the base year (2013), the input data of the optimization model related to the variables of each power plant, including capital costs, fixed operating costs, variable operating costs, are placed separately in the tabs related to each power plant in the software (Table 1). According to the parameters, LEAP software algorithms are discussed in Sect. 4.

4 LEAP algorithm

In the LEAP software, the parameters are calculated in the following steps.

4.1 Energy demand simulation

In the LEAP software, the final energy demand is defined as the product of the total activity level and the energy intensity in each branch or sector:

$$ED_{b,s,t} = TA_{b,s,t} \times EI_{b,s,t} \tag{1}$$

In Eq. (1), ED is the final energy demand, TA is the total activity level, EI is the energy intensity, b is a technology branch for a certain fuel, s is the scenario and t stands for the time (year).

4.2 Energy consumption for transformations

The net total energy consumed for transformations is calculated as follows:

$$EP_p = ETP_{t,m,s} \times \left[\frac{1}{f_{t,m,s}} - 1 \right] \tag{2}$$

In Eq. (2), ET is the net energy consumption for the transformation process, ETP is the energy transformation product, $\int$ is the energy transformation efficiency, m denotes the technology, s denotes the primary energy type, and t the secondary energy type.

4.3 GHG emission

The total emission due to final energy consumption is calculated as follows:

$$\text{GHG} = \sum_i \sum_j \sum_n \text{AL}_{n,j,i} \times \text{EI}_{n,j,i} \times \text{EF}_{n,j,i} \tag{3}$$

In Eq. (3), GHG denotes the emission, AL is the activity level, EI is the energy intensity, and EF is the emission factor based on the type of energy consumed n by the equipment *j* of sector *i*.

GHG emission due to energy transformation is calculated as follows:

$$\text{GHG}_T = \sum_s \sum_m \sum_t \text{ETP}_{t,m} \times \frac{1}{f_{t,m,s}} \times \text{EF}_{t,m,s} \tag{4}$$

In Eq. (4), GHG_T is the GHG emission due to energy transformation, ETP is the energy transformation product, *f* is the energy transformation efficiency, EF is the emission factor for the transformation of a unit of energy from type t to type n by equipment *m*.

4.4 Cost measurement

Total cost measurement is according to the following equations:

$$
\begin{aligned}
\text{Total cost} = \Bigg(&\sum_t \sum_r df(r) * \Bigg(\sum_m \text{anninvcost}(m,r,t) * \text{resid}(m,r,t) \\
&+ \sum_m \text{fixcost}(m,r,t,) * \text{cap}(m,r,t) + \sum_m \text{varcost}(m,r,t) * \text{act}(m,r,t) \\
&+ \sum_v \text{envcost}(v,r,t) * \text{emis\_i}(v,r,t) \Bigg) \Bigg)
\end{aligned}
$$

4.5 (5)

In Eq. (5), *df(r)* is the total discount rate of region *r*. Fixcost(*m,r,t*), anninvcost(*m,r,t*) and varcost(*m,r,t*) refer to the unit supply cost for any technology *m* that has the following functions: the annualized investment cost per unit capacity; energy source and raw material supply; the fixed operational and maintenance cost per unit capacity, as well as variable operational and maintenance costs per unit activity of the technology m in period t and region *r*. Resid(*m,r,t*) refers to the residual capacity of technology m in region *r* and period *t*.

This capacity refers to those invested capacities before starting the planning horizon, but they still exist in periods. Act(*m,r,t*) and cap(*m,r,t*), respectively, refer to activity and capacity of technology m in the region r and period *t*. Emis_i(*v,r,t*) represents the emission of emitter *v* from industrial production. Envcost(*v,r,t*) refers to applied environmental costs for emitter *v* in region *r* and period *t*. For further details regarding other parameters and their units, the Table 4 is provided as Appendix. Scenario-based thinking provides individuals and groups with a way to deal with future threats and opportunities and their potential impact on the organization or community. In the next part of the paper, different evaluated scenarios of both supply and demand of Iran's electricity system are stated.

5 Scenario design

5.1 Simulation scenarios

5.1.1 Reference scenario

A scenario called the Reference scenario (REF) was created to provide a baseline for analysis and comparison. The Reference scenario was used to analyze the trend of energy demand of sectors and its relation with fuel type, the trend of social costs of power plants and its relation with fuel type, and the trend of GHG emission from the base year to the end year in both supply and demand parts.

The Reference scenario, which follows the same trend as the business-as-usual (BAU) scenario, provides a baseline for comparing the effects of different alternatives and scenarios. The results of this scenario are the outcomes that can be expected to happen without any government involvement in energy policy and reflect the effect of past policies in future. Thus, creating a Reference scenario is a basic prerequisite for any energy planning and projection.

5.1.2 DSM scenario

This scenario was designed to represent the energy conservation that can be achieved by changing the power consumption patterns of the household sector and reducing transmission and distribution losses with the goal of preserving national energy resources and protecting the environment. Designed based on the status reports of the electricity sector, this scenario assumes that the average annual consumption of energy intensive appliances in the household sector will show a 5% decline by 2035.

5.2 Scenarios of electric sector optimization

The scenarios of electric sector optimization were created in the following steps to determine the least cost electric sector expansion solutions that meet the demand of the end year (2035).

5.2.1 Step 1: Determining the least-cost power plant expansion solutions with the environmental costs taken into account

In this step, several simple scenarios, each allocated to only one production technology (Steam Only, Gas-turbine Only, Combined-cycle Only, and Diesel Only), were created and then investigated with their environmental costs taken into consideration.

5.2.2 Step 2: Using the optimization capability to determine the least-cost solution and the solution subject to maximum pollutant emission constraints

The optimization capability of the LEAP software was used to define a basic optimization scenario (hereafter referred to as Optimized), where a set of power plants was automatically formed in a way that the incurred cost would be minimized. We also defined another scenario (hereafter referred to as Limit) to determine how considering a maximum

emission allowed affects the choice of technology type (type of power plant) and ultimately the increase in energy efficiency under the optimization process. In the next part of the paper, the results and findings of the methodology are presented according to all scenarios of both models and evaluated parameters.

6 Results

6.1 Simulation results

6.1.1 Forecast of pollutant and GHG emissions of thermal power plants in the DSM scenario

The predicted trends of pollutant and GHG emissions of thermal power plants in the Reference scenario and DSM scenario by 2035 are portrayed in Fig. 2. Based on the software calculations, in the Reference scenario, pollutant and GHG emissions of thermal power plants will increase from 148.8 $MtCO_2$ in 2013 to 456.8 $MtCO_2$ in 2035. In the DSM scenario, pollutant and GHG emissions of thermal power plants in 2035 will reach 429 $MtCO_2$, which is markedly lower than the alternative figure. The illustrated trends clearly demonstrate the effect of DSM on the GHG emissions of thermal power plants. The GHG emissions of thermal power plants in the Reference scenario and the DSM scenario are compared in Fig. 2.

6.1.2 Forecast of social costs of thermal power plants in the DSM scenario

Figure 3 shows the trends of social costs of thermal power plants in the Reference scenario and DSM scenario from 2013 to 2035. According to these results, in the Reference
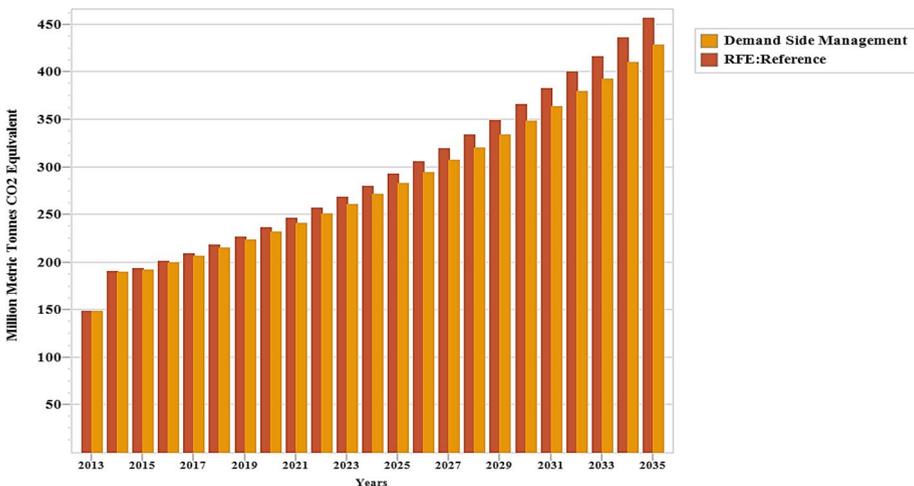

Fig. 2 Forecasts of total GHG emission of thermal power plants from 2013 to 2035 in the Reference and DSM scenarios ($MtCO_2$)
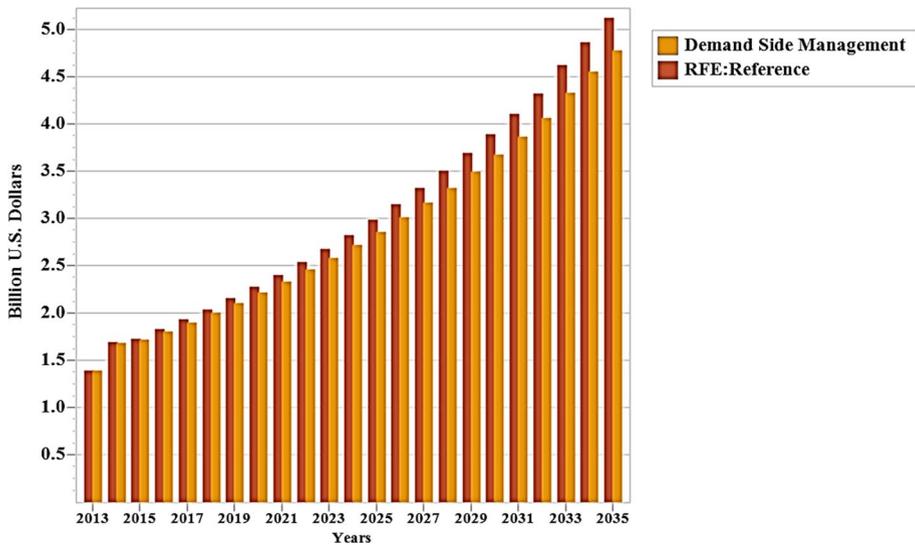
Fig. 3 Forecasts of social cost of thermal power plants from 2013 to 2035 in the Reference and DSM scenarios (Billion U.S. Dollars)

scenario, social costs of thermal power plants will increase from 1.4 Billion U.S. Dollars in 2013 to 5.1 Billion U.S. Dollars in 2035. In the DSM scenario, the final social cost of these plants in 2035 will be 4.8 Billion U.S. Dollars. These trends also show the significant effect of DSM on the social cost of thermal power plants. Figure 3 compares the social cost of thermal power plants in the Reference scenario and the DSM scenario.

Before using the electric sector optimization capability of the LEAP software to determine the least-cost electricity generation pathway, we need to predict the electricity demand in 2035. The software forecasts for the electricity demand are shown in Fig. 4. This forecast was made in the Reference scenario from the base year (2013) to the end year (2035). As this figure indicates, the total electricity demand in Iran is expected to increase from 280.8 Thousand GWh in 2013 to 745.9 Thousand GWh in 2035.

6.2 Electric sector optimization results

The steps taken to achieve the research objectives using the electric sector optimization model are described in the following.

In the electric sector optimization model of the LEAP software, Iran's electricity demand in the presence of capacity expansion plan grows from zero in the base year to 745.9 Thousand GWh by the end of the period (2035). Thus, all scenarios are evaluated with the goal of meeting this demand by 2035.

6.2.1 Step 1: The least-cost thermal power plant expansion solution with the environmental costs taken into account

According to performed calculations, Fig. 5 shows social costs of scenarios for the use of Diesel Only, Steam Only, Gas-turbine Only, and Combined-cycle Only based on the investment cost,
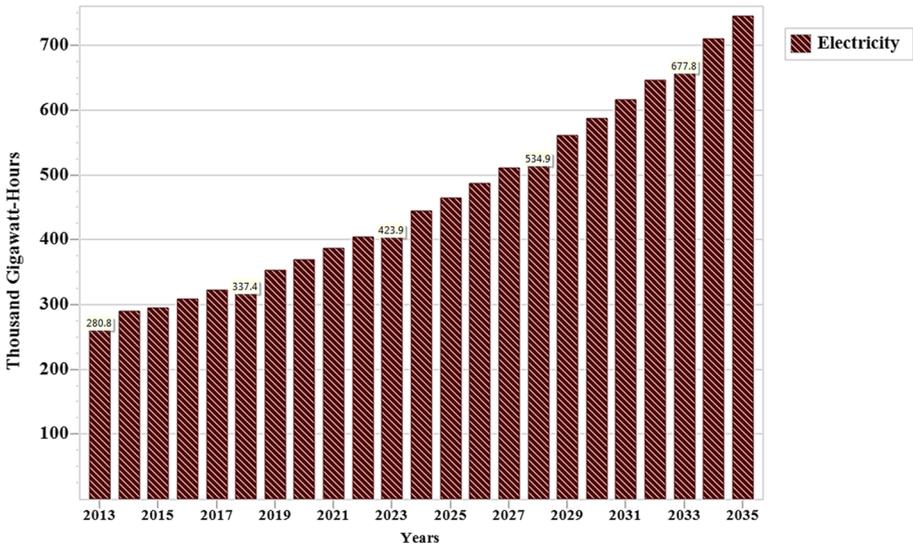
Fig. 4 Trend of electricity demand from 2013 to 2035 in the Reference scenario (Thousand Gigawatt-hours)
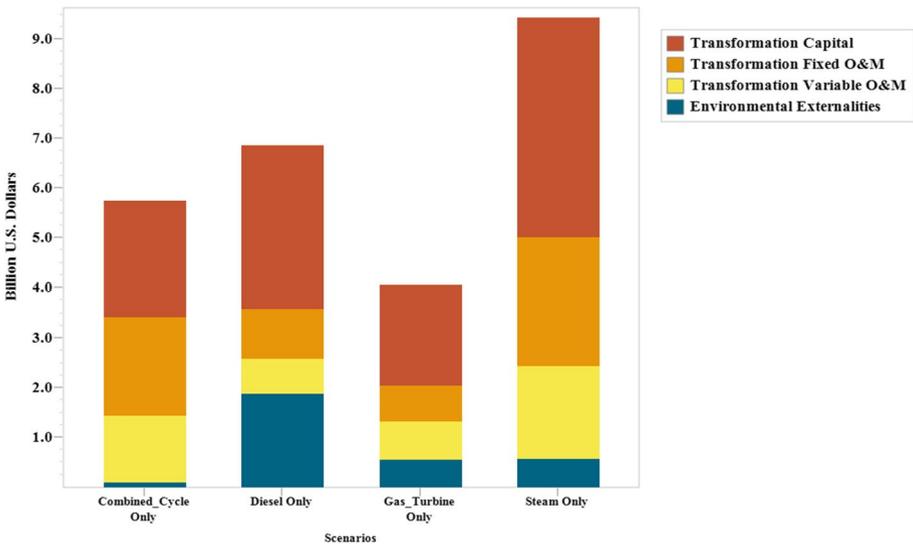

Fig. 5 Social costs in the first step of power generation optimization in 2035 (Billion U.S. Dollars)

fixed and variable operation, and maintenance costs in 2035. As it is shown in Fig. 5, the use of simulation capability of the software in this step revealed that with the environmental costs taken into account, the social costs of Diesel Only, Steam Only, Gas-turbine Only, and Combined-cycle Only scenarios in 2035 are 6.9, 9.5, 4.1, and 5.7 Billion U.S. Dollars, respectively.

As these scenarios show, the use of "Gas-turbine Only scenario" has the lowest social cost with an investment cost of 2 Billion U.S. Dollars, fixed operation and maintenance cost of 0.7 Billion U.S. Dollars, variable operation and maintenance cost of 0.8 Billion U.S.

Dollars, and environmental cost of 0.6 Billion U.S. Dollars. It is worth noting that in line with the primary goal of optimization, all scenarios had to meet the same level of electricity demand and all results were obtained with the environmental costs taken into consideration.

6.2.2 Step 2: The least-cost solution with optimization constraints

In this scenario, the optimization capability of the software was utilized to determine the least-cost power generation pathway.

In this Optimized scenario, the social costs of power plants were minimized, and the most economical pathway to generate electricity was obtained. The result of this pathway, which has a social cost of 5.1 Billion U.S. Dollars, is shown in Fig. 6. This scenario is the most economical type of electricity generation.

The Limit scenario was employed to apply the constraint of maximum emission level which is allowed on the choice of the type of power plant during the optimization process. The Limit scenario was found to have a social cost of 5.1 Billion U.S. Dollars and the same power generation pathway as the Optimized scenario (Fig. 6), which is because of the type of power generation technology suggested by the software (Fig. 7). To facilitate the selection of technology type (power plant), the least-cost generation pathway under the Optimized and Limit scenario was obtained.

The least-cost (optimal) power plant solution, obtained in Optimized and Limit scenarios, is the combined cycle power plant with the output of 918.6 Thousand GWh (Fig. 7). Likewise, in the Limit scenario, the combined cycle power plant was found to be the best option for power generation in 2035 (see Fig. 7). Thus, according to the base year data, converting the country's gas turbine power plants (with 30.9% efficiency) to the combined cycle power plant (with 44.1% efficiency), will lead to 13.2% increase in the efficiency of thermal power plants, which results in an increase in the efficiency of the entire energy system.
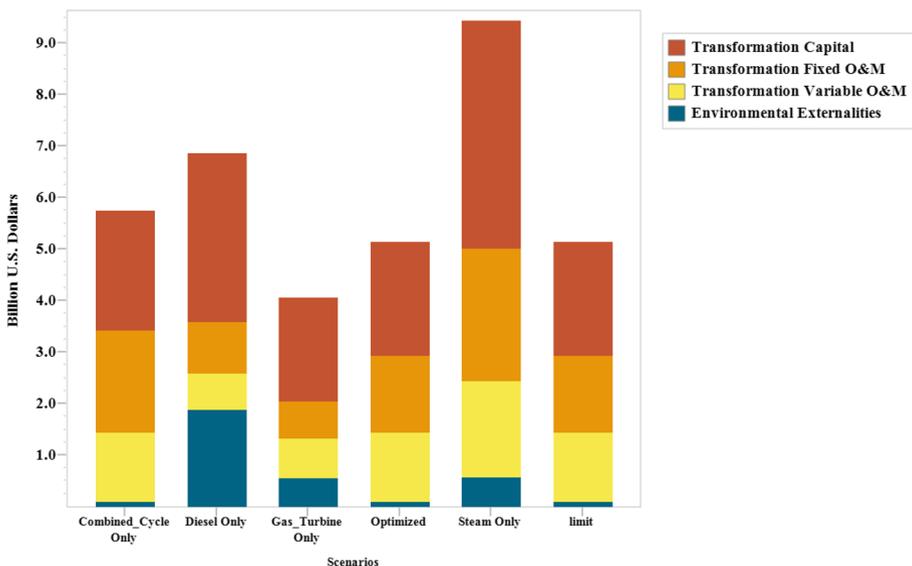

Fig. 6 Social costs in the second step of power generation optimization in 2035 (Billion U.S. Dollars)
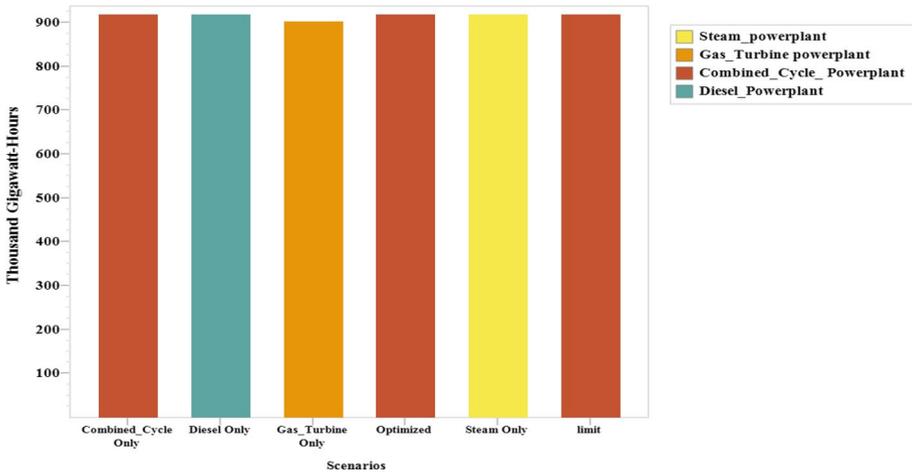
Fig. 7 Electricity generation of power generation optimization in 2035 (Thousand GWh)

6.3 Pollutant and GHG emissions in different scenarios and Optimized and Limit scenario

The results of calculations performed to determine the pollutant and GHG emissions of different scenarios in 2035 are presented in Fig. 8. The results indicate the highest pollutant and GHG emissions is 698.2 $MtCO_2$ which belongs to the diesel power plant scenario and the lowest is 144 $MtCO_2$, related to Combined-cycle Only, Optimized, and Limit scenarios.
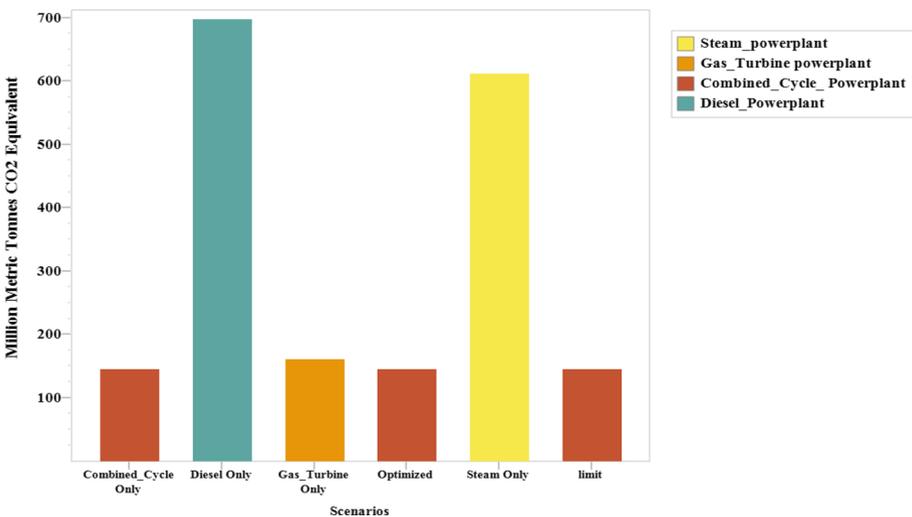

Fig. 8 Pollutant and GHG emissions of power plants in different scenarios in 2035 ($MtCO_2$)

6.4 Comparison between results of the electric sector optimization and DSM scenarios

As it is shown in Fig. 9 and Table 2, all pathways available for optimizing the power system from both supply-side and demand-side perspectives were assessed. In Table 2, all social costs and GHG emissions of power plants in the electric sector optimization scenarios (Combined-cycle Only, Steam Only, Diesel Only, Gas-turbine Only, Optimized, Limit) and in the DSM scenario are summarized. The social cost of the DSM scenario was lower than that of the Reference scenario, and the social costs of the Optimized and Limit scenarios were lower than those of other electric sector optimization scenarios.

Moreover, the least-cost pathway to power generation in Iran in 2035 was determined. After comparing the DSM and Optimized scenarios, it was found that although the DSM scenario has a lower social cost, the Optimized scenario has a lower emission. Nevertheless, the DSM scenario has a lower GHG emission (429 MtCO$_2$) compared to the steam and diesel scenarios. Section 7 of the paper examines the implementation of management and policy considering the importance of clarifying the perspectives facing managers and politicians.

7 Policy and managerial implementation

One of the most central issues on the agenda of policy-making and planning sections is to create a balance between electricity supply and demand and maintain its quality to develop sustainable and secure energy supply. For this reason, different scenarios have been studied to optimize Iran's electricity supply and demand.

Since the proper use of energy ensures sustainable development in any society, the preservation of valuable energy resources and proper management of its consumption
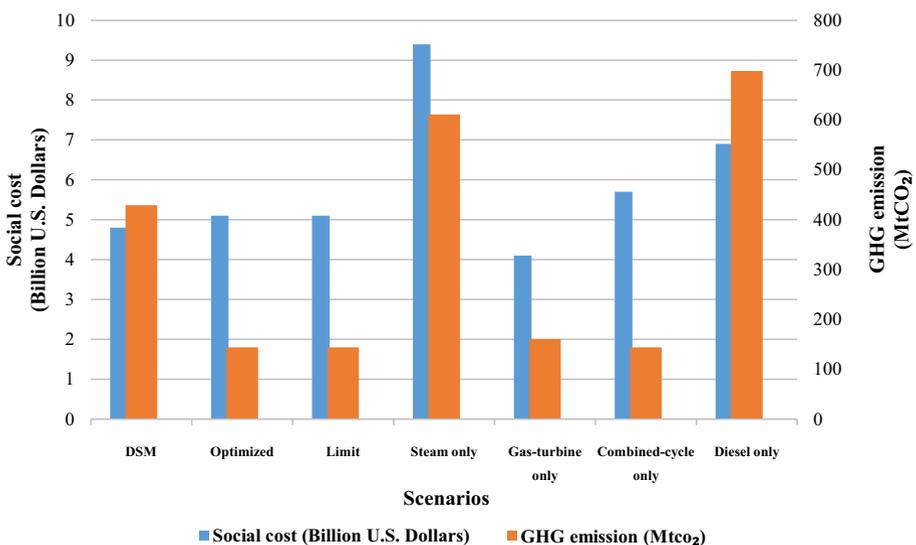

Fig. 9 Social cost and GHG emissions in all scenarios in 2035 in both model capabilities as electric sector optimization and DSM scenarios

Table 2 Social cost and GHG emissions in all scenarios in 2035 in both model capabilities as electric sector optimization and DSM scenarios

Model capabilities	Simulation	Electric sector optimization					Optimization	
	Simulation	Simulation					Optimization	
Scenarios	DSM	Combined-cycle Only	Diesel Only	Steam Only	Gas-turbine Only		Optimized	Limit
Social cost (Billion U.S. Dollars)	4.8	5.7	6.9	9.5	4.1		5.1	5.1
GHG emission ($Mt\,CO_2$)	429	144	698.2	611.3	160.3		144	144

is one of the most important issues in all countries, and all policymakers, governments, and stakeholders in the energy sector have come up with ways to tackle the problem of increasing waste consumption and thus controlling energy costs.

With regard to save and improve the pattern of electricity consumption and conserve the country's energy reserves and protect the environment, the social costs and emissions of thermal power plants in Iran will be significantly reduced by 2035 in this paper by applying the DSM (demand side management) scenario. Comparing these results with similar studies in other geographical regions of the world makes it possible for researchers and politicians to gain a deep and clear understanding of the challenges and dimensions of achieving goals.

In the model of optimizing the supply of energy system (electricity generation), the results obtained by the scenario of limiting the emission of environmental pollutants in thermal power plants try to point out the necessary points to improve the environmental conditions by providing a forecast of the release of environmental pollutants to policymakers in various fields, especially in the field of development. It also provides powerful tools for improving management, policy-making, decision-making, and setting environmental strategies. This study helps to formulate and support environmental laws and policies by combining the results of models for optimizing Iran's electricity supply and demand.

This research attempts to find solutions to important problems in society with regard to electricity consumption and the electricity generation industry. The problem here does not mean a defect or a flaw, but rather adds to our knowledge base. Applied research has been considered because of its ability to respond to the current economic and social problems of society, so with experimental studies, the real impact of one factor on another factor can be predicted by considering other environmental factors.

Due to the practicality of this research, regular and organized efforts have been made to investigate the problem that needs a solution. The predictions made provide a clearer perspective for researchers and managers so that they can make decisions based on it and solve problems. The results of this research can be a clue for future research to test theoretical concepts in real-life situations and solve problems in the electricity industry. Even a full understanding of the research direction of the present paper will be a great help to future research using different parameters. In the next section, the importance of the findings of the present paper is interpreted and explained in light of previous knowledge in the scientific field of the paper.

8 Discussion

Regarding the management of demand and supply of Iran's electricity system, and based on REF, DSM, Limit, Optimized scenarios, it was observed that increasing energy consumption and increasing the cost of electricity generation lead to emissions and increasing social costs in the electricity industry, but the difference between the above values will not be the same between the considered scenarios. Government interventions through careful policies and planning will reduce the cost of electricity generation and reduce the destructive effects of pollution on the environment. In this case, the amount of social costs and emissions of thermal power plants will be significantly reduced.

The results of this research are in line with Bautista (2012), who analyzed Venezuela's energy sector to determine the total cost of energy production and greenhouse gas emissions in four scenarios by 2050, and concluded that emissions will decrease as energy

efficiency increases. Furthermore, the results of Ghadaksaz and Saboohi (2020), who examined low-cost options to improve energy efficiency and reduce greenhouse gas emissions in the energy supply sector, were consistent with the present research. They concluded that the amount of greenhouse gas emissions will be significantly reduced by 2030 due to the application of different scenarios in their paper.

The results of this research are also in line with Mahbub et al. (2017) on optimization at each stage to minimize the total annual energy system cost and annual CO_2 emissions.

It should be noted that the optimization of the energy system in a number of references has been done with different models and only one side of the energy system (supply or demand) has been examined, which is seriously different from the evaluation path of this research.

The rise of DSM and "least cost planning" in the United States inspired other countries. In 1988, the Canadian province of British Columbia initiated a DSM initiative (Pape-Salmon & Berkout, 2018), and in 1989, the province of Ontario found both supply and demand in its power grid planning (Love 2015). Energy efficiency programs have focused on the economic rationale of "demand side control" being a lower cost alternative than supply side services in the public utility grid planning since the 1980s, through times of market consolidation, to the present day (Eto, 1996; ACEEE, 2018; Rosenow, 2012; Jaccard, 1992; Love 2015).

The technical and economic efficiency of energy consumption, the loss of nearly a third of all energy in energy-consuming processes, and the resulting environmental problems are some of the problems that have highlighted the need for energy management for many years. The rising cost of electricity generation, the large investments required to build power plants, and the environmental pollution associated with electricity generation in recent years have made it important to optimally manage electricity supply and demand. Song et al. (2019) presented China's energy security index based on three dimensions of supply, technical and economic, and environment using 18 indicators.

The findings of the present research are very similar to Le and Nguyen (2019), which showed that energy security will lead to economic growth using econometric methods. This index reflects the capacity of an energy system in a clean, low carbon, and enhanced state for sustainable development. Perissi et al. (2021) have modeled the economics, environmental constraints, and biophysics and the relationship between the two using energy transfer scenarios from a new set of evaluation models (MEDEAS).

In the present paper, the reduction of pollutant emissions and social costs of power plants are estimated using optimal electricity supply and demand management scenarios. Using such an approach, it was observed that the emission values of environmental pollutants are reduced in different scenarios by optimizing both sides of the energy system and determining the emission limit. As a result, the social cost will also decrease significantly. The last part of the paper concludes and summarizes the subject of the paper and the importance of conducting the study according to the obtained results.

9 Conclusions

In this study, the capabilities of the LEAP software were used with the purpose of optimizing both electricity supply and electricity demand in Iran. The results showed that in the electric sector, optimization scenarios, i.e., Combined-cycle Only, Steam Only, Diesel

Only, Gas-turbine Only, Optimized, and Limit, the social costs of power plants in 2035 would be 5.7, 9.5, 6.9, 4.1, 5.1, and 5.1 Billion U.S. Dollars, respectively; however, in the DSM scenario, this cost would be only 4.8 Billion U.S. Dollars.

The results obtained in the present study showed that using DSM scenario (5% decrease in electricity consumption of sectors and 5% decrease in transmission and distribution losses) and the least-cost optimization of Iran's electric sector in order to produce 745.9 Thousand GWh of electricity can have positive effects on reducing the social costs.

Investigations conducted to reduce social costs and identify the optimal power generation pathway with the electric sector optimization capability of LEAP showed that among the studied technologies (combined-cycle, steam, diesel, and gas-turbine power plants), the most efficient power generation technology for Iran is the combined cycle power plant, the use of which will improve the efficiency of the electric industry.

The results indicate that in the electric sector optimization scenarios, i.e., Combined-cycle Only, Steam Only, Diesel Only, Gas-turbine Only, Optimized, and Limit and the DSM scenario, the GHG emission of the studied thermal power plants in 2035 will be 144, 611.3, 698.2, 160.3, 144, 144 $MtCO_2$, and 429 $MtCO_2$, respectively. As it was shown, both approaches result in a notable emission reduction.

With the growing environmental concerns of global community, the UN aims to adopt stricter rules to force all countries to further reduce their GHG emissions. These rules, which are widely regarded as the cornerstone of an unprecedented agreement, are to be implemented by 2020 (European Commission 2014). Since Iran is among the top 10 countries with the highest CO_2 emission (IEA, 2012), and considering the significant share of power plants in its total GHG emission (about 1/3 of total emission), the results obtained for the energy system in the Optimized and DSM scenarios can provide a road map for the future expansion of electric power sector in this country.

Optimizing power generation processes and strengthening monitoring and regulation may help improve electricity generation technologies (Zhou et al., 2015). Optimization and planning techniques and strategies such as the integrated resource planning (IRP) (Shrestha & Marpaung, 2006), energy cost planning (Li & Huang, 2012; Park et al., 2011), demand side management (DSM), and demand response (DR) (Ming et al., 2013; Siano 2014) can play a significant role in achieving higher energy efficiency and lower emission.

Among all the scenarios studied in this paper, the Optimized, Limit, and Combined-cycle, Only scenarios had the lowest GHG emission. The reason why these scenarios had the same emission is the similarity of the electricity generation technology suggested by the software (i.e., the combined cycle power plant).

The GHG emission of thermal power plants was lower in the electric sector optimization scenarios than in the DSM scenario, but the opposite result was obtained for social cost. Thus, simultaneous optimization of both electricity supply and electricity demand can be expected to be a considerably positive step toward sustainable development, especially in electricity industry.

Given the strong correlation of economic growth with electricity consumption (Ferguson et al., 2000), the growth of power plant sector is of immense importance for the growth of Iranian energy system as well as economy (Kachoee et al., 2018).

The type and level of research activities is considered as one of the main indicators of development and progress. Success in all industrial development activities depends in some way on the development of research activities. A more general and comprehensive study and research in each article can be a guarantee of sustainable progress and development in any country.

As a result, the necessity and importance of the present study is in response to the assumptions of both supply and demand sides of the Iranian energy system. Both models of optimization of supply and demand side of Iran's energy system according to the scenarios of supply and demand side as well as the scenario of emission limit (Limit) have been presented comprehensively until 2035. Reducing the social costs and emitting environmental pollutants of Iran's thermal power plants on both sides of the energy system (supply, demand) will help achieve the goals of economic, social and environmental development that are key factors in achieving development in any country. The present compares its findings with the findings of new papers.

Environmental issues caused by the electricity industry have attracted more attention from sustainable development professionals and environmental activists. The problems arising from this industry in the discussion of sustainable development can be attributed to the increase in energy consumption of power plants. Hence, the present research has examined DSM scenario to save and improve the pattern of electricity consumption and conservation of the country's energy reserves and environmental protection. To this end, the parameters of social spending and the release of environmental pollutants have been evaluated. Optimized scenario to generate cheaper electricity will reduce social costs and environmental emissions.

One of the goals of any country is to achieve sustainable development and the environment. Sustainable development addresses three important categories: economy, society, and the environment. Maintaining the health of the environment is essential to achieve sustainable development. In this regard, macroeconomic policies are highly effective in the environment, so that sustainable development and the environment have been expressed as the most important concerns for civilized humanity. This prompted planners to pave the way for environmental protection.

In the present paper, the amount of social costs and emission of environmental pollutants of thermal power plants will also be reduced according to the scenario of emission limit of pollutants (Limit). The results and studies of this research have the greatest impact on environmental sustainability.

Many laws and regulations have been developed and are being implemented to prevent pollution and environmental degradation, but the implementation of these laws and regulations is in many cases left to set rules and standards. Establishing standards can greatly help industries to improve the environment and maintain justice and sustainable social development.

Suggestions are made for the development of the electricity industry given the reduction of social costs caused by the country's power industry and focusing on emission reduction patterns.

Given the experiences gained during this research, it is suggested that the capital produced by the electricity demand and supply-side optimization can also be injected to the same sector or other sectors of the economy to accelerate the development in the desired area. Researchers interested in this topic are recommended to focus on identifying executive and managerial solutions for reducing electricity consumption in different sectors of the economy such as the household sector. Another line of research can be examining a greater set of power generation technologies intended for optimizing electricity supply and demand in Iran.

On the other hand, finding appropriate mechanisms to reduce electricity consumption in the domestic sector and reducing the emission limit of pollutants will pave the

way for reducing CO_2 related to electricity generation. Installing solar panels by electricity consumers in the household sector and generating renewable electricity in the summer and peak electricity consumption will be a good way to minimize the electricity crisis. Comparing the results of both models together can create a clearer outlook for boosting economic growth and the use of new technologies, environmentally friendly, and appropriate for current and future infrastructure.

Appendix A

See Tables 3 and 4.

Table 3 Evaluated parameters in the present paper in both electricity supply and demand optimization models

Evaluated parameters	Scenarios	Models
GHG emission	(REF) Reference	Simulation
Social cost		
GHG emission	(DSM)	
Social cost	(Demand Side Management)	
GHG emission	(Optimized)	Electric
Social cost	Determining the least-cost power plant expansion solutions with the environmental costs taken into account	sector optimization
GHG emission	(Limit)	
Social cost	Using the optimization capability to determine the least-cost solution and the solution subject to maximum pollutant emission constraints	

Table 4 Parameters units in LEAP modeling

Parameters	Unit
Social cost	Billion U.S. Dollars
GHG emission	Million Metric Tons CO_2 Equivalent ($MtCO_2$)
Electricity demand	Thousand Gigawatt-hours
Electricity generation	Thousand Gigawatt-hours
Energy efficiency	Percent (%)

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