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An overview of energy planning in Iran and transition pathways towards sustainable electricity supply sector

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ABSTRACT

Despite a substantial potential of renewable energy sources, the current energy supply system in Iran relies almost entirely on fossil fuel resources. It has imposed significant financial burden on the country and has led to considerable GHG emissions. Moreover, the country is confronting several challenges for harnessing alternative clean energy sources and promoting rational energy policies over the recent decades. To probe the root cause of these problems, this paper first provides an overview on the previous energy planning attempts in Iran. It shows that adequate commitment to a long-term energy planning could have meaningfully prevented these serious challenges. However, the previous studies have had some limitations in terms of employing appropriate planning tools, comprehensive evaluations, and scenarios definition and ranking. This paper thus proposes a power planning framework to assess the sustainability of future electricity scenarios for the period 2015–2050. MESSAGE, a systems engineering optimization model, is employed to evaluate the potential impacts of transitioning to a low-carbon electricity supply system. Using a combined AHP-TOPSIS method, the scenarios are then ranked based on 18 different techno-economic, environmental, and social dimensions of sustainability. The results indicate that scenario Cl_32, in which the share of non-hydro clean energy for electricity generation reaches 32%, is ranked best.

1. Introduction

According to the OPEC estimates, Iran holds the world's largest proven gas and oil reserves. In more details, 16.8% and 10.5% of the total world's gas and oil reserves are located in Iran, respectively [1]. Besides the abundant fossil fuel resources, Iran possesses a significant potential of renewable energy sources including water, solar, wind, biomass, and geothermal.

Despite the huge potential both in fossil and non-fossil energy sources, Iran is facing some problems in its energy sector, more specifically in the power sector. High dependency on fossil fuels is one of these challenges. The share of renewable resources in electricity generation is about 5% [2], where wind power and solar PV (photovoltaic) altogether have a small share of less than 0.4% [3]. Currently, more than 98% of the national energy consumption is from fossil fuel energy carriers [4]. Significant fossil fuel consumption has also caused a disastrous air pollution. This has also placed the country among the top ten GHG emitters in the world [5]. GHG emissions from power sector accounted for around one third of Iran's energy sector emissions [4]. Moreover, from an economic perspective, the current electricity generation mix is unsatisfactory. Manzoor and Aryanpur [6] quantified the likely benefits of commitment to the long-term energy planning in Iran. They have shown that developments in the power sector have mainly resulted from short-term plans, while the commitment to the long-term energy planning would have reduced the power system costs by $0.7-$3.0 billion per year. Moreover, long-term planning would have ensured 15%–33% cut in total CO_2 emissions over the past three decades.

The interaction between energy demand, economic growth,

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technology advancement, and sustainable development has made energy planning a complex problem with multiple variables and constraints. Accordingly, as a result of the oil crisis in the mid-1970s, several types of energy planning models have been developed to help policy making [7]. Well-developed decision-support tools such as Wien Automatic System Planning Package (WASP) [8], Model for Energy Supply Systems and their General Environmental Impact (MESSAGE) [9], Long Range Energy Alternatives Planning System (LEAP) [10], Energy Flow Optimization Model (EFOM) [11], MARKet ALlocation (MARKAL) [12], the Integrated MARKAL-EFOM System (TIMES) [13], Balmorel [14], and EnergyPLAN [15], have been used for planning in large-scale energy systems. Based on detailed input data, these tools help to reflect the entire energy or power supply system. These models mainly explore the proper supply of energy at the lowest possible price to meet the present and future energy demands. Other criteria, such as energy resource availability, environmental, and social concerns are generally considered as constraints [16]. These energy planning tools can prepare a framework for testing different policies and scenarios at national, multi-regional, and global levels [17].

Many researches around the world have considered the application of energy planning tools to investigate the optimality of the national energy plans. These research works include: long-term CO_2 emission reductions in UK energy sector [18], the contribution of innovative power generation technologies in GHG mitigation in China [19], an infrastructure for a hydrogen-based transport system in Germany [20], demand response from a microeconomic perspective and future energy system in Denmark [21,22], the role of bioenergy to achieve low-carbon and high-security energy scenarios in Ireland [23,24], the economic impact of gas dependence in power generation in Thailand [25], a sustainable energy plan for Cuba [26], future perspectives of renewable energy in the power-generation sector for UK [27] and Portugal [28], the costs of a low-carbon power supply in Malaysia [29], the impact of nuclear power plants and CCS (carbon capture and storage) on the future structure of energy system in India [30], the United Arab Emirates [31], Brazil [32], and Korea [33].

In addition to the national level, some previous studies have tried to use the energy planning models for analyzing multi-regional and international case studies. Exploring energy supply options and energy supply security in the Baltic States [34], surveying investment opportunities in the Nordic electricity system [35], investigating the global energy transition pathways [36], and the stabilization of atmospheric concentrations of GHG emissions [37] are among these efforts.

Some studies have focused on energy modelling as the most appropriate and effective mean for energy policy analysis [38–45]. Nearly all of these studies strongly recommend decision-makers to obtain energy policy options from the results of modelling tools. Iran, as a country with different sources of energy, has an urgent need to take advantages of modelling tools in preparing its long-term power plan. Although different studies have emphasized long-term energy planning in Iran, the energy and power sector developments in the country have mainly resulted from short-term obligations [6]. Moreover, most of them paid particular attention to the economic criteria, but environmental and social criteria are generally ignored [46–54]. Therefore, this paper first aims to prepare a review on the country's energy plans undertaken over the past years. This review would assist us to create a foundation for the future energy strategies and could result in a more comprehensive plan by avoiding the previous limitations. Next, this paper proposes a power planning framework to assess the future electricity scenarios. MESSAGE, a systems engineering optimization model, is employed to evaluate the potential impacts of transitioning to a low-carbon electricity supply system. Furthermore, using Multi-Criteria Decision Making (MCDM) methods, the scenarios are ranked based on the 18 different techno-economic, environmental, and social dimensions of sustainability.

The novelty of this paper, therefore, is fourfold: firstly, it comprehensively reviews national energy planning studies in Iran; secondly, it suggests a framework based on MESSAGE planning tool to achieve a sustainable energy planning and policy making; thirdly, it assesses the sustainability of future power generation scenarios in Iran; and finally, it attempts to rank different low-carbon scenarios using MCDM methods.

The remaining paper is structured as follows: Section 2 provides a review of Iran's energy and power system planning. Then the methodology and data used in this work are outlined in Sections 3 and 4, respectively. Section 4 also describes the future scenarios and sustainability indicators. The results are discussed in Section 5, and finally the conclusions are drawn in Section 6.

2. An overview of energy planning studies in Iran

Iran's energy sector has experienced significant changes over the past decades. Because of easy access to fossil energy resources, the total final energy consumption during the past three decades has increased from less than 350 to more than 1300 million barrels of oil equivalent (BOE) [4]. Moreover, the installed power plant capacity in the same period has grown more than 5.5 times and has reached from less than 14 GW in 1987 to about 79 GW in 2017. As a result of this capacity expansion, electricity generation has increased more than sixfold during this period [2]. These changes are mainly the result of executing short-term plans, where investment on developing electricity and energy sectors are predicted according to a national annual budget. In this section, the previous studies about Iran's energy planning, including governmental and academic studies, are comprehensively examined with the purpose of developing a more practical plan for the power sector, considering the strengths and limitations of the previous attempts.

2.1. Energy planning studies undertaken by government sector

The earliest national energy planning studies have been carried out during the 1970s by Stanford Research Institute. Since the mid-1990s, several energy planning and national electricity development studies have been carried out by governmental organizations. These studies are described in the following subsections.

2.1.1. Long-term energy plan for Iran

This study was conducted by Stanford Research Institute in 1973 [46]. The domestic demand for energy in Iran was projected by energy types, end-use sectors, and provinces up to 1997. The forecasting methodology was based on empirical relationships between energy consumption and economic, demographic, industrial output, and price parameters in each end-use sector.

Seven energy demand scenarios were analyzed to determine the effect of economic growth rates, natural gas use, energy prices, and nuclear power growth on energy demands. The base case scenario reflected the most likely pattern of economic growth, a relatively high rate of increase in natural gas use, and a rapid expansion of nuclear power. In this scenario, the total installed capacity was projected to increase from about 3900 MW in 1977 to more than 43000 MW in 1997. The main recommendations are as follows:

- Expanding natural gas use as rapidly as possible;
- Encouraging and promoting the use of liquefied petroleum gas (LPG);
- Holding fossil fuel prices at current levels as long as revenues cover costs;
- Gradually increasing electricity price to cover increasing costs;
- Developing hydropower resources that are economically competitive with fossil fuel plants;
- Continuing exploration studies to determine the amount of coal reserves;
- Establishing a research and development program focusing on

renewable energy technologies, solar power in particular;
- Encouraging energy conservation through regulatory and tax measures rather than by increasing energy prices.

2.1.2. Prospects for development of energy sector in Iran

In 1994, the Institute for Advanced Studies in Planning and Development, a subsidiary of the management and planning organization of Iran, explored the prospects of the development of the energy sector [47]. The study considered a planning period from 1994 to 2021. Addressing both demand- and supply-side, the work tried to analyze the entire energy system through a comprehensive approach. Based on an economic growth model, the demand-side was evaluated regarding domestic demands of electricity, oil, and natural gas, primary energy reserves, economic rate of return, and global energy prices. The supply-side was assessed considering different energy sources, techno-economic changes, and environmental concerns. The key results were as follows:

- Crude oil production increases from 2.95 to 4.6 million barrels per day;
- Annual natural gas production from 332 reaches 355 billion BOE;
- Power generation grows from 79 to 167 billion kWh;
- The share of hydropower in total power generation becomes almost four-fold.
- By an annual growth rate of 1.3%, the installed power capacity reaches 40 GW;
- The share of gas turbine and steam power plants gradually decreases, and substituted by combined cycle power plants.

2.1.3. Twenty five-year plan for optimal energy supply system

The study covered a 25-year horizon, where the base year was 2004 [48]. By employing Energy Flow Optimization Model (EFOM-ENV), the focus of the study was on the power capacity expansion, regarding the renewable energies and interactions between power and the other sectors of energy systems. The key suggestions were as follows:

- About 59 GW power capacity should be installed at the end of the planning horizon;
- More than 90% of the power generation would be relied on fossil fuel technologies;
- To limit GHG emissions, energy efficiency improvement is preferred rather than the renewable technologies development;
- Power export is suggested according to a trade-off between electricity generation costs and global electricity prices.

2.1.4. Long-term energy planning in Iran

The Ministry of Energy developed an integrated energy model to comprehensively assess different energy pathways in Iran from 2014 to 2041 [49]. To forecast energy demand and optimal energy supply in different scenarios, top-down assumptions including population growth, technological progress, economic development, and lifestyle changes were combined with bottom-up constraints. The integrated approach incorporated two main modelling tools: MAED and MESSAGE.

The study presented a 27-year period analysis of the energy system to achieve an average economic growth rate of 5.5% per year. The demand projections were estimated and then the optimal structure of the energy supply system for different sector was presented. The main findings were as follows:

- Total final demand would experience an average annual growth rate of 3.7%;
- Installed capacity of oil refineries should be increased from 1.7 to 3.1 million barrels per day; The share of natural gas liquids as an input in oil refineries increases from 2% to 32%;
- The potential of natural gas export may reach 220 million cubic meters per day;
- The share of renewable technologies (including hydropower) in total installed capacity would rise to 30%;
- The transition pathway requires at least a cumulative investment cost of $563 billion.

2.2. Energy planning studies undertaken by the academia

During the two recent decades, numerous academic researchers paid particular attention to energy planning in Iran. This section investigates some of these studies.

2.2.1. Energy supply planning in Iran by using fuzzy linear programming

Sadeghi and Hosseini [50] in 2006 used a linear programming with fuzzy objective function coefficients to cope with uncertainties in energy planning. They mainly focused on uncertainty of investment costs for Iran's energy supply system. The uncertainties predominantly emerged from insecurity in the Middle East region, inflation and unemployment crises, obstacles in private ownership, instability of laws and lack of updated laws, and lack of transparency in foreign investments acts. Each of these would make foreign and domestic investors uncertain about investing in Iran and thus, ignoring these uncertainties would significantly bias the results of planning.

In this study, the reference energy system consisted of four subsectors including oil, gas, coal, and electricity. The time horizon of the study was 10 years, from 2004 to 2014. The fuzzy model and its equivalent crisp model were run and the results compared with each other. The results showed that uncertainty substantially affects natural gas supply systems. In the electricity sector, investment costs uncertainties mostly affected the main fuel of steam power plants. Finally, the total required investment cost in the crisp model was estimated to be about $10 billion dollars less than what in the fuzzy model is.

2.2.2. Integrated energy planning for transportation sector

Sadeghi and Hosseini [51] in 2008 explored the optimal consumption pattern of transportation fuels from 2005 to 2029 in Iran. To assure a cost-efficient energy supply and to analyze the corresponding environmental impacts, EFOM-ENV model was applied for designing the reference energy system and scenario analysis. The main objective of the model was to meet transportation demand for passengers and freight in both rural and urban areas. The results showed that the fuel consumption can be lowered by 14%, which most part of the reduction belongs to gasoline and gas oil. Moreover, total discounted cost of transportation system can be reduced by 14% during the time horizon.

2.2.3. Integrated resource planning for Iran

Amirnekooei et al. [52] developed a detailed reference energy system according to Iran energy balance. The entire energy system was simulated using LEAP model for a 25-year period from 2011 to 2035. Four different scenarios were defined to investigate the supply- and demand-side policies on depletion of fossil fuel resources and implications for emissions reduction. To estimate the total primary energy supply, the model considered key energy demand sectors, transportation and distribution losses, and various conversion technologies with different efficiencies, as well as energy carrier imports and exports.

Scenario analysis showed that up to 2035, crude oil and natural gas savings will be equivalent to 1.24 to 3.22 times Iran total primary crude oil and natural gas supply in 2009. It was predicted that in the best circumstances the depletion years of natural gas and crude oil reserves will be 2080 and 2076, respectively. To hold hydrocarbon reserves, the study strongly recommended energy efficiency improvement, particularly in the electricity supply system.

2.2.4. Optimal deployment of renewable energy sources

Aryanpur and Shafiei [53] in 2015 constructed some scenarios to show the optimal strategies for substituting fossil fuel power plants with renewable energy sources. The study paid particular attention to the cost-effectiveness of carbon taxes and direct incentives and the implications for emissions reduction from 2015 to 2045. To suggest the lowest-cost technology options, MESSAGE model was employed.

Scenarios analysis demonstrated that wind, solar PV, concentrating solar power (solar CSP), and biomass are promising non-hydro renewable technologies for Iran over the medium-to long-term period. Technologies based on oil products are gradually replaced with those with natural gas fuel. The findings denoted that alternative green scenarios can lead to about 1000–1600 million tonnes reduction in CO_2 emissions over the study period. This reduction is associated with efficiency improvement of fossil fuel power plants, fuel switching, and increased share of low/zero emission technologies. The findings also indicated that the carbon tax give rise to substantial renewable electricity generation. However, the carbon tax would not individually be a cost-effective strategy to reduce GHG emissions.

2.2.5. Iran 2040 project

This project seeks to envision the outlook for natural gas, electricity, and renewable energy in Iran and forecasts their trends through 2040. The study conducted by Azadi et al. [54] in 2017 analyzed the historical development and current situation of Iran's energy sector, and provided some suggestions for future expansions.

From a natural gas point of view, the results showed that the annual natural gas production is likely to rise to 336 and 420 billion cubic meters by 2022 and 2040, respectively. Smaller capacity of future greenfield projects and the expected drop in extraction from existing fields are the major reasons for a significant decline in the growth of natural gas production beyond 2021. Expansion of export capacity seems unlikely as domestic demand increases considerably. This is due to the replacement of petroleum products by natural gas for electricity generation and for space heating as well as development of petrochemical plants and energy-intensive industries. On the other hand, to meet the electricity demand in 2040, Iran will need to add a total of 54000 MW of power plant capacity at annual rates of 3000 MW in the short-term period and 1300 MW as 2040 approaches.

2.2.6. Multi-objective optimization for the power sector

Atabaki and Aryanpur in 2018 [55], developed a multi-objective linear programming model based on the reference energy system to prepare a sustainable plan for Iran's power sector. A 35-year time span from 2015 up to 2050 was considered. Besides cost optimization, minimization of CO_2 emissions and maximization of created jobs were evaluated as the other objectives. Employing the analytical hierarchy process (AHP), experts' opinions were utilized to determine the weights of the objectives for solving the multi-objective model.

The results showed that combined cycle would be the dominant technology in Iran's long-term power sector. Moreover, electricity generation from non-hydro renewables, solar PV in particular, should grow faster than the total power generation. The findings indicated that following an economic-optimal plan, Iran cannot fulfill the international mitigating commitments in full, thus environmental criteria should be considered in the power sector development policy. Furthermore, concerning non-cost criteria, including CO_2 emissions and job creation leads to the high technology diversification in capacity mix. Multi-objective analysis showed that significant improvements in emissions and job can be obtained by only a small increase in the total cost.

2.3. Insight from the power sector development plan

Table 1 summarized the previous attempts in providing an energy plan for Iran. As Table 1 shows, sustainability issues have been overlooked or sparsely addressed in former studies. Thus, this paper aims to develop a framework to prepare the power expansion plan with respect to a wide range of criteria in three categories including techno-economic, environmental, and social factors.

As Table 1 indicates, the previous studies are confronted with some limitations in terms of employing appropriate planning tools, scenario building, and ranking of scenarios. The proposed framework also tries to cope with these limitations by utilizing the MESSAGE model as a planning tool, defining different scenarios on clean technologies development, and ranking scenarios using MCDM approaches.

This framework can prevent the creation of some irrational outputs in previous studies such as underestimation of required capacity, overestimation of hydropower generation [47], low priority of renewable technologies [48], and considerable substitution of natural gas and petroleum products by coal [52].

2.4. The proposed framework for sustainable development of the power sector

Economic growth, security of supply, environmental stability, and social acceptability are among the objectives that today have been considered by the energy planners and policy makers of Iran. However, these objectives sometimes contradict each other. In the best case, any decision regarding the future path of Iran's power industry should maximize the satisfaction of all the stakeholders by taking their respective objectives into account. Accordingly, an appropriate analytical framework for energy planning should consider all these objectives. As Fig. 1 presents, the proposed framework consists of four main steps as follows:

2.5. Step 1. scenario definition

In Step 1, some power sector outlooks are depicted in different scenarios. Different data and assumptions on power plant technologies, techno-economic parameters, power demand, fuel resources and prices, emission factors, grid losses, capacity and generation constraints, and trading limits are used as the main inputs.

2.6. Step 2. energy supply optimization model

In Step 2, the optimal electricity generation mixes are provided applying MESSAGE planning tool. MESSAGE model is one of energy supply planning tools which was developed at the end of 1970s in International Institute of Applied Systems Analysis (IIASA). The International Atomic Energy Agency (IAEA) acquired MESSAGE in 2000 and further enhanced it. The IAEA provides it free to member states through their representatives. This model is based on the reference energy system which reflects energy flows from resource extraction and processing to conversion and storage, transmission, distribution, and consumption. In this model, the total supply system costs are minimized for supplying the final energy demand. The model thus provides an adequate tool for medium-to long-term planning for the energy supply sector. The model logic is the dynamic optimization based on system engineering in which complex integer linear programming is used [9].

2.7. Step 3. sustainability assessment

In this Step, the power sector development plans as the outputs of the energy supply model are assessed based on the sustainability criteria. The scenarios have diverse technical characteristics, require different investments, vary from environmental impacts, and cause various levels of social acceptability. Thus, in this step, the appropriate sets of criteria are identified to evaluate the development plans form technical, economic, environmental, and social perspectives.

2.8. Step 4. scenario ranking

Using MCDM methods, the scenarios are ranked in this step. The

Table 1
Key characteristics of previous studies for analyzing energy planning in Iran.

No.	Short title	Institution	Planning period	Methodology	Scope	Limitation	Strength	Key output
1	Long-term energy plan for Iran [46]	Stanford Research Institute	1973–1997	Simulation	Entire energy sector	Limited number of supply-side technologies	Different demand scenarios	Developing solar power and particular focus on energy conservation
2	Prospects for development of energy sector in Iran [47]	Management and planning organization	1994–2021	Integrated energy planning	Entire energy sector	Lack of transparency in the research procedure and model development	Analyzing both demand and supply sides	Higher demand growth in industrial and transportation sectors, Development of combined cycle power plants
3	Twenty five year plan for optimal energy supply system [48]	Ministry of Energy	2004–2029	Optimization with EFOM model	Power sector	Focusing on a single sector of the energy system	Give emphasis on renewable energy development	Necessity for quick action on energy efficiency improvement
4	Energy supply planning in Iran by using FLP [50]	Academic study	2004–2014	Fuzzy optimization	Entire energy sector	Mid-term planning period	Considering uncertainty in objective function coefficients	Uncertainty substantially affects natural gas supply system
5	Integrated energy planning for transportation [51]	Academic study	2009–2029	Optimization with EFOM model	Transportation sector	Focusing on a single sector of the energy system	Considering both demand and supply sides	How to achieve great decrease in costs of transportation system
6	Integrated resource planning for Iran [52]	Academic study	2011–2035	Bottom-up simulation with LEAP model	Entire energy sector	Limited attention to distributed generation	Simultaneously evaluating demand and supply in different scenarios	Estimation of depletion time for natural gas and crude oil reserves
7	Long-term energy plan for Iran [49]	Ministry of Energy	2014–2041	Integrated energy planning: MAED and MESSAGE	Entire energy sector	Exogenous demand does not adjust if energy prices change	Linking demand and supply model, Considering the different sectors of energy	Decreasing share of gasoline in transportation, great increase in natural gas demand
8	Optimal deployment of renewable electricity technologies [53]	Academic study	2015–2045	Optimization with MESSAGE model	Power sector	Less attention to social criteria	Investigating the impacts of carbon taxes and fossil fuel prices on power sector	Carbon tax coupled with direct renewables subsidies suggested to reduce GHG emissions
9	Iran 2040 project [54]	Stanford university	2015–2040	Simulation	Natural gas and power sectors	No scenario analysis and low policy options	Conducting the entire Iranian economy and the possible implications in a global context	Petroleum products are replaced with natural gas for electricity generation
10	Multi-objective optimization for the power sector [55]	Academic study	2015–2050	Linear programming	Power sector	Fully quantitative approach	Considering CO_2 emissions and job creation criteria	Cost-optimal power sector development cannot fulfill international mitigating commitments

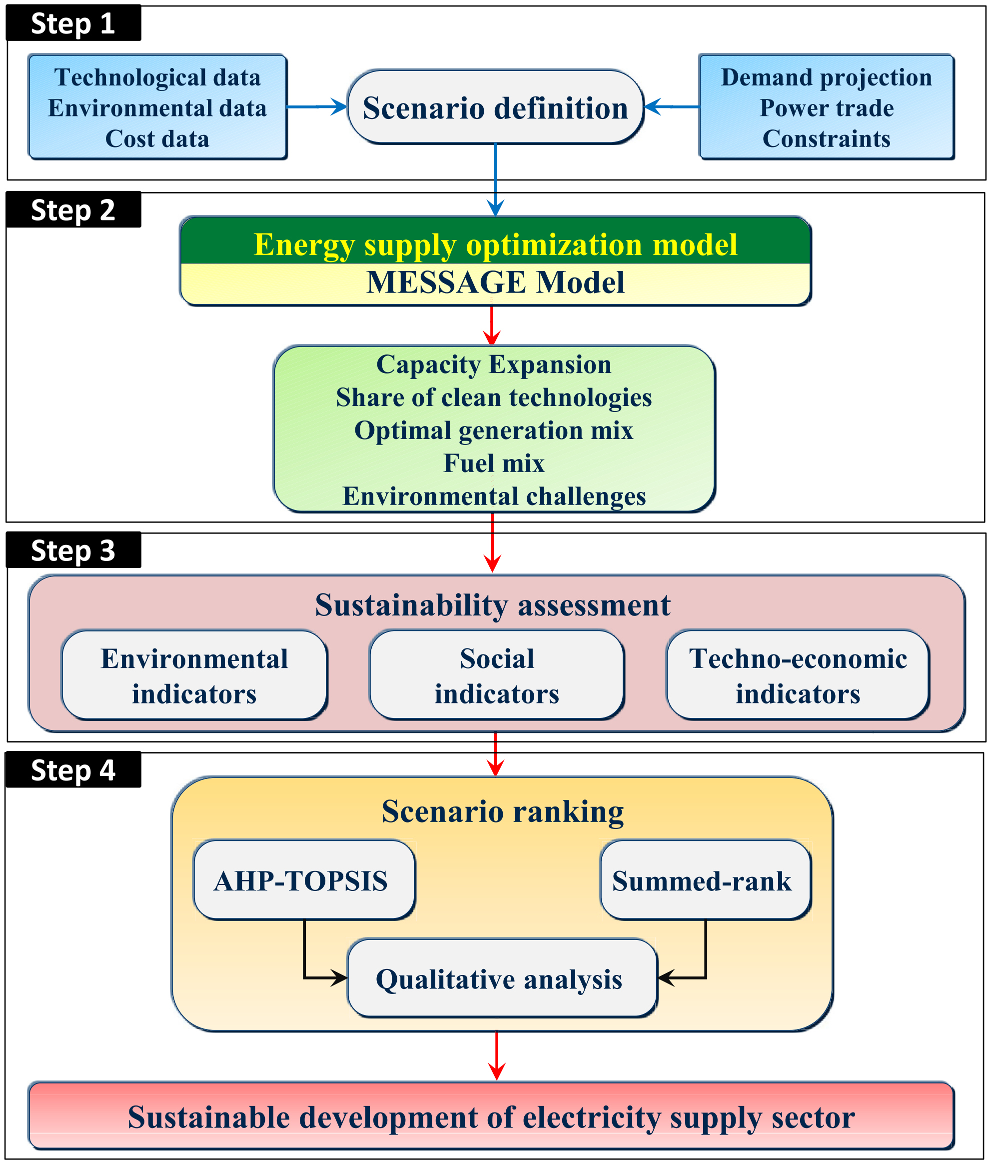

Fig. 1. Schematic of the proposed framework for sustainable development of the power sector.

ranking gives an insight into the overall sustainability of the scenarios. For ranking the scenarios and finding the best one, two quantitative and one qualitative analyses are accomplished as follows:

I. Summed-rank analysis as the first quantitative approach is applied, that was used in some previous works to deal with energy decision making problems [56]. In this method, at first each scenario is ranked according to each sustainability indicator. Then the summed ranks are created for each techno-economic, environmental, and social dimension; and finally, the overall ranking is estimated based on the summed ranks.
II. In the second quantitative method, AHP is combined with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to rank the scenarios based on the expert opinions. By breaking down the complex decisions in a hierarchical tree, implementing pairwise comparisons, and then synthesizing the results, AHP helps the decision maker to set priorities (see Refs. [58,59] for AHP procedure). Here, AHP hierarchy consists of two levels: goal and criteria. The goal is the sustainable power development and the criteria include techno-economic, environmental, and social dimensions. Pairwise comparisons are carried out according to a numerical scale from 1 to 9, where the higher the number, the higher the preference. In AHP, the quality of expert judgments can be evaluated using the consistency test. If the consistency ratio is lower than 0.10, then the weight results are valid; otherwise, they are inconsistent [60].

The basic principle of TOPSIS relies on the concept that selective alternative should have the nearest distance to the ideal choice and farthest distance to the negative-ideal choice [61]. In order to compare the alternatives and upgrade the final ranking, the Euclidean distances between each alternative and both the ideal and the negative-ideal choices are determined, and then the closeness coefficient is calculated to measure the two distances respectively (see Ref. [62] for TOPSIS procedure).

In combined AHP-TOPSIS approach, at first AHP is used to determine the weights of the sustainability dimensions, then TOPSIS is employed to prioritize scenarios regarding the AHP weights. AHP-TOPSIS decreases the uncertainty in group decision making and thus, ensures a robust solution [57].

III. A qualitative assessment is conducted since the decision making based on the numerical outputs of the MCDM methods is sometimes deceptive. In the qualitative analysis, the performance of the scenarios, particularly those suggested by the quantitative methods, is taken into consideration regarding each indicator, so that the challenging scenarios are avoided.

3. Data and scenarios

3.1. Electricity supply system

The electricity supply system comprises different power generation technologies, including conventional, advanced, distributed, and centralized ones. It also incorporates the transmission and distribution network with the possibility of electricity trading with neighboring countries. Based on Iran's condition, a reasonable set of power generation technology, including combined cycle, gas turbine, steam turbine, gas engine, coal power plant (conventional, advanced supercritical, and IGCC), hydropower (small and large), wind turbine, solar photovoltaic (off-grid and on-grid), Solar CSP, geothermal, light water nuclear power plant, and biomass (incinerator and landfill), are considered.

3.2. Technologies techno-economic data

The required technical and economic data related to conversion technologies are the investment cost and its annual reduction rate, repair and maintenance fixed and variable costs, efficiency, capacity factor, self-consumption, lifetime, and construction time. This information is reflected in Table 2. For evaluating the present value of all the costs of energy supply system, a 10% discount rate is used in the model. The base year is set to 2014, the beginning year for modelling is 2015, and a 35-year time span is covered up to horizon 2050. The modelling results in 2015 are compared with actual data in the same year. This will help to ensure that reasonable results are produced from the model.

Table 3
Fossil fuels prices in the base year and their annual growth rates.

Fuel	Price[a]	Average annual growth rate (%)[b]
Natural Gas (cent/m^3)	20	1.1
Fuel oil (cent/lit)	38	1.1
Diesel (cent/lit)	52	1.1
Thermal Coal ($/ton)	65	1.1

U.S. Energy Information Administration (EIA) has reported the average price of thermal coal as about 2.2 dollars per million btu [75]. With the assumption of 30 GJ/Mt heat value, the coal price is about 65 dollars per ton. In the same reference, the price of natural gas with 37 MJ/m^3 heat value has been reported about 5 dollars per million btu, which is approximately equivalent to 20 cents/m^3.

[a] Petroleum products price has been sourced from OPEC bulletin, and is based on FOB Persian Gulf average price in the last 2 month of the year 2014 [74].

[b] Based on the annual average price growth of crude oil, natural gas, and coal in the reference scenario of EIA [75]. It is assumed that petroleum product price growth is also affected by crude oil price growth.

3.3. Other assumptions

The transmission and distribution loss in the base year is equal to 14%, and according to the Ministry of Energy plans it is expected to reduce to 9% in 2026. The average costs for transmission and distribution of electrical energy are considered 0.8 and 0.7 cent/kWh, respectively [72].

One of the main parameters in energy planning is the amount of electrical demand. In MESSAGE, the demand is considered as an exogenous parameter. Final electricity demand and its trend forecasting during the study period is extracted from the "Long-term energy plan

Table 2
Techno-economic data for power generation technologies [53,55,63–71].

Technology	Construction time (year)	Life time (year)	Capacity factor (%)	Self-consumption (%)	Efficiency (%)	Maximum yearly added capacity[a]	Capital cost ($/kW)[c]	Fixed O&M ($/kW)	Variable O&M ($/MWh)
Nuclear LWR	7	40	80	10	31	–	4000	74	0.7
Nuclear ALWR	8	60	85	8	33	–	4200–3550	69	0.5
Conventional gas turbine	2	12	60	0.8	34	–	550	4.5	0.6
Advanced gas turbine	3	15	60	0.8	40	–	780	24	4.3
Gas engine	1	10	90	0.7	40	100–700	770	8	5.1
Conventional combined cycle	5	30	70	1.9	47	–	700	4.4	0.42
Advanced combined cycle	5	30	80	1.9	58	–	1140–840	21	2.6
Steam power plant	5	30	70	6.8	38	–	900	9.5	0.48
Diesel generator	1	10	70	6.5	31	–	550	3.8	0.75
Conventional coal power plant	3	30	75	5.5	35	–	1600	64	–
Advanced supercritical coal	4	40	80	6.5	46	–	2200	88	–
IGCC	4	40	80	10	45	–	5500	92	6.5
Biomass (landfill)	2	20	70	3	30	10–100	3300	2	1.7
Biomass (incinerator)	3	25	75	5	22	10	6400	640	–
Geothermal	7	30	80	8	–	55	5800	84	1.1
Small hydropower	4	40	35	0.5	–	20–100	2000	14	–
Large hydropower	7	50	18	0.5	–	400 [b]	1200	10.8	–
Wind turbine	2	20	30	1.4	–	300–5000	1400–1200	48	–
Solar CSP	2	30	38	–	–	300–5000	4300–2750	64	–
Solar photovoltaic	1	20	18	–	–	300–5000	1200-790-630[d]	24	–
Solar photovoltaic (DG)	1	20	17	–	–	300–5000	1500–1000	37	–

[a] Left values represent current limitations and those are in right are about horizon 2050.
[c] Left numbers denote base year data and right values are expected values in 2025.
[d] Left value indicates base year capital cost, the middle is about 2025 and the right represents capital cost at the end of planning horizon.
[e] Based on the maximum capacity addition during the recent years [4].

for Iran" performed in the Ministry of Energy [49]. The results of the study state that the electricity consumption increases by a rate of 3.4% until 2040. In the present study it is assumed that this rate continues until 2050.

The price of fossil fuels based on the base year price is presented in Table 3. For nuclear power plants, it is assumed that the sum of the costs of imported fuel and waste management is equal to 1 cent/kWh [73].

3.4. Fuel availability

Investigating the shares of different fuels in Iran's power sector during the previous three decades shows that the natural gas contributes between 42% and 75%, and the rest share belongs to liquid fuels [2,72]. It is assumed that the highest amount of available natural gas for power plant consumption in the base year is 70%. But regarding the development of the natural gas upstream sector, specifically South Pars fields, it is expected that this limitation is gradually relaxed in the future years. Accordingly, it is supposed that the share of natural gas used in power plants increases from 70% to 100% in medium-term. Regarding coal and nuclear power plants, it is expected that the required fuel will be supplied from either domestic or imported sources.

3.5. Scenarios

In this paper, the continuation of the current trend is defined as the reference scenario. Because of the low price of fossil fuels and their moderate increasing rate, in this scenario the share of clean energy technologies, including nuclear power plants and non-hydro renewables (solar, wind, biomass, and geothermal) in the total generation will be lower than 10% in long-term (about 2050).

However, the growth rate of fossil fuel prices plays a significant role in the competitiveness of clean energy technologies. In the present study, instead of only economically dealing with the national power sector development, the aim is also taking into consideration the role of other factors including environmental and social criteria in order to attain sustainability. Accordingly, 10 substitute scenarios are defined in which developing clean technologies is imposed to the model. These scenarios are adjusted so that the total share of nuclear and non-hydro renewables in 2050 generation will be in the range of 12%–48%. The scenarios are illustrated in Fig. 2. In this figure, for example, Cl-12 stands for 12% clean energy technologies.

3.6. Sustainability criteria

Eighteen criteria are considered as sustainable development indicators. The criteria are selected based on the previous studies in sustainability of the energy and power systems, and also according to the national general policies to attain sustainable growth [56,76–78]. The results of the scenarios are compared with each other from the viewpoint of each one of these criteria. These criteria are given in Table 4.

The data associated with the techno-economic criteria are the same as used in MESSAGE model. Table 5 presents environmental and social data for each conversion technology.

4. Results and discussion

4.1. Capacity and generation trends

Fig. 3 shows the optimal trend of the total installed capacity and the corresponding generation in the reference scenario. As Fig. 3 indicates, by an average annual growth rate of 3%, the installed capacity in the reference scenario increases from 73 GW in 2015 to 214 GW in 2050.

It is expected that the gross electricity generation, starting from 274 kWh in the base year, reaches 880 kWh in 2050, by an average annual growth rate of 3.2%. At the end of the planning horizon, combined cycle technology, coal power plant, gas turbine, and wind power respectively, with the shares of 58%, 20%, 9%, and 8% give higher contributions in the total generation. Accordingly, the share of clean technologies in total power generation would be lower than 10% in 2050.

In Fig. 4, the electricity generation mix in alternative scenarios is depicted. As was pointed out in the definition of scenarios, in alternative scenarios the minimum share of clean technologies was imposed as a constraint on the model. Because of the same assumptions for power demand and network losses, the needs of gross electricity generation in all scenarios are similar to each other. In the short-to medium-term, i.e. before 2030, the results of the scenarios have lots of similarities. In all the scenarios, the share of steam power plant gradually decreases, the contributions of coal and combined cycle power plants increase, and the capacity of gas turbine stabilizes. The distinction between these scenarios is clearer in the later periods (2035–2050), where in line with the increase in the share of nuclear and non-hydro renewables, the contribution of combined cycle decreases. While the share of combined cycle technology at the end of the planning horizon

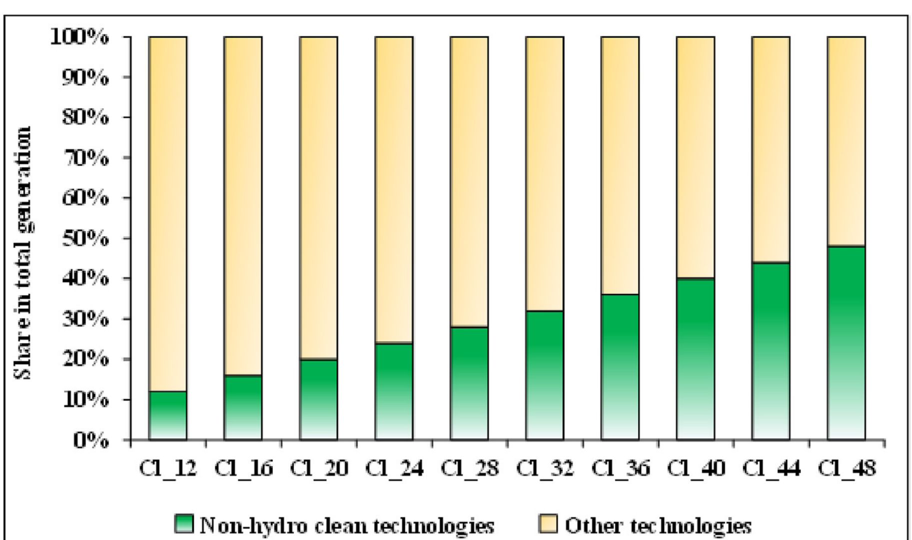

Fig. 2. Scenarios on non-hydro clean energy technologies development.

Table 4
Criteria used for assessing the sustainability of electricity scenarios.

Dimension	Indicator	Unit
Techno-economic	Capacity factor (power output as a percentage of the maximum possible output)	%
	Economic dispatchability (ratio of investment cost to total levelised cost)	%
	Investment cost	cent/kWh
	Fuel cost	cent/kWh
	Operation and maintenance costs	cent/kWh
	Levelised cost of electricity (generation cost per unit of electricity)	cent/kWh
	Sensitivity to fuel price changes (ratio of fuel cost to levelised cost)	%
	Construction time	year
Environmental	Global warming potential (greenhouse gas emissions)	gr CO_2eq/kWh
	Acidification potential (emissions of SO_2, NO_x, HCl, and NH_3)	gr SO_2eq/kWh
	Land use (area occupied over time)	m^2.yr/MWh
	Water consumption	gal/MWh
	Direct employment (job creation)	person.year/TWh
	Fossil fuel consumption	m^3NGeq/kWh
Social	Fuel imported dependency	MJ/TWh
	Human toxicity potential	gr 1,4 DCB[a]eq/kWh
	Nuclear waste generation	m^3/TWh
	Power supply diversification	Score (0–1)

[a] 1,4-Dichlorobenzene.

Table 5
Data related to environmental and social criteria for each type of technology [56,79–82].

Criterion Technology	Land use	Water consumption	Acidification	Job creation	Human toxicity Potential
	m^2 yr/MWh	gal/MWh	gr SO_2-eq/kWh	Job yr/GWh	gr 1,4. DCBeq/kWh
Steam power	0.41	826	0.221	0.11	3.40
Combined cycle	0.41	198	0.221	0.11	3.40
Gas turbine	0.41	0	0.221	0.11	3.40
Coal power	27.28	505	0.836	0.11	57.34
Hydropower	4.44	4491	0.016	0.27	3.58
Wind	0.26	0	0.021	0.17	6.33
CSP	9.00	52	0.032	0.23	4.27
Solar PV	9.92	26	0.075	0.87	21.67
Biomass	466.60	35	0.319	0.21	38.20
Geothermal	0.17	135	2.733	0.25	8.80
Nuclear	0.54	672	0.037	0.14	13.12

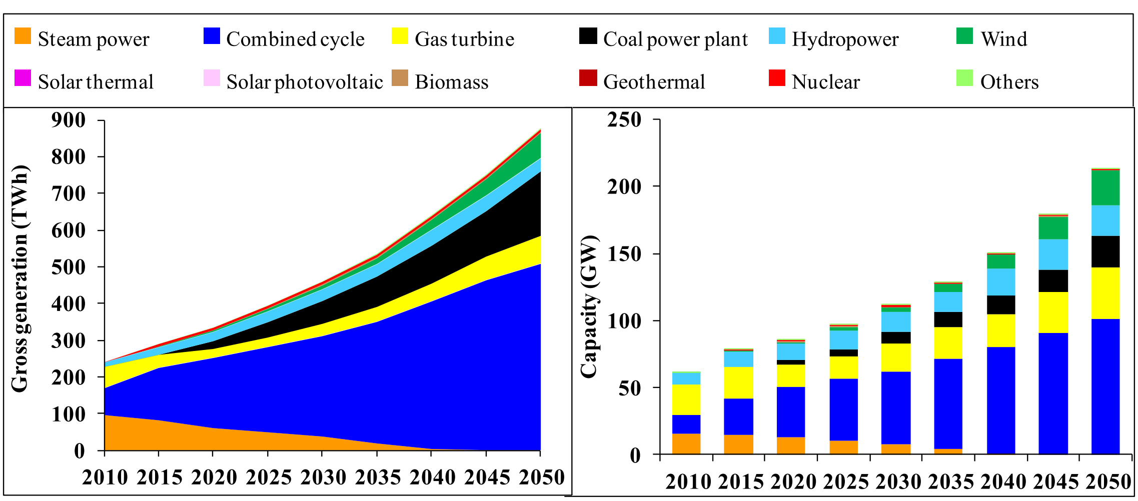

Fig. 3. Capacity expansion and generation mix in the reference scenario.

of the reference scenario is about 47%, in scenario Cl_48 it is near 12%.

The total installed capacity is expected to grow up to 222 GW in scenario Cl_12; however, it would reach up to 250 GW in scenario Cl_28, and more than 262 GW in scenario Cl_48. This means that the increase in the share of renewable technologies, that, if compared with the fossil fuels and nuclear technologies have lower capacity factors, promotes more capacity expansion. By comparing the results of the alternative scenarios with the reference scenario, it can be observed that among non-hydro clean technologies, wind power has a higher priority for fast development. Moreover, developing photovoltaic plants is suggested as the second priority. Although significant development of solar PV shows a 10% delay compared to wind turbine, its capacity would reach 50 GW at the end of the study horizon in scenarios Cl_28 to Cl_48. The results show that among non-hydro clean technologies,

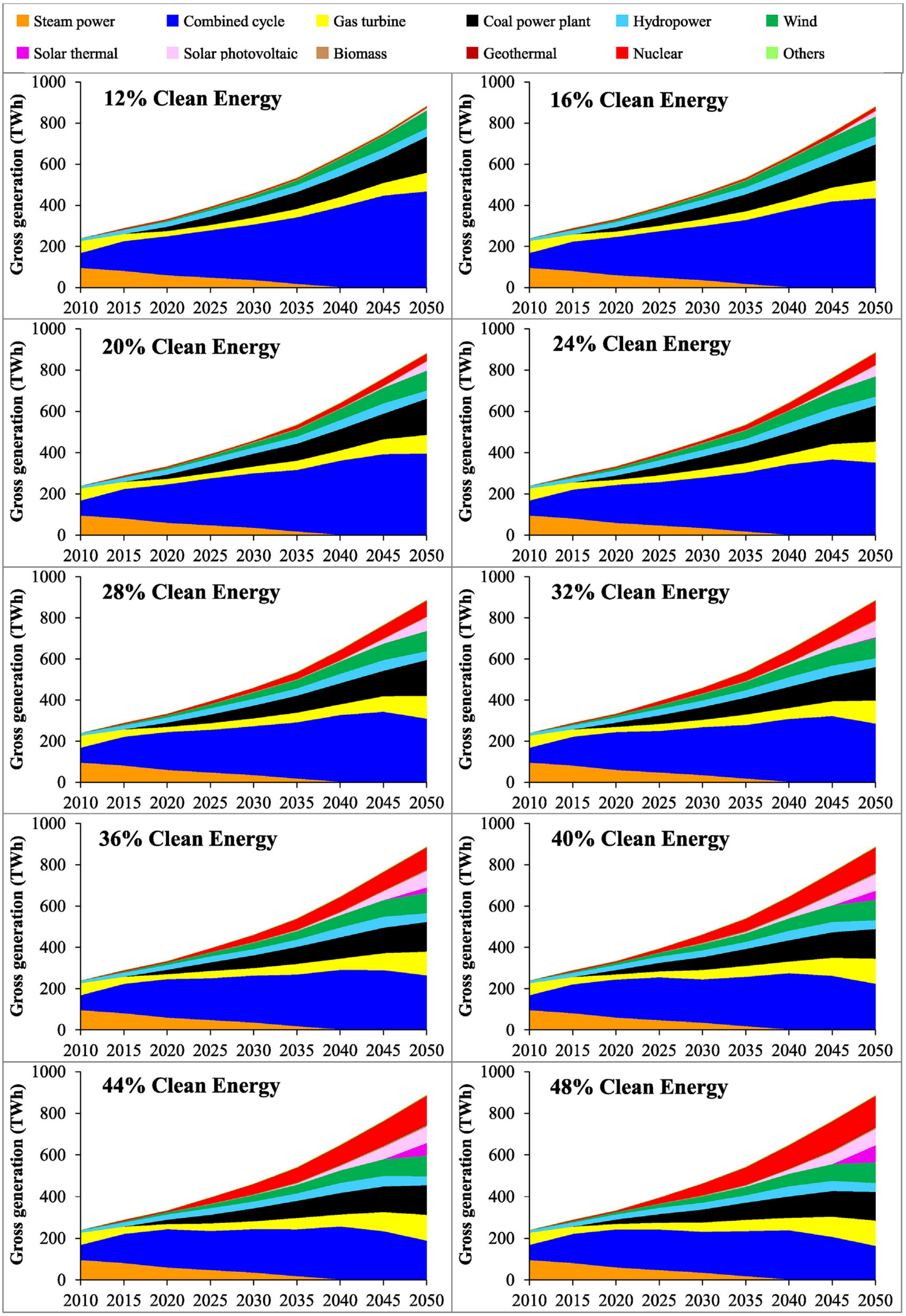

Fig. 4. Generation mix in different scenarios.

developing nuclear power plants is considered as the third option, since it takes a significant share in the total installed capacity in scenarios Cl_28 to Cl_48. Moreover, solar CSP technology is the next choice, where a capacity about 6 GW is suggested to be installed at the end of the planning period in scenario Cl_36. Up to 19 GW of installed capacity of this type of technology is proposed in scenario Cl_48.

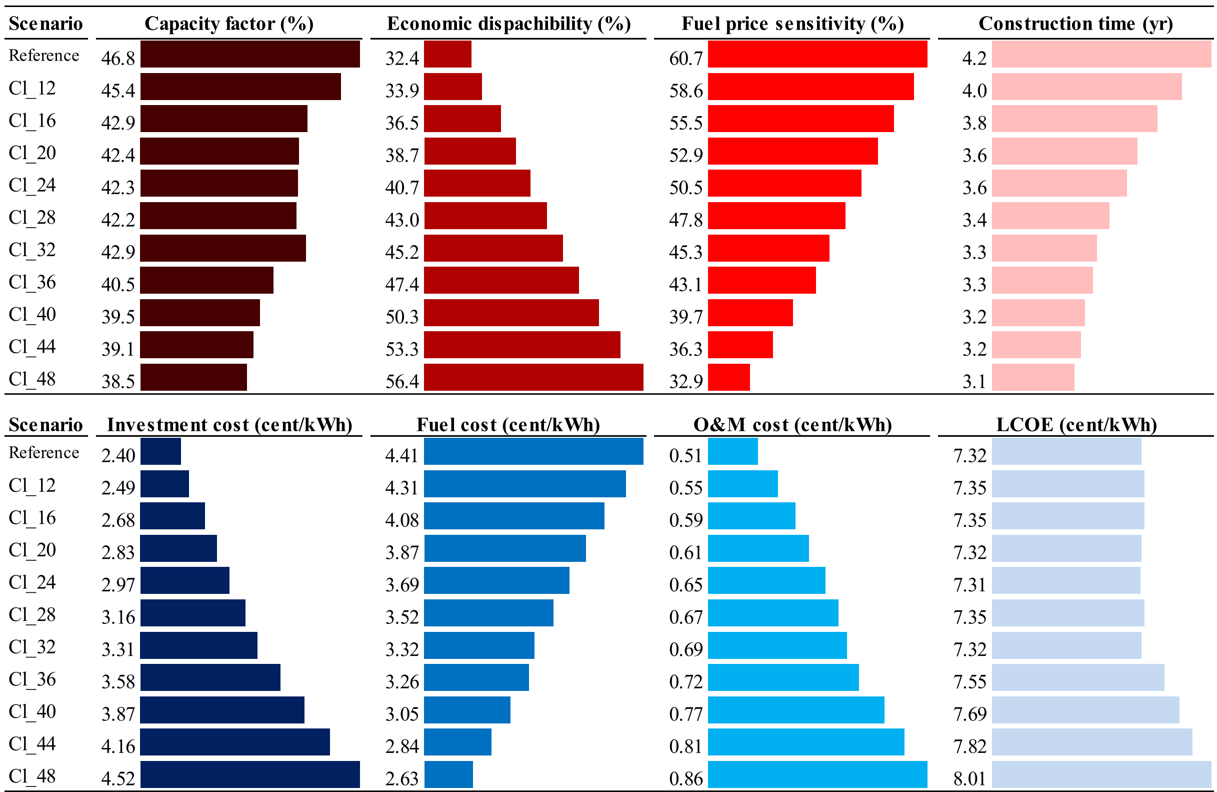

Fig. 5. Scenarios assessment in 2050 from techno-economic perspective.

4.2. Scenarios assessment from a sustainable perspective

In this section, the sustainability impacts of the power sector development scenarios are evaluated. The results for techno-economic sustainability are presented in Fig. 5. The environmental sustainability is presented in Fig. 6, and the social sustainability is depicted in Fig. 7.

4.2.1. Techno-economic sustainability assessment

4.2.1.1. Capacity factor. Almost in all the scenarios the capacity factor increases until 2040 and then, in the remaining 10 years, it follows a decreasing trend. The reason for its increase during the first 20 years is the development of combined cycle, coal, and nuclear power plants, having a capacity factor higher than the network average. The reason for the reduction throughout the latter decade is the significant development of renewable technologies with low capacity factor. Concerning this criterion, the best rank in 2050 is related to the reference scenario at about 47% capacity factor.

4.2.1.2. Economic dispatchability. Moving away from the reference scenario to scenario Cl_48, by increasing the share of renewable technologies, economic dispatchability increases owing to the fact that renewable technologies in comparison with the fossil fuel units require higher investment costs. This fact causes the reference scenario to be the best one in this criterion. It is noteworthy that also in the other scenarios, as a result of renewable technology developments during the planning period, economic dispatchability keeps an increasing rate.

4.2.1.3. Investment cost. Because the investment cost of renewable and nuclear technologies is higher than that of the thermal power plants, by increasing the share of these technologies in the generation mix, the average levelised investment cost of electricity increases. In 2050, the investment cost of 1 kWh electricity in the reference scenario is 2.4 cents, while it is 4.52 cents in scenario Cl_48. Accordingly, the reference scenario with the least investment cost is the best scenario.

4.2.1.4. Fuel cost. By developing the high efficiency types of

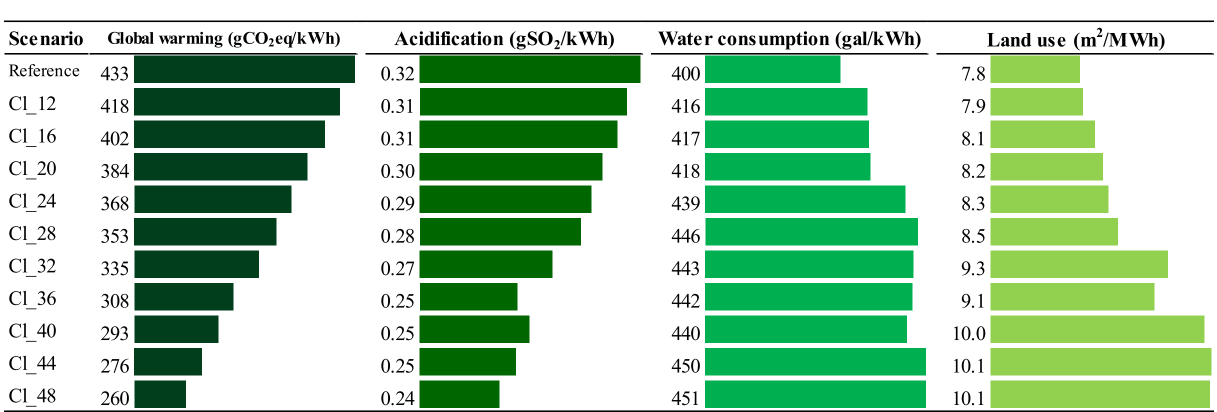

Fig. 6. Scenarios assessment in 2050 from environmental perspective.

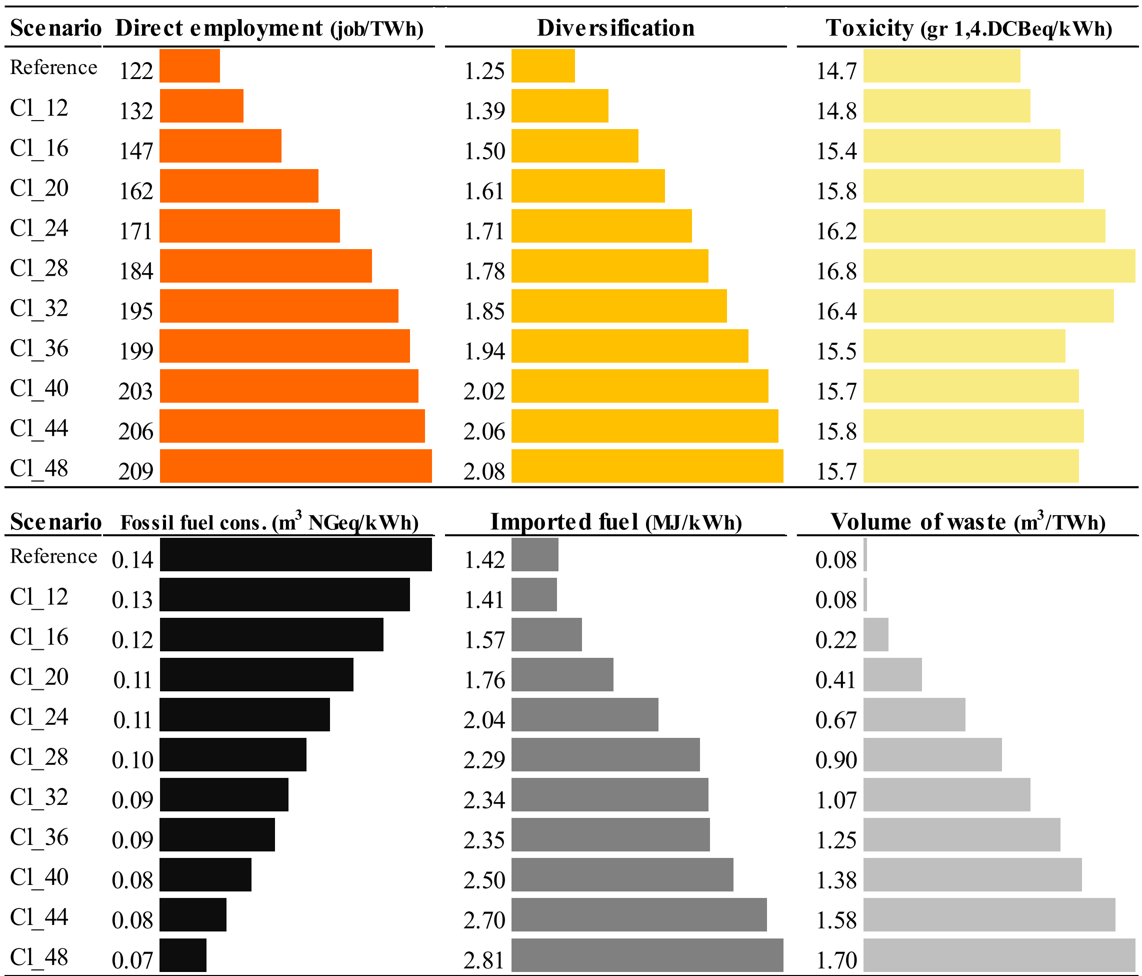

Fig. 7. Scenarios assessment in 2050 from social perspective.

technologies, such as combined cycle and supercritical coal units in the early periods, and also installing renewable technologies including wind and photovoltaic at the late periods, the fuel cost for each unit of electricity reduces. In this regard, scenario Cl_48 with the highest share of clean technologies and the least fuel cost is considered as the best scenario.

4.2.1.5. Operations and maintenance cost (O&M). By increasing the share of clean technologies during the study horizon, O&M cost increases in different scenarios. Because of this, the best rank according to this creation belongs to the reference scenario and scenario Cl_48 is in the last rank.

4.2.1.6. Levelised cost of electricity (LCOE). The LCOE is the most important criterion in the economic evaluation of the scenarios. At the end of the planning horizon, the least LCOE is 7.31 cent/kWh for scenario Cl_24 and the highest LCOE is 8.0 cent/kWh for scenario Cl_48.

4.2.1.7. Fuel price sensitivity. The trend in this criterion is similar to the fuel cost indicator. The lower the fuel cost, the lower the sensitivity to price. In 2050, the best and worst scenarios regarding fuel price sensitivity are scenario Cl_48 and the reference scenario, respectively.

4.2.1.8. Construction time. Because the short construction time of renewable technologies, by increasing the share of these technologies in the electricity supply mix, the average time for power plants construction in all the scenarios during the study horizon reduces. Accordingly, scenario Cl_48 has the best rank in this criterion.

4.2.2. Environmental sustainability assessment

4.2.2.1. Global warming. Since a positive relationship lies between the global warming and the fossil fuels consumption, it is obvious that by developing renewable technologies and reducing the fossil fuels consumption, the GHG emissions and subsequently the global warming potential reduces. Thus, scenario Cl_48 is the best scenario from the global warming point of view.

4.2.2.2. Acidification potential. After geothermal technology, coal power plant and natural gas-burning power plants emit more SO_2 per unit of electricity generated. Thus, it is expected that scenarios with lower shares of coal and thermal power plants have a better performance regarding this criterion. Comparing the scenarios on the basis of the acidification indicator shows that scenario Cl_48 has the best rank with 0.24 gr/kWh SO_2 emissions in 2050.

4.2.2.3. Land use. Based on land use indicator, the best scenario at the end of the planning horizon is the reference scenario in which 7.8 m^2 of land is occupied for 1 MWh electricity. In this respect, scenario Cl_48 with 10.1 m^2/MWh land occupation is the worst scenario.

4.2.2.4. Water consumption. In all the scenarios, the required water follows a decreasing trend during the planning period. One of the main reasons for this reduction is the gradually phasing out of steam power plants, which causes a decreasing trend for the share of this technology. From the reference scenario to scenario Cl_48, in line with the increasing share of renewable technologies, which have lower water consumption if compared to the thermal power plants, a decreasing

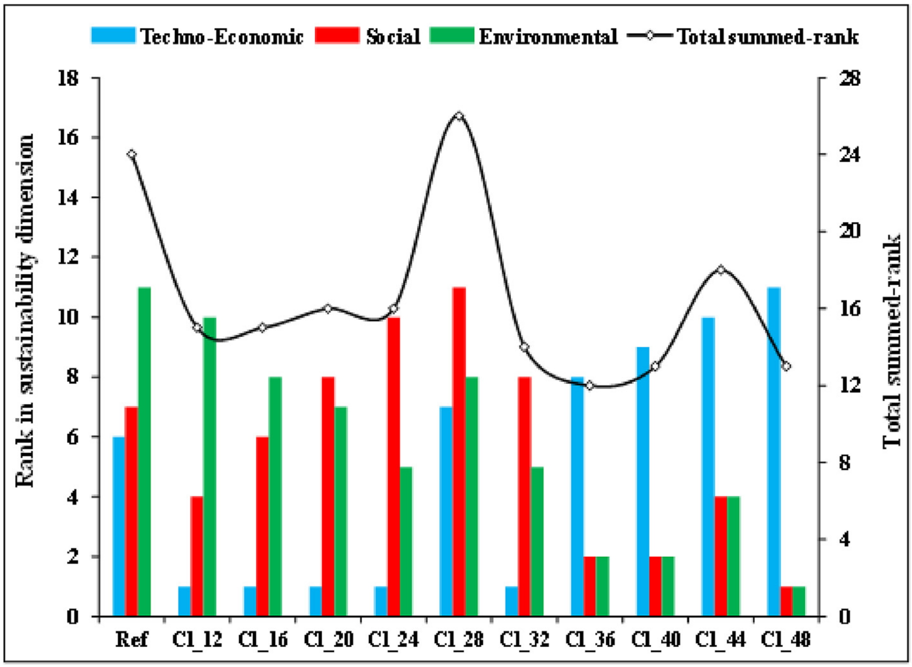

Fig. 8. Ranking the scenarios based on summed-rank method.

trend in this indicator is expected. However, since nuclear technology requires a large amount of water, an increase in the share of this technology causes the increase in water consumption. Therefore, the best scenario with respect to water consumption is the reference scenario, which consumes 400 gallons of water per 1 MWh electricity.

4.2.3. Social sustainability assessment

4.2.3.1. Direct employment. In consonance with the increasing share of renewable technologies within the planning period, direct employment increases for each unit of electricity generated. This is because of higher job factor in the renewables technologies, especially photovoltaic systems, compared to the thermal power plants. In the last period, scenario Cl_48, with higher shares of solar PV and solar CSP is the best scenario based on the job creation index.

4.2.3.2. Fossil fuel consumption. By developing the renewable units and efficiency improvement of thermal power plants, fossil fuel consumption per unit of electricity generated reduces. Reduction in fossil fuel consumption not only improves energy supply security, but also alleviates the progressive depletion of fossil fuel reserves. At the beginning of the study period, for 1 kWh electricity, the reference scenario consumes 0.22 m^3 natural gas-equivalent oil and gas reserves. However, by a 36% decrease, this amount reduces to 0.14 m^3 in 2050. The reduction in fossil fuel consumption in the other scenarios is more significant because of the clean technologies development. As a result, the best and worst scenarios regarding this criterion are scenario Cl_48 and the reference scenario, respectively.

4.2.3.3. Imported fuels. Although Iran has significant oil and gas reserves, the country is facing some limitations for supplying other fuels including coal and uranium from domestic production. For instance, the domestic coal resources are adequate for at most 4000 MW generation. The best scenario regarding the imported fuel is the reference scenario. Moreover, because of the high share of coal power plants in scenario Cl_28, this scenario is the worst one from the imported fuel point of view.

4.2.3.4. Human toxicity potential. Since the sum of the shares of coal, biomass, solar PV, and nuclear power plants in the reference scenario is the lowest among the scenarios, this scenario has the best performance in the toxicity indicator. Furthermore, because scenario Cl_28 has the highest share of coal power plants, this scenario is the worst one regarding the toxicity potential.

4.2.3.5. Nuclear waste generation. Because in the reference scenario and also scenario Cl_48, the installed capacity of nuclear power plants stabilizes over the entire period, by increasing the total generation in these scenarios, nuclear waste per unit of electricity reduces. In scenario Cl_16, although the development of nuclear power plants is suggested after 2030, the increase in the total power generation does not let this indicator vary during the planning periods. In the other scenarios, however, in line with the installing more capacity of nuclear technologies, nuclear waste per unit of electricity increases. In 2050, nuclear technology contributes only by 1% of the generation mix of the reference scenario, but in scenario Cl_48 its share reaches 17%. Accordingly, scenario Cl_48 and the reference scenario are the best and the worst scenarios in this criterion, respectively.

4.2.3.6. Power supply diversification. In the reference scenario, the changes in the diversification index within the study period is not significant. But moving away from scenario Cl_12 towards scenario Cl_48, this criterion keeps an increasing trend. Indeed, when the share of clean technologies in the alternative scenarios grows, the increasing rate of diversification also grows.

4.3. Ranking the scenarios

The aim of this section is the evaluation of the scenarios in order to select the most appropriate one. For this purpose, the MCDM methods are employed, in addition a qualitative analysis is performed.

4.3.1. Summed-rank analysis

In this method, first the rank of each scenario based on each indicator is determined. Then, the ranks in each dimension are estimated by summing up the ranks in all indicators of the sustainability dimension. Finally, the overall ranking is estimated based on the summed ranks for the three dimensions. In this method, all indicators have the same importance in the sustainability assessment.

The results of the ranking based on each sustainability dimension and also the total summed-rank are presented in Fig. 8. Scenario Cl_36 with the lowest total summed-rank is the best scenario. This scenario has the second rank in environmental and social dimensions and the eighth rank in the techno-economic dimension. Accordingly, the total summed-rank of this scenario is 12, which is the lowest among the scenarios. Although scenario Cl_36 has not a good performance from the techno-economic perspective, because of the acceptable condition of the environmental and social standpoints, it is known as the best scenario according to the summed-rank method. After scenario Cl_36, the next ranks belong to scenarios Cl_40 and Cl_48, likewise scenario Cl_36, are desirable scenarios from the social and environmental perspectives.

4.3.2. AHP-TOPSIS method

To perform pairwise comparisons, a questionnaire was provided as Appendix A and distributed among 25 Iranian energy experts from Iran power generation transmission & distribution management company and the Ministry of Energy. Based on the analysis of 21 valid responses, AHP resulted in weights equal to 0.67, 0.23, and 0.1 for techno-economic, environmental, and social dimensions, respectively. These weights are considered as inputs for the TOPSIS method. For this purpose, the weight of each dimension is uniformly distributed among its indicators.

Fig. 9 represents the ranking results based on the AHP-TOPSIS method. Despite the summed-rank technique in which the lower the score, the better the option, in AHP-TOPSIS, the higher weight implies the better option. It can be seen that moving away from scenario Cl_32, the weights gradually decrease. This means that very low or very high shares of clean technologies are not desirable. According to this approach, scenario Cl_32 with the highest weight is the best scenario. This scenario ranks first in techno-economic, fifth in environmental, and eighth in social dimensions. It is noteworthy that the high weight of techno-economic dimension causes scenario Cl_32 to be the best scenario, since it has an acceptable performance regarding the techno-economic dimension.

The main difference between AHP-TOPSIS method and summed-rank analysis is that the former takes experts' opinions into account. Since the experts have allocated a relatively high weight to techno-economic dimension, the preference of scenario Cl_36 in AHP-TOPSIS method decreases and instead, scenario Cl_32 with a good techno-economic performance moves up to the first rank.

4.3.3. Qualitative analysis

Decision making based on the quantitative method results is sometimes misleading. Thus, a qualitative analysis is required to perform for avoiding challenging scenarios. Although the reference scenario, which emphasizes on fossil fuel technologies, results in advantages such as lower investment cost, economic dispatchability, and self-dependence in fuel supply, it causes environmental and social challenges. On the other hand, developing the power sector based on scenario Cl_48, in which the share of clean energy technologies in generation rises to about 50%, has some advantages, such as smaller sensitivity to fuel prices, lower global warming potential, and higher diversification. But in terms of LCOE, the occupied land, and nuclear waste, this scenario is challenging.

Scenario Cl_32 and Cl_36, as the selected scenarios, are not challenging based on any indicator, and they have a good and average condition almost in all the criteria. However, as the AHP results show, the stakeholders consider a high weight for the techno-economic criteria. In spite of the scenario Cl_32, which has the first rank in techno-economic dimension, scenario Cl_36 has an undesirable performance in this dimension. Thus, taking all analysis into consideration, scenario Cl_32 is preferred over the other scenarios.

5. Conclusion and recommendations

In this paper, the major long-term energy planning studies in Iran were reviewed. The reviews show that energy and power sector developments have mainly resulted from short-term plans and accordingly, the present situation is unsatisfactory. Substantial energy subsidies to both energy supplier and end-users have prevented the utilization of more efficient technologies, which imposed a huge economic burden on the country, and also gave rise to terrible local and global emissions. It can be stated that one of the main reasons for the current challenging situation of Iran's energy sector is the lack of effective connection between the energy planning studies and energy policy making. Based on this analysis, the following is recommended to address this challenge:

- The policy makers must seriously seek to establish a suitable link between the results of scientific studies and decision making processes.
- Decision makers should be trained to realize the modelling and planning results to devise long-term energy policies.

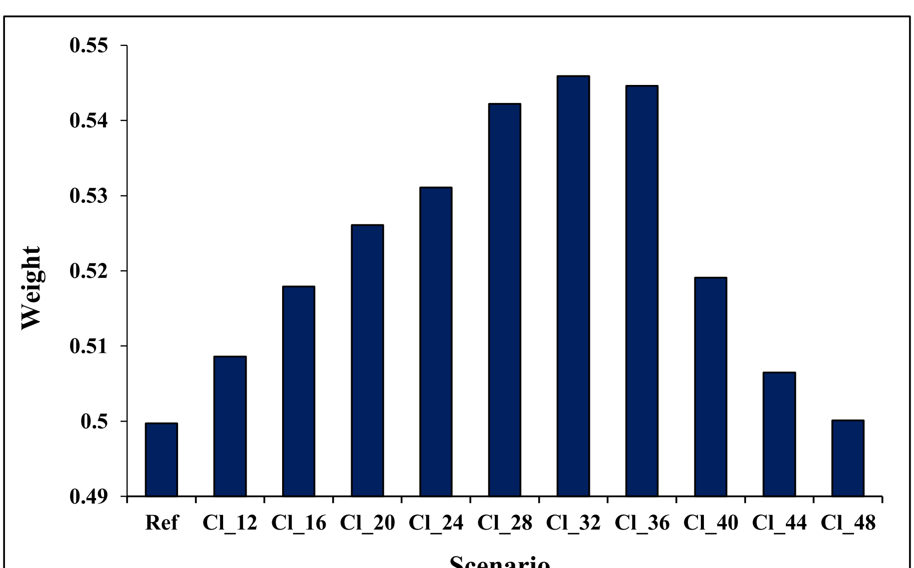

Fig. 9. Ranking the scenarios based on AHP-TOPSIS method.

- To meet the future energy demand, the transition pathways should be assessed based on their sustainability performance.
- Various integrated and comprehensive energy modelling studies should be performed in which reliable data are employed for the analysis, thus an ensured validation could be obtained.

On the other hand, the previous studies generally suffer from lack of employing appropriate planning tools, comprehensive evaluation of energy plans, and scenario definition and ranking. This paper thus aimed to overcome these weaknesses. A framework was proposed for sustainable development of the electricity supply sector, wherein MESSAGE model was employed as the planning tool, 10 scenarios defined on the share of non-hydro clean technologies, 18 different techno-economic, environmental, and social criteria defined for sustainability assessment, and MCDM methods used for ranking of scenarios. The main findings are as follows:

- The pathway in scenario Cl_32, where the share of non-hydro clean technologies reaches 32%, is ranked best. In this pathway, the global warming potential would result in 23% lower than what the reference scenario indicates in 2050. This is in accordance with the moderate growth scenario of the World Energy Council, which forecasts clean technologies account for about 37% share of global generation in 2050 [83].
- If an equal weighting of the sustainability indicators is assumed, a large expansion of clean technologies seems to be the most attractive scenario. However, the implementation of this expansion seems impractical owing to the huge financial resource requirements. Scenario analysis based on an open stakeholder dialogue would pursue a more economic pathway. These show the importance of employing MCDM approaches to involve stakeholders in evaluating the power sector development scenarios.
- The higher share of clean energy technologies would cause more financial burdens, smaller global warming potential, lower acidification rates, much required water, broader land use, further jobs, more nuclear waste, better capacity diversification, lower toxicity potential, and less fossil fuel consumption.

In the current study, business as usual scenario was probed as a predictive scenario, and the long-term share of renewables was evaluated through some normative scenarios. However, conducting a comprehensive evaluation based on different explorative scenarios on cost and demand parameters which are subject to much uncertainty can be a valuable analysis for the future studies. Moreover, a modelling framework, which is able to consider hourly dynamics of electricity supply and demand within the long-term energy plan, and to evaluate their interactions from various sustainability dimensions could be helpful for more insights.

Appendix A. AHP questionnaire

For each row in Table A1, please answer the following question:

To develop a sustainable plan for Iran's power supply sector, how much criterion i preferred to criterion j?

Instructions

- The interpretation of numbers is as Table A2.
- Only one number in each row should be checked.
- If the criteria have equal preference, then check number 1.
- If the criterion on the left (right) is more preferred than the criterion on the right (left), please check the scale on the left (right) of 1 regarding its relative preference.

Table A.1
Pairwise comparison questionnaire

Goal: Sustainable development of Iran's power sector																		
Criterion i	Preferences																	Criterion j
Techno-economic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental
Techno-economic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Social
Environmental	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Social

Table A.2
Interpretation of numbers in pairwise comparisons

Number	Interpretation
1	Equal preference
3	Moderate preference
5	Strong preference
7	Very strong preference
9	Extreme preference
2, 4, 6, and 8 are intermediate values	

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