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Energy transition in petroleum rich nations: Case study of Iran

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ABSTRACT

Energy modeling and planning problems associated with technical, economic, political, and social development have been critical concerns in energy system planning and greenhouse gas emission control for both national and worldwide for many years. This paper modeled and analyzed the current and future energy supply and demand for an oil-rich energy system because energy intensity is very high in such countries. A high shared fossil fuels energy system is modeled, and an appropriate energy mix is proposed to meet the national commitment in Paris Agreement.

The EnergyPLAN is used to model the energy system. Hourly actual energy demand and supply are provided for 2004–2016 for all energy sectors and subsectors and anticipated 2030. Five different scenarios are analyzed, and results show that the power sector is more influential than other energy demand sectors. Efficiency improvement of the thermal power plans and the integration of renewable energy resources into the power sector are more useful for reducing Total Primary Energy Consumption, CO2, and variable cost than other scenarios. In the proper scenario, a 1% improvement in the thermal power plants efficiency and 22% annual average growth rate in renewable energy capacity, 4% CO_2 reduction can be achieved.

It is concluded that in oil-rich counties such as Iran, the energy system efficiency improvement, particularly in electricity production, is more useful for the overall CO_2 reduction goals. Efforts for total CO_2 reduction benefit the national energy system economy, and the international community will benefit from a more efficient energy system. We believe that by total primary energy supply reduction in oil-rich countries, the international market's energy supply will be increased, which further reduces the pressure on the global oil and gas prices.

1. Introduction

In the past five decades, the world energy system has experienced an extensive growth rate. In most developing and developed countries, excellent infrastructures have been installed, mostly based on centralized large-scale fossil fuel combustion technologies [1]. This immense energy consumption emits great amounts of greenhouse gases to the surrounding environment, contributing to global warming through the greenhouse effect. Global warming is a severe problem for the global climate. Commonly referred to as climate change, global warming is the observed increase in the Earth's climate system's average temperature. As it is computed by many researchers such as the “National Science Academies of the Major Industrialized Nations,” by the lowest greenhouse gas (GHG) emission scenario, the global surface temperature is likely to be raised 0.3–1.7 °C [2]. In the highest emissions scenario, it would be 2.6–4.8 °C [3]. Scientists believe that the future climate change and its impacts will differ from region to region [4]. Still, many scientists expected that the effects are the rising global sea levels, increase by global temperatures, changing precipitation (increase or decrease depending on the location), land-use change, and expansion of deserts [5,6]. Long-term temperature observations are among the most consistent and widespread evidence of a warming planet. Temperature (and, above all, its local averages and extremes) affects agriculture productivity, energy use, human health, water resources, infrastructure, natural ecosystems, and many other essential aspects of society and the natural environment. Recent data add to the weight of evidence for rapid global-scale warming, the dominance of human causes, and the expected continuation of

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increasing temperatures, including more record-setting extremes [7].

The largest human-made greenhouse gas source is fossil fuel burning for electricity generation, heat supply, industry, and transport. A sustainability approach to fossil consumption is one of the most important ways to diminish its total consumption, as proposed by Ref. [8]. Scientists and policymakers have been trying to find solutions for many years, and several international agreements are in force to control the GHG emission from past to now. The Paris Agreement (PA) is the latest one approved by several nations around the world. For the first time, the P.A. brings all countries into a common cause to commence ambitious efforts to combat global warming and adjust to its effects, with technological aid to assist developing nations in functioning actively [9,10]. P.A.'s central aim is to strengthen the global response to the threat of global warming by keeping global temperatures rising below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase even lower than 1.5 °C [10].

According to the Intended Nationally Determined Contributions (INDCs) report of each country, they are committed to reducing CO_2 emission in a certain way and amount by 2030 [11]. Thus, the nations are moving towards developing a green economy based on a low carbon system and raising their efforts to decrease GHG emissions as they committed in their INDC. To reach the defined goals in INDCs worldwide, developed countries must be reduced their emissions as they committed and have to support developing countries on appropriate policy, financial aid, new technology transfer, and enhanced capacity building. In this regard, policy-making and energy system modeling are key issues in the early stage of sustainable energy system development, one of the weak issues in developing counties and needs to be supported by developed nations.

Climate change mitigation and a transition to a low-carbon energy system are pressing issues in policy discussions and international negotiations. The scientific community supports the political debate through a wide range of future energy system projections, pathway simulations, and scenario analyses of the national energy system and its development over the next decades. Accomplishing a balance between national economic development goals needs to respond to the global warming risks and to ensure energy security makes a substantial challenge that the policy-makers are faced today [12]. Both energy system modeling and sustainable energy planning are useful methods and tools to assist developers and policymakers in making an appropriate decision by receiving reliable data and information from the energy models. Integration of energy systems is significant to manage the energy system with a low total primary energy supply [13].

Energy models are useful tools to discover directional changes that result from implementing various policies and testing them under varying technological, social, and economic conditions [14,15]. Always policymakers need up-to-date information, meaningful figures, and analyses on the impact of their policy measures. Energy systems modeling can provide them with all of this information [16,17]. During the last two decades, energy modeling was one of the main tools for decision making and energy planning [18]. Applying suitable modeling tools, most challenges of today's complex energy systems can be assessed [19]. For future energy systems with an increasing share of variable renewables, there are some challenges such as short-term variability representation in long-term studies, incorporating the effect of global warming, and ensure openness and transparency in modeling studies [20,21].

For accurate energy system modeling, several factors (such as technical, social, and economic) need to be considered by the energy modelers, planners, and decision-makers in energy systems. The complexities of generating the desired sustainable and green energy management decisions may be intensified by uncertainties in the related system components in different counties with diverse energy system components [12,22]. Furthermore, the uncertainties and complexities may be further amplified by interactions and dynamics among various sub-energy system components and the potential for exaggerated emission evaluation and economic penalties [23]. Several criteria and/or objectives have been considered in many energy system modeling problems, leading to multiple criteria and objectives decision-making approaches [24,25].

To provide insight for decision-makers on complicated relationships between the energy planning practices, and to address the need for determining strategies to maintain energy systems sustainability, integrated multi-resource energy system analyses that comprise simulations of social behaviors, economic change and emission control, optimization of resource allocation with low carbon content, and analysis of associated uncertainties [26,27] is necessary.

According to the scenario of 2DS (2°) of the IEA, the most extensive contributions to emissions reduction throughout 2016−2050 would be about 38% from electricity efficiency and end-use fuel and 32% from renewable energy resources. Carbon Capture and Storage (CCS) would come in third place with 12%, 10% for a change in fuel use, and nuclear energy 7%, respectively [28]. In other words, GHG emissions from heat generation and electricity production and consumption contributed 75% of the last decade increase and followed by fuel production and transmission by 16% and 8% for refining petroleum. However, the sector emissions were mainly carbon dioxide, the methane releases by 31% primarily from coal and gas production and transmission, and indirect N_2O (9% mostly from fuel-wood combustion and coal) [29].

Like most countries worldwide, the energy landscape in oil-rich countries is rapidly changing with wide-reaching implications. There are many uncertainties in this energy transition. Still, most of the forecasts provided by various organizations show that the share of renewable energies (RE) in the energy mix is rising [30,31]. Considering the characteristics of the oil-rich countries' energy systems like Iran, developing an energy model toward sustainability is very substantial in showing a pathway to transition from an unsustainable energy system towards a more sustainable energy system. Aghahosseini et al. [32] modeled a 100% renewable energy system for Iran intended for 2030. Their model only covers the power generation sector, non-energy industrial synthetic natural gas (N.G.) production, and water desalination. As a result, the levelized cost of electricity (LCOE) in its integrated scenario discovered that renewable energy production options are the most competitive and least-cost solution between all the alternatives to accomplish a net zero-emission energy system [33].

1.1. Research objective

The energy transition toward a cleaner energy system in oil-rich countries is complicated because of subsidized low fuel costs. In this paper, a transition towards reliable and sustainable energy system is modeled with an hourly resolution for 10 years from 2006 to 2016. Based on historical trends the demand prediction was modeled for 2030. It is modeled and analyzed the current and future energy supply and demand for an oil-rich high energy intensity system. A high shared fossil fuels energy system is modeled, and an appropriate energy mix is proposed to meet the national commitment in Paris Agreement. This approach can be applied for most high-energy-intensity oil-rich countries because the energy supply pattern is almost similar in such countries.

The proposed method is for Iran's energy transition towards a low carbon energy system for four different energy demand sectors, including electricity, heating, transportation, and the industry is the first of its kind to the best authors' knowledge. A bottom-up model using EnergyPLAN is developed to compute the CO_2 emissions of different proposed scenarios to find a more reliable energy mix to fulfill the county's Unconditional Mitigation Action (UMA) in INDC, which is 4% CO_2 reduction from the BAU. Hourly based actual energy demand and supply are provided for all energy demand sectors and subsectors. Finally, the energy demand and supply are predicted for 2030 using a regression model.

2. The methodology of energy system analysis

Reducing the carbon content of the oil-rich nation's energy system while ensuring availability, reliability of new technologies, supply, and cost competitiveness is a very complex task. The energy system transition does not happen suddenly but needs a well-designed and well modeled, and analyzed pathway to meet political, social, economic, and ecological expectations [34]. To predict the future by scenarios, there are several possible ways including predictive (what will happen?), explorative (what can happen?), and normative (how can a certain target be reached?) [35]. In this research work we try to reach a specific target of emission which was defined by INDC.

Future projections and scenarios analysis are important for decision for policy makers. But the accuracy of past projections can be valuable for both developers and scenario users, for understanding on current projection uncertainty, and for guiding improvement efforts [36]. Policymakers need proper advice from energy experts to make an effective decision on proposed future energy systems. Such consultancy requires a reliable method to assess the feasibility of future energy system configurations. There are different way to predict the future The concepts for low-carbon energy supply systems have been provided with different studies worldwide, particularly in developed countries [37,38]. Still, so far, a comprehensive analysis of the energy transition pathway for oil-rich nations' energy systems has been missing. Realistic and comprehensive computing models based on existing reliable data are essential to model such transition pathways to a low carbon energy system. Such energy system models should be as realistic as necessary and as simple as possible. This means that the developed model must reflect all relevant energy system components such as power generation and storage technologies, heating, cooling, transportation, and industry connecting different supply energy resources and their locations [39]. Recently, the number of developed energy models has grown tremendously, and a considerable variety of models are created with different characteristics and features. Each energy model is developed to address a specific question or set of questions and is only suitable for a particular purpose.

In this study, the bottom-up EnergyPLAN model is used to investigate the energy systems in oil-rich countries (case of Iran) to find the best energy mix for low carbon (as defined in INDC) economy. The EnergyPLAN model has been used widely in the last years for energy system modeling in many developed and developing counties. It has a high capacity for renewable energy integration into the given energy system. It can be used for energy scenario making and optimal energy systems and pathways [40,41]. The EnergyPLAN model, as a deterministic output/input energy system modeling tool [42], uses some general inputs such as the renewable energy resources capacities, system demands, costs of energy sources, on-renewable energy capacities, and several optional economic and technical regulation strategies [43]. On the other hand, it seems the integration of four energy sectors, including heat, transportation, industry, and electricity sectors, is necessary to investigate the effect of different renewable energy sources integration into existing energy systems [44]. The general flow diagram of the EnergyPLAN model is shown in Fig. 1.

Current research's main objective is modeling and analyzing the existing and future energy system demand and supply for oil-rich energy systems. The fundamental purpose of using EnergyPLAN is to design regional or national energy planning strategies based on economic or/and technical analysis, resulting from modeling different investments and energy systems. EnergyPLAN can reach the energy system's optimum economical operation and the optimal technical operation, as another key advantage [45].

Lund and Mathiesen [46] have studied the Danish energy system using EnergyPLAN by considering the goal of 100% renewable energy systems (RES) with a mix of wind, biomass, solar, and wave energy resources to gain a balance between demand and supply for electricity until 2050. In this research, the feasibility of achieving 100% RES in 2050 and 50% RES in 2030 has been investigated, and found that achieving 100% RES scenario can be possible, along with energy savings. Mathiesen et al. [47] continued this work to plan future smart systems by combining different technologies, including multi-generation systems, energy storage systems (ESS), and the development of biofuels in transportation and electrification of transport. They found that integrating the different energy sectors, such as heating, electricity, and transport, can lower costs and energy efficiency in the future. In this case, achieving 100% RES can be possible [47]. Also, many other studies were using EnergyPLAN to optimize the combination of renewable energy sources, showcasing the tool's ability for such kinds of tasks [23,48].

The sustainable energy system modeling can assess the impacts of energy production, transformation, and consumption, with a different policy in the national economy and climate. The aim is to increase the transparency of the existing energy system to the decision-makers to make a robust and transparent decision for the 2030 energy mix. The transparency of energy mixes for 2030 would lead policymakers to plan a more robust and powerful energy system for 2050. The appropriate sustainable energy model for 2030 for oil-rich countries would help define the direction and pathway of future energy simulation and the simulation methodology to be applied.

As shown in Fig. 1, the proposed model consists of three main steps: inputs, process, and outputs. The sustainable energy system modeling process can be summarized in six steps. In step 1, the component of the system is defined, simplified, and conceptualized. Required input demand and supply data and their hourly distribution for the entire are determined. In the second step, all components' growth rates, including demands and different supply energy carriers, are computed for 2030. In step 3, the modeling goal, which is 4% of CO_2 reduction to meet UMA in Iran's INDC, is defined. In step 5, different possible scenarios with different possible energy mixes are assigned. In the 6th step, the models are run, and results are compared to a proposed suitable scenario with lower TPES, lower thermal power plant capacity, higher renewable energy share, and lower total variable cost. In the final step, the model results are interpreted and discussed in relation to the defined goal. All six steps are essential to achieve robust and transparent results.

3. *Current Iran energy system and challenges*

Iran, as a petroleum-rich country, has one of the world's fastest energy demand growth rates. Its economy is highly dependent (35% in 2019) on oil and oil products export. The patterns of Iran's present energy consumption impact its economy and future development path. The rapid growth of the energy demand in an oil-rich developing country such as Iran results from a high population growth rate, living standard improvement, and a low subsidized energy price. Iran is an energy superpower country, particularly in

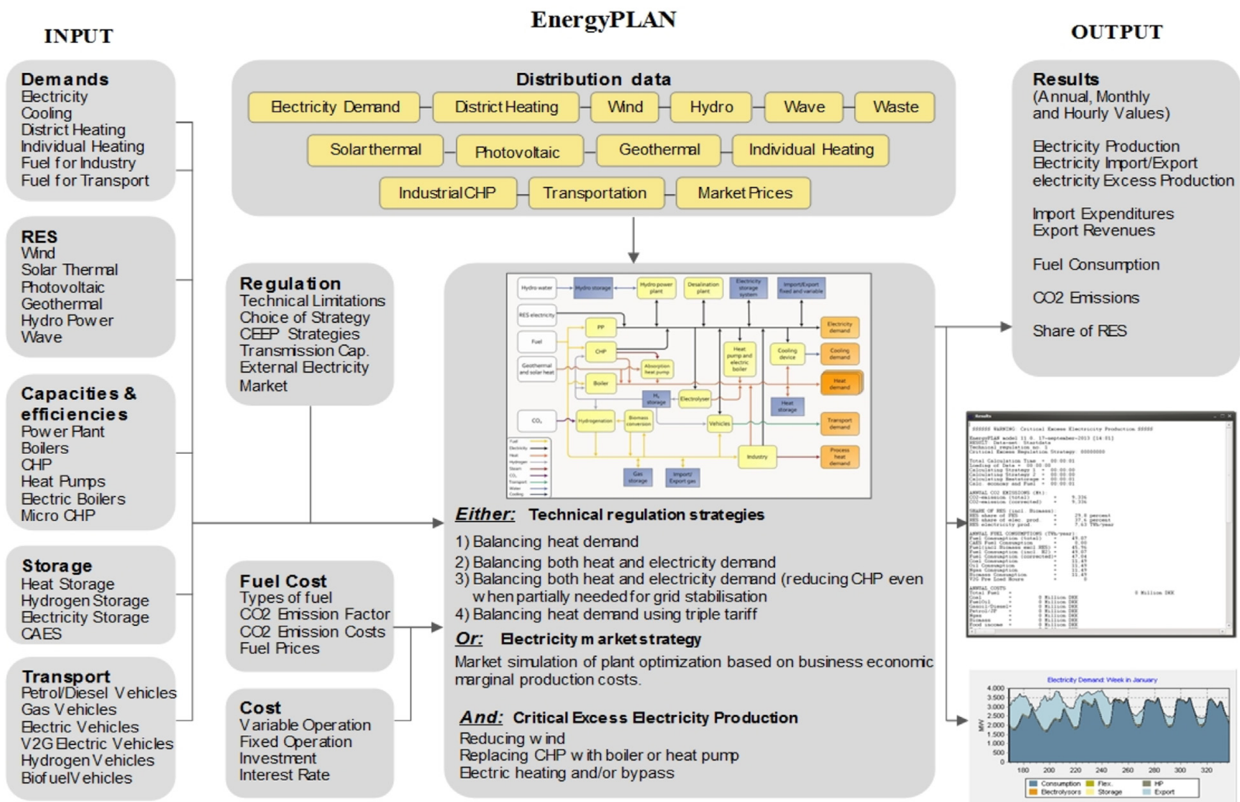

Fig. 1. The structure of the EnergyPLAN tool [39,49].

fossil fuel resources, the 4th largest oil reserves owner, and 2nd major natural gas reserves globally [50].

Consequently, Iran's energy system and economy are highly dependent (35% in 2019) on fossil fuels. The country's TPES in 2016 was 2860 TWh [51]. Its share by fuel type is shown in Fig. 2. As can be seen, Iran's TPES has been increased intensely in recent decades. Therefore, about 97.5% of the country's total primary energy is supplied by oil and natural gas. The massive dependence on fossil fuels has deeply affected Iran's energy infrastructure and socio-economic life [33,52]. Fig. 3 shows the energy consumption for producing 1000 USD (2010) for some selected countries. Iran has a too high energy consumption per capita or GDP. This is because of high levels of subsidies on energy and fuel for all types of consumers, which does not incentivize efficient energy use. Fig. 3 represents TPES per GDP in some selected countries in 2016. The TPES per GDP in Iran is 3 and 10 times higher than the world

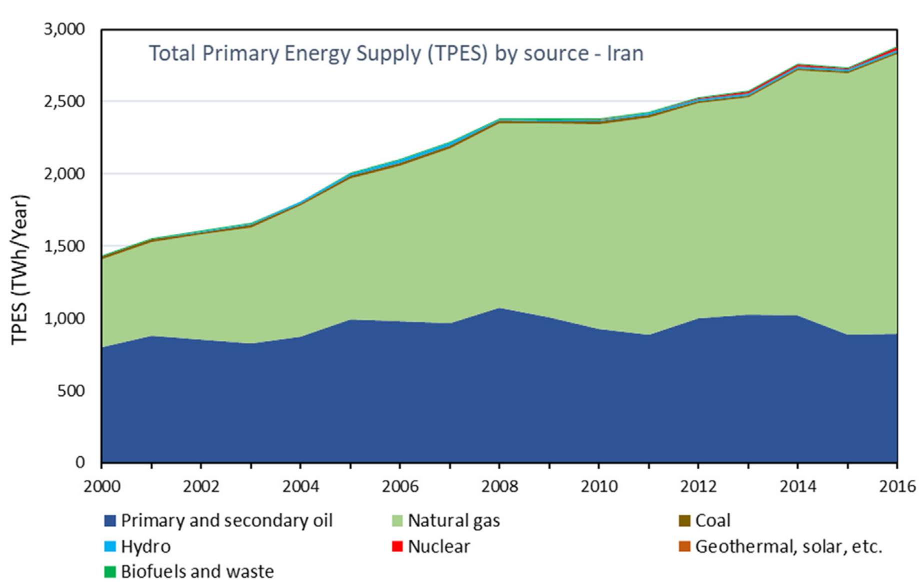

Fig. 2. Total primary energy supply in Iran by the source 2000–2016 [55].

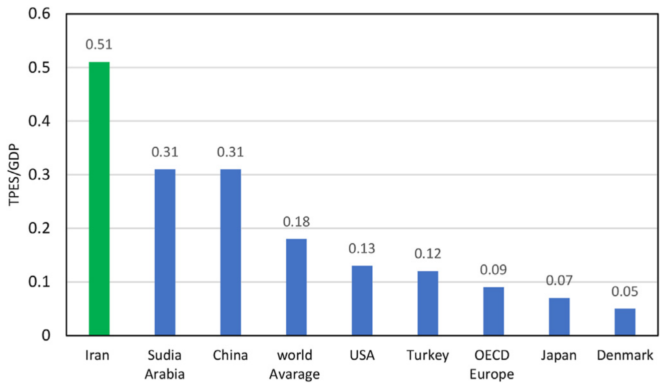

Fig. 3. TPES per GDP, in USD for some selected countries in 2016 and compare with Iran.

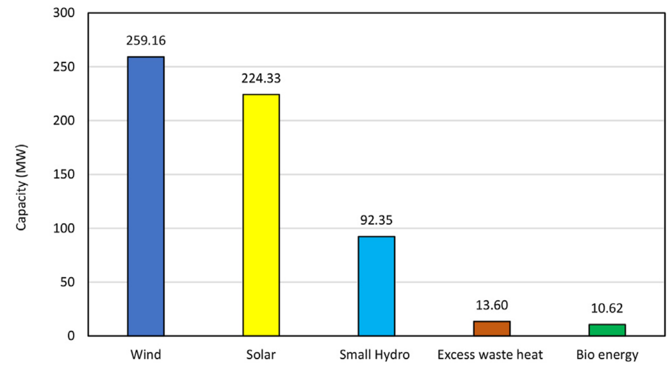

Fig. 4. *Renewable energy power plant actual capacity in 2018 in Iran after* [57].

average and Denmark.

In the past four decades in Iran, TPES has been growing very fast, which negatively affected its economic growth. From 1976 to 1987, during the Iran and Iraq war, the TPES growth rate was slowed down to 5.21% [53]. From 1990 to 2003, TPES has continued to grow at an annual average rate of 5.32% throughout three Iranian promotion plans. Also, in this period, the country's energy mix has evolved towards the natural gas source. The N.G. share reached 36.31%, and the electricity share in the energy mix was almost doubled from 4.11% to 8.93% in this period. By increasing these two energy carriers' share, domestic consumers' share of liquid oil has dropped from 84.33% to 53.42% [51,54]. Table 1 shows the energy mix of the country from 2000 to 2016 for different energy sources.

Iran started to produce electricity from renewable resources in the 1990s. The utilization of renewable energy resources has been increased during the past decades, particularly in the last 3 years after the initiation of the new feed-in-tariff scheme by the Iranian Ministry of Energy. Thus, generating electricity from renewable resources was 560 MW in 2018 and reached 861 MW in summer 2019 [56]. Fig. 4 shows the installed capacity of RE power plants in Iran. During the last decade, 4171 GWh of electricity is generated from renewable energy power plants in Iran. As a result, the consumption of 785000 m^3 of freshwater is saved compared to developing the same amount of power by existing thermal power plants. Water-saving is very important for an arid country like Iran [57].

In its Fifth National Development Plan (NDP) from 2010 to 2015, the Iranian government announced installing renewable energy power plants up to 5000 MW by providing incentives using a feed-in-tariff scheme. This target was ambitious for Iran and was not reached because the renewable energy sector is in its infancy. Secondly, the international sanctions were an influential factor in failing to meet the target. A new reformulated same target has been set in the Sixth NDP for the 2016 to 2020 period. The National Power Generation, Transmission, Distribution, and Management Company evaluated that Iran's RE power production capacity will reach up to 10% of its electricity demand (10,000 MW) within the next 5 years. The primary energy demand of different sectors, including electricity, heating, industry, and transportation, are shown in Table 1. Based on the energy consumption growth rate in the last 5–10 years in each sector, the energy demand for the year 2030 is projected. The annual average growth rate (AAGR) for these four sectors is shown in Table 1.

Table 2 presented the energy demand in each sector by each energy source for 2016 and predicted 2030. In the electric sector, the N.G. is dominated and followed by oil in 2016. The prediction results discovered that in 2030, the natural gas demand would be doubled, but oil increases only by 42%. In the heating sector, natural gas increases by 27%, and oil is reduced by 59%. It means that the heating sector is going to be supplied mostly by N.G. in 2030. In the industrial sector, the N.G. is also dominated and will continue to do so in 2030.

Managing and planning the energy system in oil-rich countries like Iran is highly complex. Energy system modeling of these countries with an emphasis on greenhouse gas reduction and resource diversification faces many challenges, including:

- Energy security depends on a single energy source (fossil fuels), and reducing its share in the energy system is difficult. This high carbon energy source reduction requires careful decision and systematic analyses
- High dependence on oil and gas export revenues in the government's budget
- Misappropriated investment and funding in natural resources development
- International relationship issues such as securities and sanctions
- Low productivity and high energy intensity
- Meager domestic energy prices because of energy subsidies [58].
- Unclear production scheme on shared oil and reservoirs with neighboring countries
- Difficulties of physical energy security issues because of the large geographic area
- Political behavior on resource exploration and extraction
- The behavior of consumers to the energy price changes cannot be predicted

Table 1
Energy consumption for 2016 and prediction for 2030 by the BAU scheme.

Energy consumption Sector	2016 (TWh/year)	2030 (TWh/year)	Annual average growth rate %
Electricity	285.37	429.42	2.96
Heating	585.52	707.95	1.37
Industry	678.00	1102.24	3.53
Transportation	562.71	798.09	2.53

Table 2
Iran energy demand in each sector by each energy source (carrier) for 2016 and prediction for 2030.

Electric production (TWh)			Heating (TWh)			Industry (TWh)			Transportation (TWh)		
Fuel	2016	2030	Fuel	2016	2030	Fuel	2016	2030	Fuel	2016	2030
Coal	2.39	2.36	Coal	0.17	0.17	Coal	10.33	12.44	JP	19.06	30.28
Oil	127.70	174.67	Oil	39.73	16.19	Oil	66.60	50.70	Diesel	207.88	253.77
NG	581.08	1224.1	NG	543.42	689.39	NG	601.07	1039.1	Petrol	260.24	395.55
Biomass	0.09	5.07	Biomass	2.20	2.20	Biomass	0	0	NG	75.53	118.49
Nuclear	7.4	7.4							LPG	0.00081	0.0035
wind	0.27	4.65									
Solar	0.41	5.59									
Hydro	16.4	16.4									
River hydro	0.69	0.69									
Excess Heat	0.07	0.07									
Geothermal	0	0.48									

Given these challenges, the analysis of Iran's energy system requires a systematic and strategic approach. Such an approach must consider various aspects of the problem and its impacts on the whole system and its environment [59].

3.1. Iran Intended Nationally Determined Contributions for Paris Agreement

NDCs are at the core of the P.A. and the achievement of long-term goals. It represents the efforts of the nation to reduce emissions and adapt to climate change goals. The Islamic Republic of Iran submitted its new climate action plan [60] to the "*UNFCCC*" in Nov. 2015. Based on the submitted INDC, Iran has approved 4% and 12% GHG reduction by two kinds of mitigation actions, including "Unconditional Mitigation Action" (UMA) and "Conditional Mitigation Action" (CMA) receptively [60].

The TPES of the country from 2007 to 2016 is used to compute and predict the future energy needs from 2017 to 2030 with different assumed annual average growth rates (AAGR). Fig. 5 shows the TPES of the country and its prediction with the additional growth rates for 2030. The TPES for 2030 was computed using different AAGR from 3.37 to 10%, shown in Table 3. The Table also provides corresponding CO_2 emission for each AAGR that is modeled using EnergyPLAN. The computed CO_2 emission reduction potential for TPES with different AAGRs is presented in Table 3. As shown in the Table, there is a significant potential for CO_2 emission saving in Iran's energy system based on UMC and CMA scenarios found in most oil-rich countries. In the case of technological support, international financial resources availability, and the national development program requirements, CMA can also be applied, which corresponds to the total CO_2 reduction of from 135 to 325 Mt for different TPES growth rates, respectively.

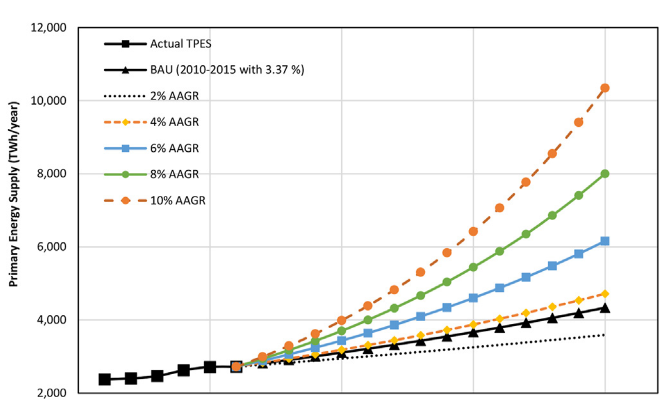

Fig. 5. Total national primary energy supply 2011–2016 and prediction for 2030 with the different AAGR (Y-axis is zoomed and started from 2000).

4. Iran energy system analysis for 2030

The main challenge for oil-rich nations is the interruption of their energy business models. They need to know how to integrate a low carbon strategy into the existing energy system. At the same time, these high fossil fuel economy dependent nations with proved underground reserves face the challenge of monetizing their extensive resources and the risk of losing revenues for multiple decades. It could interrupt their economic and social security. Consequently, the key question is, "how should oil-rich countries position themselves in the transition era to be part of the renewables "revolution" and ensure long-term energy sustainability?" A successful adaptation strategy needs a well understanding of the existing energy system's nature and its future energy demand and resources. As decisions on adapting strategy and model involve knowing in what way and how fast the energy transition can happen, which existing technologies have to prevail, and how the ultimate energy mix after the transition is accomplished.

The oil-rich countries are challenging with a strategic problem here. By postponing the adaptation strategy to reduce the uncertainty, they create an opportunity for other energy resources. In oil-rich countries, the strategic dilemmas are the structural transformations of the existing energy sector and the national economy. New resources' interventions towards defined new sectors, including renewables, do not produce the sizeable revenue as the oil and gas industry.

As described in previous sections, Iran's energy system highly depends on fossil fuels, and it makes the country one of the leading GHG emitting nations in the world. However, it has to struggle with domestic energy shortages, economic losses because of energy subsidization, and inadequate energy-consuming infrastructures. Moreover, GHG and air pollution are rapidly increasing and pose a growing risk to the local environment and the global climate. With these high energy demand trends, Iran may even be a net energy importer over the next decades. Therefore, sustainable energy resource allocation and utilization are crucial challenges for Iran because domestic energy demand stands versus the export of energy carriers [59]. High domestic energy consumption would reduce the export and national revenue. As the Iranian energy systems are highly dependent on inefficient fossil fuel-consuming infrastructures and the energy intensity is very high compared to the even world average, Iran has considerable potentials for energy saving and CO2 emission reduction by efficiency improvement by this high energy intensity and renewable energy resources development.

Theoretically, Iran is one of the top regions for renewable energy

Table 3
TPES and CO_2 emissions and reduction potential for different energy consumption growth rates.

TPES with different AAGR Scenarios	TPES (TWh)	CO_2 emission (Mt)	Target CO_2 emission by UMA (Mt)	CO_2 reduction potential by UMA (Mt)	Target CO_2 emission by CMA (Mt)	CO_2 reduction potential by CMA (Mt)	Total CO_2 reduction by UMA + CMA (Mt)
Actual TPES 2016	2717.96	709.58					
TPES in 2030 by 3.37% (Ava. of 2010–2015)	3595.03	1125.38	1080.36	45.02	1035.35	90.03	135.05
TPES in 2030 by 6%	6160.01	1603.19	1539.06	64.13	1474.93	128.26	192.38
TPES in 2030 by 8%	8002.62	2093.35	2009.62	83.73	1925.88	167.47	251.20
TPES in 2030 by 10%	10346.59	2716.02	2607.38	108.64	2498.74	217.28	325.92

resources, such as wind [61], geothermal [62], solar, biomass, and tidal energies. With this very high energy demand, excessive energy intensity, and valuable renewable resources, the Iran energy system has a very high potential to shift to a more energy-efficient, clean, and sustainable energy system.

The Iran Energy System Sustainability Analysis (IESSA) will model and compute the energy system to analyze and investigate different assumptions about supply and demand technical and economic conditions to find and propose optimal low carbon and low energy intensity solution for policymakers. The outputs would be elaborating on the system feasibility, GHG emissions, cumulative financial costs, total primary energy use, and fully renewable energy share. The results can effectively contribute to the system's optimal overall operation, changing engineering design, or developing appropriate energy policies to meet national emission goals.

Different energy scenarios are illustrated as alternative pathways to a low carbon economy for the post-fossil economy in the initial stage for 2030 and further developed for 2050. In this study, five different scenarios are proposed for the Iran energy system. The proposed energy system with varying energy mixes is computed, and the results are analyzed for three different AAGRs (3.3, 6, 8%) of TPES. The model's primary goal is to find a technically proper feasible energy supply mix to meet INDC in the P.A., presented in Table 3. Five different proposed Iran's energy system scenarios are:

- IESSA1, Business-as-Usual (BAU) with 6% AAGR,
- IESSA2, to meet INDC goal (of 4% CO_2 reduction) only by efficiency improvement in the thermal power production sector
- IESSA3, each energy production, transformation, and consumption sector meet its reduction share in INDC based on UMA
- IESSA4, INDC goal would be met by electricity consumption and generation and transportation sectors
- IESSA5, to meet the UMA in INDC only by electricity production from RE sources in different AAGR

The inputs for each scenario are summarized in Table 4. The IESSA1 is a BAU scenario, which means that the energy demand and supply would be ahead to 2030 in the same trends of the previous five years (2011–2016). The BAU is a reference case and shows only the current energy demand and supply of the country. During this period, the country's industry and infrastructure development were highly affected by U.S. Sanctions. Thus, the last few years' growth rates could not be a useful reference for modeling the future development growth rate and would not be a corresponding energy demand growth rate for coming years. To develop a reasonable model, the AAGRs of 6–10% for TPES are computed for each energy source's demand and each energy carrier supply, including electricity (Table 4). There is a specific change in the configuration of the Iran energy system by this scenario. Based on the rise of energy demand, the energy supply increased using the same technologies.

To compute the IESSA2 scenario, it is assumed that all other three energy demand sectors (heating, industry, and transportation) are not obligated to do any energy-saving. They can continue all their activities in the same as previous ways. In this scenario, just the power plant sector is engaged to fulfill all national commitments (INDC) for CO_2 saving. Reduction of primary energy demand is carried out by thermal power plants efficiency improvement, increasing the capacity of new combined cycle power plants, installation of renewable energy power plants(such as wind, solar, geothermal, bioenergy, and river hydro) in the same growth rate of BAU without any more investment in RE. All inputs for the proposed scenarios are shown in Table 4.

The power sector is responsible for CO2 reduction in this scenario-in base years (2016)- the thermal power plants installed capacity is about 75 G W s which has to be increased to 100 GW for 2030. H class gas turbines with almost 61% efficiency of the combined cycle are planned to install. By installing these 25 G W. high efficiency (61%) and 75 G W. of exciting power plants with an average efficiency of 37.8%, the power production sector's overall efficiency will be about 44.4% in 2030.

In the IESSA3 scenario, each energy demand sector, including electricity, heating, industry, and transportation, is responsible for its own 4% CO_2 reduction goal. This scenario can be fulfilled by end using energy-saving or/and energy sector production and transformations saving. In this scenario, the average power plant efficiency is increased by 0.8% (from 37.8 to 38.6%), wind, solar, and other RE power capacities are remain constant in the power generation sector. For all other sectors, just 4% reduction in demand is projected. Because of high energy loss in Iran's energy system, using simple energy-saving methods can be useful for 4% of energy-saving plans in this scenario and do not need to use high technology energy-saving systems.

The IESSA4 scenario simulates meeting the UMA goal defined in INDC by energy-saving and CO_2 reduction only in electricity generation and transport sectors without any obligation to the industry and heating sectors. Thus, in this scenario, the industry and heating sectors would be continuing as they are, and electricity generation and transportation are obligated to all national CO_2 reduction by INDC in P.A. Table 4 shows the main inputs (supply and demand) of the scenario. From a technological perspective, in this scenario, the power sector will use the same technical method described in scenario IESSA2. For the transportation sector, new imported cars from developed countries will be replaced low efficient national vehicles. The average fuel consumption of nationally produced cars is 8 km/l of gasoline, varying from the international average.

The IESSA5 scenario is designed to meet the INDC goal only by increasing renewables such as wind, solar, geothermal, river hydro, and geothermal heat pumps in the electricity and heating sectors. Installed renewable energy power capacities are used to predict possible future capacities using different proposed annual average growth rates (20, 25, and 30% AAGR) are shown in Fig. 6. The final selected energy mix of renewables with the lowest CO_2 emission is inserted in Table 4 as a proper RE mix (IESSA5). In this energy mix,

Table 4
Inputs for scenarios of proposed energy models for 2030.

Scena.	Electricity (M.W.)		Heating (TWh/year)		Industry (TWh/year)		Transportation (TWh/year)	
IESSA1	Max. Th. Power Plants Cap. and efficiency % inside ()	111451(37.8)	Coal	0.17	Coal	23.96	JP	44.22
	Nuclear	1000	Oil	92.17	Oil	154.49	Diesel	482.23
	Hydro	11943	NG	1260.62	NG	1394.37	Petrol	603.72
	Wind	5159.16	Biomass	5.099	Biomass	0.00	NG	175.21
	PV	3024.33					LPG	0.002
	River hydro	792.35						
	Geothermal	55						
	Import/Export	553						
	Bio-Waste	355						
IESSA2	Max. Th. Power Plants Cap./efficiency (%)	115017(44.4)	Coal	0.17	Coal	23.96	JP	44.22
	Nuclear	1000	Oil	92.17	Oil	154.49	Diesel	482.23
	Hydro	11943	NG	1260.62	NG	1394.37	Petrol	603.62
	Wind	5159.16	Biomass	5.10	Biomass	0.00	NG	175.21
	PV	3024.33					LPG	0.002
	River hydro	792.35						
	Geothermal	55						
	Import/Export	553						
	Bio-Waste	355						
IESSA3	Max. Th. Power Plants Cap./efficiency (%)	109184(/38.6)	Coal	0.16	Coal	23.01	JP	42.45
	Nuclear	1000	Oil	88.49	Oil	148.31	Diesel	462.941
	Hydro	11943	NG	1210.20	NG	1338.60	Petrol	579.57
	Wind	5159.16	Biomass	4.90	Biomass	0.0000	NG	168.17
	PV	3024.33					LPG	0.002
	River hydro	792.35						
	Geothermal	55						
	Import/Export	553						
	Bio-Waste	355						
IESSA4	Max. Th. Power Plants Cap./efficiency (%)	109111 (40.8)	Coal	0.17	Coal	23.96	JP	42.01
	Nuclear	1000	Oil	92.17	Oil	154.49	Diesel	458.12
	Hydro	11943	NG	1260.62	NG	1394.37	Petrol	573.53
	Wind	7259.16	Biomass	5.20	Biomass	0.00	NG	166.45
	PV	5824.33					LPG	0.0013
	River hydro	792.35						
	Geothermal	55						
	Import/Export	553						
	Bio-Waste	355						
IESSA5	Max. Th. Power Plants Cap./efficiency (%)	96805 (38.8)	Coal	0.17	Coal	23.96	JP	44.22
	Nuclear	1000	Oil	38.44	Oil	154.49	Diesel	482.23
	Hydro	11943	NG	1206.89	NG	1394.37	Petrol	603.72
	Wind	6632	Biomass	5.20	Biomass	0.00	NG	175.21
	PV	5306					LPG	0.002
	River hydro	1885						
	Geothermal	255						
	Import/Export	553						
	Bio-Waste	550						

solar and wind power plants are the most contributing resource in the power generation sector. The geothermal heat pump corresponds as the primary RE source for supplying heating and cooling demand.

Table 1 summarized the technology, assumption, constraints, and efficiencies are used for each scenario to implement it.

Once more, it should be mentioned that, In Iran's INDC, 4% of UMA and 8% of CMA, the GHG emissions reduction by 2030 is defined based on the BAU scenario. It was chosen not to represent a certain number of backward years to predict the future. In some criteria, the policy is changed at a specific time, which is very useful in energy consumption, and the trend of energy consumption is shifted after that. The U.S. sanctions against Iran were also affected by industrial and infrastructural development; thus, we have used the backward data where it is appropriated. In this case, with no drastic change in 13 years from 2004 to 2016, all data were applied. The U.S. sanction causes more CO2 per GDP because of countries' difficulties accessing advanced technologies for industrialization and infrastructural developments. By continuing the U.S. sanctions in the future, the pursuit of national commitment in P.A. will be very difficult or almost impossible by the Iranian government.

5. Results and discussion

The model was run for different energy demand and supply policies using five predefined scenarios described in the previous section. The results are discussed here to discover the proper energy mix for minimizing GHG emission and find them more reliable energy policy to lower the TPES for the best national energy plan in Iran as a representative for oil-rich counties. As per capita, energy consumption is very high in petroleum-rich nations; thus, the energy scenarios with lower TPES, Lower CO_2 emission, higher renewable energy share, lower variable energy cost would be preferable. Results proved that the transition in the energy system in oil-rich countries is possible. The most reliable method is the power plant efficiency improvement.

Simulated scenarios for Iran's energy system are analyzed and discussed as a good representative of oil-rich nations. It can be applied to most countries with similar energy systems.

The IESSA1 scenario is "Business-as-Usual," which uses the energy growth rate of each energy source and energy carrier data from 2011 to 2016 and extrudes it linearly for 2030 to compute the energy demand and supply in that year. The details of energy consumption in the Iran energy system for 2016 and prediction for

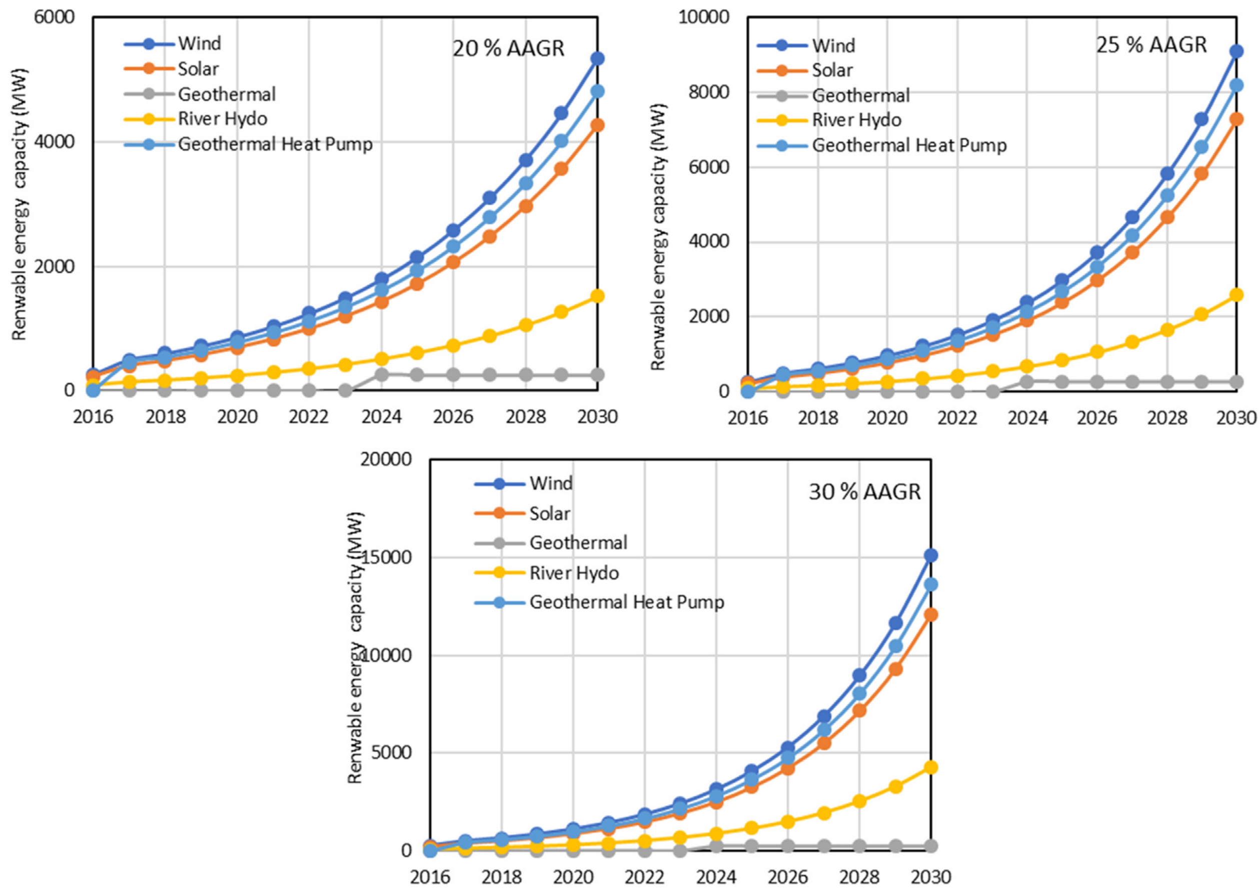

Fig. 6. Proposed renewable energies power capacities used to predict the possible future capacities using different annual average growth rates in the IESSA5 scenario.

2030 using the BAU scheme and its AAGRs are shown in Table 2. This scenario is used to find the future Iran energy system's characteristics in 2030 based on the existing energy system. The result of this scenario is used to compare with other scenarios' results.

In Scenario IESSA5, planned CO_2 emission reductions must be met by renewable energy sources to the energy system. Renewable resources can be used for power generation and heating sectors. Based on the Iran energy system's characteristics, the RE resources can only contribute to power generation and heating sectors. Thus, it is assumed that the transportation and industrial driving force are also supplied partially by electricity in this scenario. For the heating sector, the geothermal heat pump is assigned to consume the excess electricity to provide heat and cool in winter and summer. The geothermal heat pumps are useful for the energy system, particularly in the wintertime, because the excess electricity is available for a lower price to supply the required heat.

Moreover, the geothermal heat pumps are beneficial in the summertime to supply cool because of their higher COP (COP = 4.5) when replaced with existing low COP (COP = 2) air source heat pumps. For the southern parts of Iran, the geothermal heat pump would be highly advantageous because the electricity is used for cooling propose by the low COP air source heat pumps in the whole year. For this scenario, just 1% efficiency improvement of thermal power plants is assumed by installing 5000 MW of high-efficiency new power plants. The simulation model is run for different energy mixes, and the CO_2 emission is computed to meet the INDC goal, which is 65 Mt of CO_2 reduction by UMA of INDC. The simulation results are shown in Fig. 7 for CO_2 emission reduction versus total renewable energy capacity with different renewable energy AAGR.

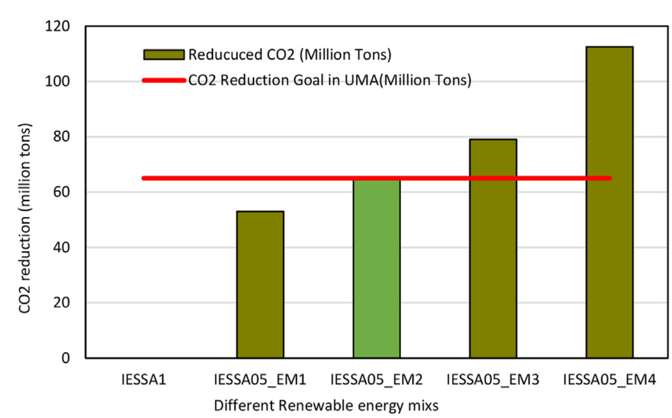

Fig. 7. Comparison of CO_2 reduction by different energy mix with AAGR with UMA.

Between diverse proposed IESSA5 energy mix, the IESSA5_EM2 is selected to be compared with other scenarios (IESSA1-IESSA4).

The IESSA2 scenario was best fitted the goal by increasing the thermal power plant overall efficiency to 44.4% (6.6% improvement), and wind (350 MW per year), solar (200 MW per year), River hydro (50 MW per year), geothermal, and bio-waste generation capacities to 5159, 3024, 792, 55 and 10 M W. respectively. By this power generation mix, the CO_2 emissions are reduced by 4% (65 Mt) from 1603 Mt to 1538 Mt.

In Scenario IESSA3, each energy demand sector corresponds to its CO_2 reduction rate of 4%. The electricity sector achieved its reduction quota by 1% in efficiency improvement (37.8−38.8%) and

2% by end-use energy savings. In the power generation sector, the total electricity demand is 115 GW. From that 110 GW is produced by existing power plants with an efficiency of 37.8%, and the remaining 5 G W. is supplied by new high efficiency combined cycle power plants with 61% efficiency (H class turbines), which shows the improvement of weighted average efficiency by 1% from 37.8 to 38.8%. In this scenario, the RE power plant capacity is similar to IESSA2. Table 5 shows the result of executing this energy model.

To reach the goal of CO_2 reduction by scenario IESSA4, it is required to increase the average efficiency of power generation plants to 40.8% (improvement by 3%). Installation of 500 and 400 MWs of new wind and solar power plants per year, respectively, 2% of end-use electric demand saving and 5% of transportation average demand saving. The results of computing these scenarios are shown in Table 5.

In the case of TPES, in all scenarios, total energy saving is in a similar order of almost 4% in comparison with the IESSA1 scenario. Fig. 8 shows TPES for 5 different proposed scenarios. In terms of total annual cost (TAC) of the scenarios, the IESSA3 is the best scenario because it is achieved mostly by end-use energy-saving than new installation and corresponds to the lower overall cost (Fig. 9). The IESSA5 is the worst with the highest TAC because of the required high capital investment for renewable energy power plants. The cost for power generation from different energy sources is shown in Table 6 as we applied for Scenarios computation in ENERGYPALN (see Table 7).

Regarding the total variable cost as shown in Fig. 10, the scenarios IESSA2 and IESSA5 are more suitable than others. They require lower annual variable cost, which is the most important for the energy system. Both of those scenarios are fulfilled by mostly focusing on the power generation sector. The IESSA2 is more focused on energy efficiency improvement and less on RE power production. The IESSA5 most focused on RE power generation than efficiency improvement of thermal power plants. For RE deployment, a substantial amount of capacity addition is needed by 2030 for the IESSA5 scenario, and it requires high investment.

A comprehensive reform plan in the energy sector involving two main long-term objectives is required: improving efficiency or end-use saving in all sectors and deploying renewable resources. All

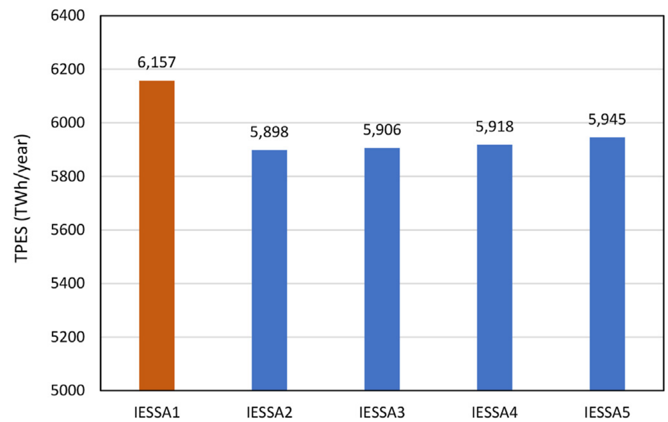

Fig. 8. TPES for 5 different proposed scenarios (Y-axis is zoomed and started from 5000).

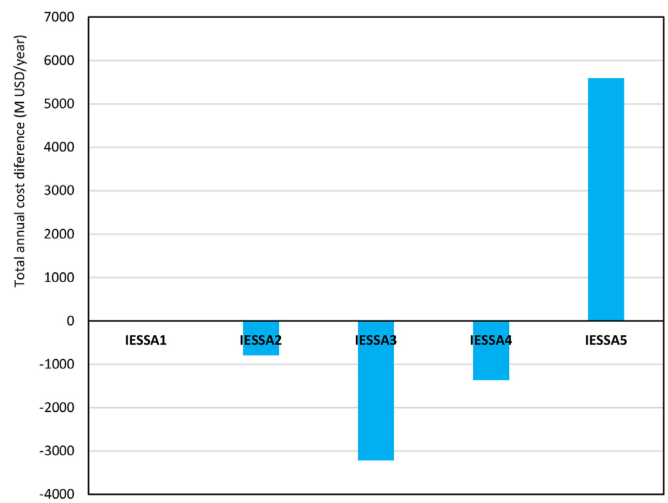

Fig. 9. Total annual cost difference for 4 proposed scenarios with the base scenario.

Table 5
Summarize the technology, assumption, constraints, and efficiencies applied in the scenarios.

Scenario Name	Energy sector	Technology*	Assumption and Constraints*	Efficiency change from the BAU*
IESSA01	Electricity	CPT, HCT	NNEPT	No change
	Heating	CPT, NGB	NNST	No change
	Industry	CPT, NGB	CPC	No change
	Transportation	CPT, R.C.	CPT	No change
IESSA02	Electricity	FCT, RE	EPPT, RE	6.6% Increase
	Heating	CPT, NGB	CPT	No change
	Industry	CPT, NGB	CPT	No change
	Transportation	CPT, RC	CPT	No change
IESSA03	Electricity	FCT, RE	EPPT, RE	0.9% increase
	Heating	EH	EH	Increase
	Industry	E.I.	E.I.	Increase
	Transportation	E.C., R.C.,	E.T.	Increase
IESSA04	Electricity	FCT, RE	EPPT, RE	0.9% increase
	Heating	CPT, NGB	CPT	No change
	Industry	CPT, NGB	CPT	No change
	Transportation	E.C., R.C.,	E.T.	Increase
IESSA05	Electricity	HCT, RE	EPPT, RE	1.1% increase
	Heating	CPT, GHP	EH	No change
	Industry	CPT, NGB	EI	No change
	Transportation	RC	E.T.	Increase

(*Continuation of Previous Technology (CPT), Efficient Power Production Technology (EPPT), Renewable Energy (RE), Efficient Transportation (E.T.), Efficient Heating (E.H.), Efficient Industry (E.I.), H-class turbine (HCT), Natural Gas Boiler (NGB), Regular Cars (R.C.), No any new energy production technology (NNEPT), No any new energy-saving techniques (NNST), Continuation of Previous Consumption (CPC), Energy-saving techniques (EST), High Efficiency, Electric cars (E.C.), F-class turbine (FCT), Geothermal Heat Pump (GHP)).

Table 6
The results of computing 5 scenarios for 2030 and the current system.

Scenario	CO2 (M. tons)	RES share of TPES (%)	RES share of elec. prod. (%)	TPES (TWh)	Max. P.P. cap. (M.W.)	New high effi. P.P.s cap. (M.W.)	Overall PP effic. (%)	Total annual cost (M USD)	Variable costs (M USD)
2016 (Actual)	709.56	0.7	6.2	2717.96	50354	0	37.8	30299	14697
IESSA1	1603.19	0.9	4.8	6157.48	115000	0	37.8	59842	33730
IESSA2	1538.03	1	4.9	5898.28	111451	32500	44.4	59047	32935
IESSA3	1537.31	0.9	4.9	5905.89	109184	5000	38.8	58210	32314
IESSA4	1537.39	1.1	6.1	5918.34	109111	15000	40.8	60270	32190
IESSA5	1537.30	2	12.7	5945.39	109048	15000	38.8	67234	32926

Table 7
The cost of power generation from different energy sources.

NO	Power plant	Investment cost (MUSD/MW)	O&M cost (%of investment)	Lifetime
1	Wind	1.911	0.5	20
2	Photo Voltaic	4.2	0.25	20
3	Geothermal	4.898	5	25
4	Thermal Power Plants (Natural gas)	1021	2.4	30
5	Nuclear	6.215	1.37	60
6	Hydro Power	3.492	2.5	25
7	River Hydro	5.128	1.5	30
8	Pump storage	3.571	3	60

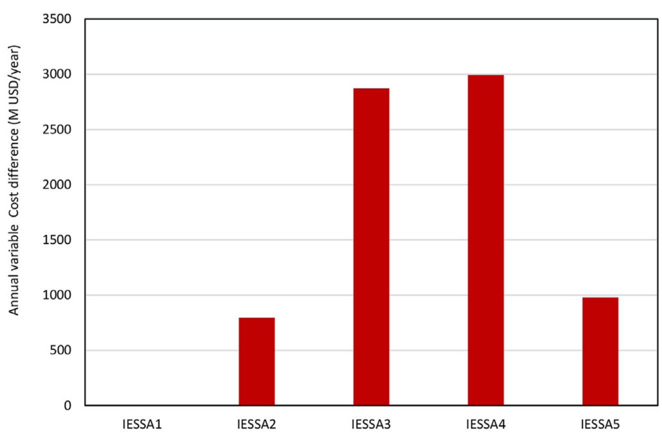

Fig. 10. Annual variable cost Difference for all four scenarios in comparison to IESSA1 scenario.

those clear long-term objectives can be achieved by substantial governmental subsidization reductions on fossil fuels to reduce its share in the future energy system. Enacting carbon tax for all energy demand sectors with a comprehensive infrastructure strategy is the main important driving-force for a transition toward low carbon energy.

From the results, it can be concluded that reaching the UMA goal in INDC is possible by achieving mixed scenarios of efficiency improvement and renewable energy development. Because of the required high industrial and infrastructure development in Iran at the Fifth NDP of the country, these sectors can be left from any forced energy reduction legislation to accomplish needed high growth.

6. Conclusion

Simulation of energy systems in oil-rich nations can effectively assess the impacts of different energy production policies, transformation, and consumption. The sustainable energy system modeling can help decision-makers and planners understand the relationships between energy system inputs and final outputs under various assumptions. Because of the low energy price in oil-rich countries, attention to energy efficiency improvements is very low for both energy system planners and final consumers. Thus, this energy model aims to increase the transparency of the existing national energy plan to the decision-makers to have a robust and transparent decision for future energy mix of county. The appropriate low-carbon energy model for 2030 in oil-rich countries such as Iran would help them to define the future energy supply and demand direction and pathway.

This research developed five different Iran's energy system scenarios as a petroleum-rich nation, focusing on the underlying RE production and efficiency improvement. The research goal is to find a specific national energy mix for 2030 and propose it to the energy planner and decision-makers to meet the NDC in the Paris Agreement, which is 4% reduction from the BAU. Based on BAU scheme, the total national CO_2 emissions would be 1602 Mt by 6% annual energy demand growth rate. Assuming 6% yearly energy demand growth rate for the next 14 years (2016–2030), the net energy consumption almost increased by 2.18 times from 2718 to 6157 TWh. Also, its CO_2 emission increased from 790 to 1602 Mt. Based on UMA, 4% reduction from anticipated emission would be 65 Mt. The first scenario, IESSA1, is the base scenario, and all four other scenarios (IESSA2-IESSA5) are designed to meet the goal (4% CO_2 reduction) with a different scheme.

Developed scenarios try to address suitable direction for the national pathway toward sustainable energy system development. The future energy mix scenarios were discussed in this study to organize general policy to achieve the INDC's goal by rearranging the national energy system toward sustainability. Therefore, the IESSA2 and IESSA5 scenarios were proposed as more probable, acceptable, and preferential national energy plans to meet INDC's to the Paris Agreement. Because most of the energy policymakers and engineers believe that for reduction of CO_2 in Iran, we have to concentrate in one or two sectors rather than all 4 energy sectors. Finally, by the IESSA2 scenario, the goal can be reached with the lowest total annual cost and lower TPES compared to other scenarios.

Developed and proposed scenarios (IESSA2 and IESSA5) and CO_2 emission predictions can be applied as a potential tool by researchers on energy planning to determine the energy strategies to direct politicians, policymakers, and managers' arena. They can consider a comprehensive general plan and make the right decision by having future images of its energy situation.

The transition towards low carbon energy system in oil-rich nations such as Iran can reduce the TPES, CO_2 emission, total variable cost, and maximum installed capacity of thermal power plants and increases the total renewable energy share in the national energy system by firstly focusing on efficiency improvement and secondly on renewable energy integration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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