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Optimal electricity supply system under Iranian framework limitations to meet its emission pledge under the Paris climate agreement

Ali Abbasi Godarzi, Abbas Maleki*

Department of Energy Engineering, Sharif University of Technology, Azadi Street, P.O. Box 11155-8639, Tehran, Iran

ABSTRACT

As part of its *Paris Agreement* commitment, Iran pledged to decrease 4 % of its carbon dioxide (CO_2) emissions from 2020 to 2030. About 29% of total emission in Iran belongs to electricity supply while energy consumption in other sectors (transport, household, and industry) have a lower share in CO_2 emission. The main concern here is finding the optimal mix of power plants in the electricity supply system that should be deployed to meet Iran's mentioned respective targets and considering simultaneously interests of consumers and producers in this energy system. So, we developed a non-linear mathematical programming model for Iran's electricity system to address this concern with changing attitude modeling from a social planner perspective to a private investor perspective. Finally, this model has been run for years between 2017–2030. Results show that a 10-20% diffusion of renewable energy, imposing Carbon tax (25 USD/tonneCO_2) and converting gas turbine power plants to gas combined cycle technology with 5% annual rate can satisfy Iran's emissions pledge under the Paris Climate Agreement with 5.33 Mt of CO_2 equivalent lower than criteria of this agreement.

Keywords

Electricity Supply System;
Energy Demand;
Modeling;
Welfare Maximization;
Greenhouse Gas Emission;
Paris Agreement;

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1. Introduction

The observed increase in global average temperatures since the mid-20th century is most likely caused by the increased greenhouse gas concentrations and some of its impacts, such as climate change, which are practically irreversible. So, the United Nations Framework Convention on Climate Change (UNFCCC) has created a structure for intergovernmental efforts to tackle the challenges posed by climate change.

The UNFCCC negotiation's goal held in Paris in December 2015 (COP21) was to enhance climate action across the globe. According to this agreement, every developed or developing nation pledged to reduce its GHG emissions in the period from 2020 to 2030 based on its INDC which determines their national post-2020 climate action commitments [1].

Iran, as one of the major suppliers of oil and gas in the world, has an estimated 960,505 PJ of proven crude oil reserves, representing almost 10% of the world's crude oil reserves, and an estimated 7,333 PJ of dry gas [2]. On the other hand, statistics indicate that more than 98% of the energy demand in the country is met utilizing these fossil energy resources, which will accelerate GHG emissions. Iran ranked 7th among the world's highest emitters of GHGs in 2018 (with 0.72 metric gigatons of GHG emissions), which are the main drivers of climate change, and its rank rose from 18th in the year 1996 [3].

Therefore, Iran has a crucial impact on worldwide GHG emissions, and its government is under tremendous pressure to reduce its emissions to reach the agreed objectives of the Paris Agreement. Nevertheless, this country has prepared and submitted its INDC in 2016 after COP21. Based on this agreement, Iran intends to participate by reducing its GHG emissions in 2030 by 4% compared to 2020 based on its INDC [4].

*Corresponding author - e-mail: maleki@sharif.edu

Iran consumed more than 11,299 PJ of primary energy in 2016, with natural gas comprising 67% of it (about 7,567 PJ) [5]. Iran's electricity supply system (power plant sector) was the largest energy consumption sector, and technological and economic advances increase the electricity and gas consumption intensity [6]. Because of the heavy reliance of this sector on fossil fuels, more than 29% of GHG emissions in Iran belong to the electricity supply system, this sector requires special attention for GHG reduction (other sectors; household, commercial and public (25%), transport (24%), industry (17%), refinery (3%), and agriculture (2%)) [7].

This paper describes an analysis for assessing the optimal electrical energy supply system of Iran in order to meet the assigned targets pledged in COP21. In particular, it proposes the specific capacities of various types of electricity production technologies that each participating nation in COP21 should deploy to meet its total energy needs and emission targets in an optimal fashion, while computing the resulting overall cost.

Many studies have investigated GHG reduction or mitigation in an energy system, but they lack an explicit description of how their analytical model could realize Paris Agreement targets. Some of these articles have presented analytical models to estimate the overall cost of meeting the emission reduction targets or have provided general strategies without proposing an optimal energy supply system mix to achieve targets of Paris Agreement.

Gao discussed the win-win cooperation model between China and other countries to prepare its guidelines in the implementation of Paris Agreement [8]. He focused on the qualified model of China's behavior for acknowledging the rationality and necessity of climate change, but in his paper, the shares of various energy production technologies in the supply side were not discussed.

Momodu developed a theoretical frame for understanding the tradeoffs between economic development and climate change and presented the nonlinear relationship between generation adequacy and GHG [9].

Singh et al. presented a mathematical programing by combination of economic input-output lifecycle assessment with multiobjective interval portfolio theory in India [10]. They resulted that the most aggressive investment options always attain a higher technical energy savings potential. Candia et al. applied an optimal dispatch model Dispa-SET in evaluating of the Bolivian power generation system flexibility in terms of energy balancing, electricity generation costs and power plants scheduling [11]. They announced that an energy supply portfolio with values lower than 30% share of solar and wind technology is required in GHG emission reduction. Greiml et al. proposed a modelling framework suitable to perform a detailed technical assessment of Multi Energy Systems (MES), and concluded that hybrid technologies such as heat pumps have crucial role in decarbonise strategies planning [12].

Chi et al. presented a dynamic CGE model to study the development trend and the changing characteristics of economy, energy consumption, and carbon emissions to 2030, but their model only estimates the energy consumption in the industry [13]. Furthermore, the amount of energy carriers in the demand side end users has not been determined. Another paper focused on the robustness of the production structure in a simulation model for EU 2020 climate policy assessment and improved on the Monte Carlo sensitivity analysis by introducing a Gauss-quadrature method for large-scale sensitivity analysis of CGE models [14]. In this analysis, only CO_2 emission and macroeconomic parameters were considered and energy modelling is not employed.

Some papers study the resource mix for an energy system; however, they either focus only on the electricity sector, provide only general qualitative analysis, or do not discuss the specific targets of the Paris Agreement. Peter applied a two-stage modeling framework to assess very strong climate change impacts on a cost-optimally decarbonized, highly renewables-based European electricity system [15]. In his article, a linear programming model based on supply side has been presented, but it does not consider the effect of demand side on the optimal value and the path dependencies of energy levels (such as production and storage) during the transition towards a decarbonized electricity system.

Tavana et al. investigated the utilization of renewable energy resources in Iran to provide detailed information about the diffusion of these resources in the electricity supply system for GHG emission reduction [16]. They did not present a mathematical programming model to simultaneously consider different energy system levels and focused on developing strategies to supply energy with 100% renewable energy sources.

Kachoee et al. evaluated the effects of different energy policies on the electricity demand and supply, the potential for reducing GHG emissions, and its cost for Iran [17]. The framework of their model is developed in LEAP, and their scenarios are not applied to the current electricity energy system in the period of Paris Agreement targets.

This paper is organized as follows. After presenting the methodology in section 2, we describe the scenarios studied in section 3: Reference scenario, Carbon Tax-1 scenario covering the carbon tax effect on GHG emissions mitigation, Carbon Tax-2 scenario designed for investigating the diffusion of renewable resources, and Combined Cycle Diffusion scenario that is likely to put the power plants sector on track to meet the Paris Agreement targets. Results are presented in section 4, highlight the impact of scenarios on energy production, demand, GHG emissions, power plant owners' profit, and energy price.

Furthermore, we discuss how to bridge the gap between Iran's INDC and the current crucial level of emissions in the generation sector. The conclusion is presented in sections 5.

2. Methodology

The assessment of GHG emissions reduction policies for climate change mitigation and achieving Iran's Paris Agreement targets, presented in this paper, builds a mathematical non-linear programming model based on maximization of demand and supply surplus. The main novelty is that the presented model in current article has also been transformed into demand (consumer) and supply (producer) simultaneous optimization where exogenous variables were considered as a time series. Moreover, model is built from a private investor perspective instead of employing a social planner perspective, which is a routine approach in energy cost modelling used in several published papers. Many models have used social planner approach to provide an estimation for common output variables of energy supply systems, [18].

The model proposed in this paper differs from the conventional energy software models in that, unlike software such as LEAP which are considered as black boxes, energy equations can be defined that can model complex energy systems and the desired approaches. The above-mentioned structure has been modified in order to cover the behavior of primary energy sources.

Similar to bottom-up models such as the MARKAL, TIMES, and MESSAGE, this paper uses a Reference Energy System (RES) to describe the whole energy flow in each energy level. Figure 1 presents a RES depicting Iran's electricity system and providing a means of

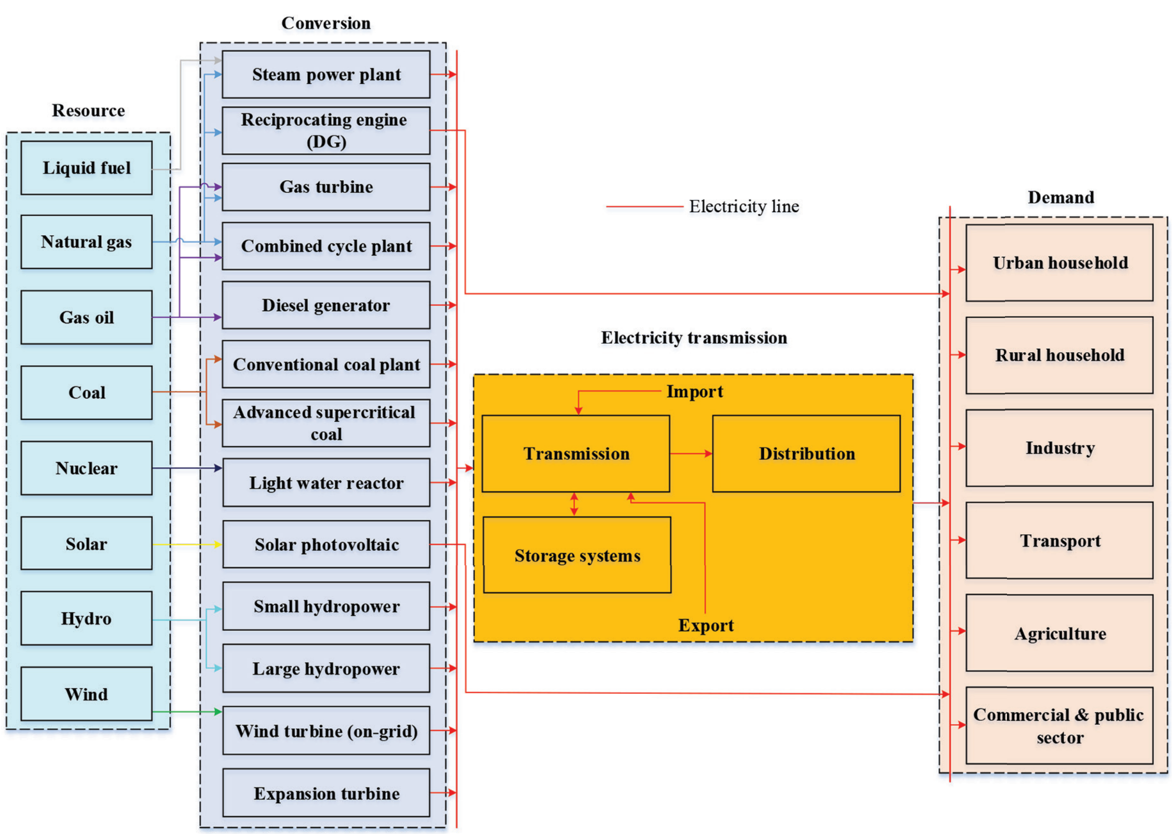

Figure 1: Reference energy system of Iran's electricity supply and demand side

representing the integration of different technologies and their interactions with each other based on the laws of mass and energy conservation [19].

According to the above RES description, the basic setting in this study is based on two sides of the electricity energy system: one is consumer surplus which is related to the demand side, and the other one is producer surplus which is related to the supply side. The main parameters and variables are presented in Table 1.

In this article, we optimized demand and supply side simultaneously based on a non-linear programming model developed in MATLAB software. At first, mathematical equations (Eq. 4 to Eq. 12) are applied in optimization toolbox of the mentioned above software and at second, GHG emission of optimum electricity production that are related to each technology is estimated. In the continuation of this section, mathematical equations of the proposed modeling are described with their details.

Table 1: Parameters and variables of this article

Parameters		**Variables**	
$P_{e.t}$	Electricity prices in USD/MWh	$Q_{i.t}$	Productions in MWh
P_i^f	Fixed Operation and Maintenance (O&M) costs in USD/MWh	$C_{i.t}$	Power plant capacities increment in MW
P_i^v	Variable O&M costs in USD/MWh	$Q_{im.t}$	Amount of import electricity in MW
b	Slope of demand function	$Q_{ex.t}$	Amount of export electricity in MW
c_i	Capital costs in USD/MW	ΔS_t	Net output energy of storage system in MW
λ_i	CO_2 equivalent emission factors in gCO_2/kWh	CS_t	Storage system capacity in MW
$\lambda_{i.co_2}$	CO_2 emission factors in gCO_2/kWh		
$\lambda_{i.c}$	Carbon emission factors in gC/kWh	*Subscripts*	
$\lambda_{i.N_2O}$	N_2O emission factors in gN_2O /kWh	i	Power plants technology number (1 to 14)
$\lambda_{i.CH_2}$	CH_4 emission factors in gCH4/kWh	t	Time
e_i	Emission costs in USD/tonneCO_2	im	Import
k	Constant factor (=0.001)	ex	Export
Pf_i	Fuel costs in USD/MWh		
η_i	Power plants efficiency in %		
$P_{im.t}$	Price of import electricity in USD/MWh		
$P_{ex.t}$	Price of export electricity in USD/MWh		
r	Annual real interest rate in %		
j	Nominal interest rate in %		
f	Annual inflation rate in %		
n	Total number of power plants technology (=14)		
D_t	Electricity demand in MWh		
EL	Electricity loss of transmission level in %		
C_i^h	Power plant history capacities in MW		
CS^h	Storage system history capacity in MW		
φ_t	Maximum capacities in MW		
h_t	Plant factors in %		
w_t	Renewable power plants share in electricity supply system in %		
by	Base year		
PL_i	Power plant technology life		
PL_s	Storage energy system life		
l	Load zone		
GWP	Global Warming Potential		
PD_t	Peak demand in MW		

Since the model determines the long-run equilibrium, the producer surplus completely covers the plant's fixed costs. Therefore, this section must cover the profits of all producers including private and government-owned power plants, prepared as following,

$$Profit_{i.t} = \frac{P_{e.t}Q_{i.t}}{(1+r)^t} - \left(\begin{array}{l} \frac{Q_{i.t}P_i^v}{(1+r)^t} + \frac{C_{i.t}P_i^f}{(1+r)^t} + \frac{C_{i.t}c_i}{(1+r)^t} + \frac{Q_{i.t}e_i\lambda_i k}{(1+r)^t} + \frac{Q_{i.t}Pf_i}{\eta_i(1+r)^t} \\ + \frac{[P_{im.t}Q_{im.t} - P_{ex.t}Q_{ex.t}]}{(1+r)^t} \end{array} \right) \quad i = 1.2.\dots.n \tag{1}$$

In Eq. 1, the variable costs and the fixed O&M costs are discounted on an annual basis at rate *r*, which is estimated as follows:

$$r = \frac{j-f}{1+f} \tag{2}$$

The real annual interest rate (*r*) is related to the nominal interest rate (*j*) and the annual inflation rate (*f*) whose values are 9.25, 18, and 8 %, respectively, in May 2017 [20].

Furthermore, Chang et al. proposed a method for demand-side modelling which estimates the size of the consumer surplus, which is employed in this study for modelling of demand side [21]. Under the assumption of a linear demand function, the consumer surplus can be calculated by examining the area below the demand function and above the price. So, consumer surplus can be derived from the bellow formula:

$$Consumer\ surplus_t = \sum_{i=1}^{n} \frac{1}{2} b Q_{i.t}^2 \tag{3}$$

Slope of power demand function *b* is estimated by data, which corresponds to mean price on years between 2017 to 2030 [16].

As mentioned, our approach in this article is from a private investor's perspective that covers profits of all producers, and the model should also consider demand side as energy consumer. An efficient resource allocation is reached when the total surplus is maximized. Under the conditions described, the optimization problem of this model which has some non-linear mathematical terms is presented by the following relations,

$$Max\ W = \sum_{i=1}^{n}\sum_{t=1}^{T} \frac{1}{2} \frac{bQ_{i.t}^2}{(1+r)^t} + \sum_{i=1}^{n}\sum_{t=1}^{T} \left[\frac{P_{e.t}Q_{i.t}}{(1+r)^t} - \left(\frac{Q_{i.t}P_i^v}{(1+r)^t} + \frac{C_{i.t}P_i^f}{(1+r)^t} + \frac{C_{i.t}c_i}{(1+r)^t} + \frac{Q_{i.t}e_i\lambda_i k}{(1+r)^t} + \frac{Q_{i.t}Pf_{i.t}}{\eta_i(1+r)^t} \right) \right] - \sum_{t=1}^{T} \frac{[P_{im.t}Q_{im.t} - P_{ex.t}Q_{ex.t}]}{(1+r)^t} \tag{4}$$

In Eq. 4, the variable costs, the fixed O&M costs, and capital costs are discounted on an annual basis at rate . Moreover, the objective function in Eq. 4 should be employed in the mathematical programing model, with its main constraints considered as follows,

Demand constraint:

$$\left[\sum_{i=1}^{n} Q_{i.t} + \Delta S_t + (Q_{im.t} - Q_{ex.t}) \right] [1 - EL] \geq D_t \tag{5}$$

Capacity constraint:

$$\sum_{t=1}^{T} C_{i.t} + C_i^h \leq \varphi_i \tag{6}$$

Energy flow constraint:

$$\frac{Q_{i.t}}{\Delta l} \leq h_i C_{i.t} + h_i \sum_{\theta = by-(PL_i - t)}^{by} C_{i.\theta}^h \tag{7}$$

Storage system constraint:

$$\frac{\Delta S_t}{\Delta l} \leq h_i \times CS_t + h_i \times \sum_{\theta = by-(PL_s - t)}^{by} CS_\theta^h \tag{8}$$

Import constraints:

$$Price\ changes:\ 55 \leq P_{im.t} \leq 70 \tag{9}$$

$$Quantity\ changes:\ 0.0125\sum_{i=1}^{n} Q_{i.t} \leq Q_{im.t} \leq 0.05\sum_{i=1}^{n} Q_{i.t} \tag{10}$$

Export constraints:

$$Price\ changes:\ 70 \leq P_{ex.t} \leq 100 \tag{11}$$

$$Quantity\ changes:\ 0.025\sum_{i=1}^{n} Q_{i.t} \leq Q_{ex.t} \leq 0.1\sum_{i=1}^{n} Q_{i.t} \tag{12}$$

In the above constraints, the market clearing condition ensures that supply by all power plants always satisfies demand, considering net energy import (import minus export) and electricity distribution loss, and the capacity of each power plant has a historic value and a new installed capacity that takes place at the following years. Furthermore, power plant productions are limited to the capacity of each installed plant type multiplied by its annual availability factor percentage (plant factor). Net output energy of storage systems is confined by old and new capacities of these systems. Finally, import and export constraints are presented.

The proposed methodology aims to estimate the accurate amount of GHGs in power plants sector and calculate their deviation from Iran's Paris Agreement target. In this article, the amount of GHG emission is considered as the equivalent CO_2 and estimated by relations that were presented in our previous paper [22]. As this study aims at setting an energy policy path for electricity supply system in alignment with the Paris Agreement targets, research and development is being done on decreasing deviation from the targets using the presented methodology which is shown in Figure 2.

3. Scenarios and data

According to changes in social, technical and environmental factors, four scenarios are defined and effects of

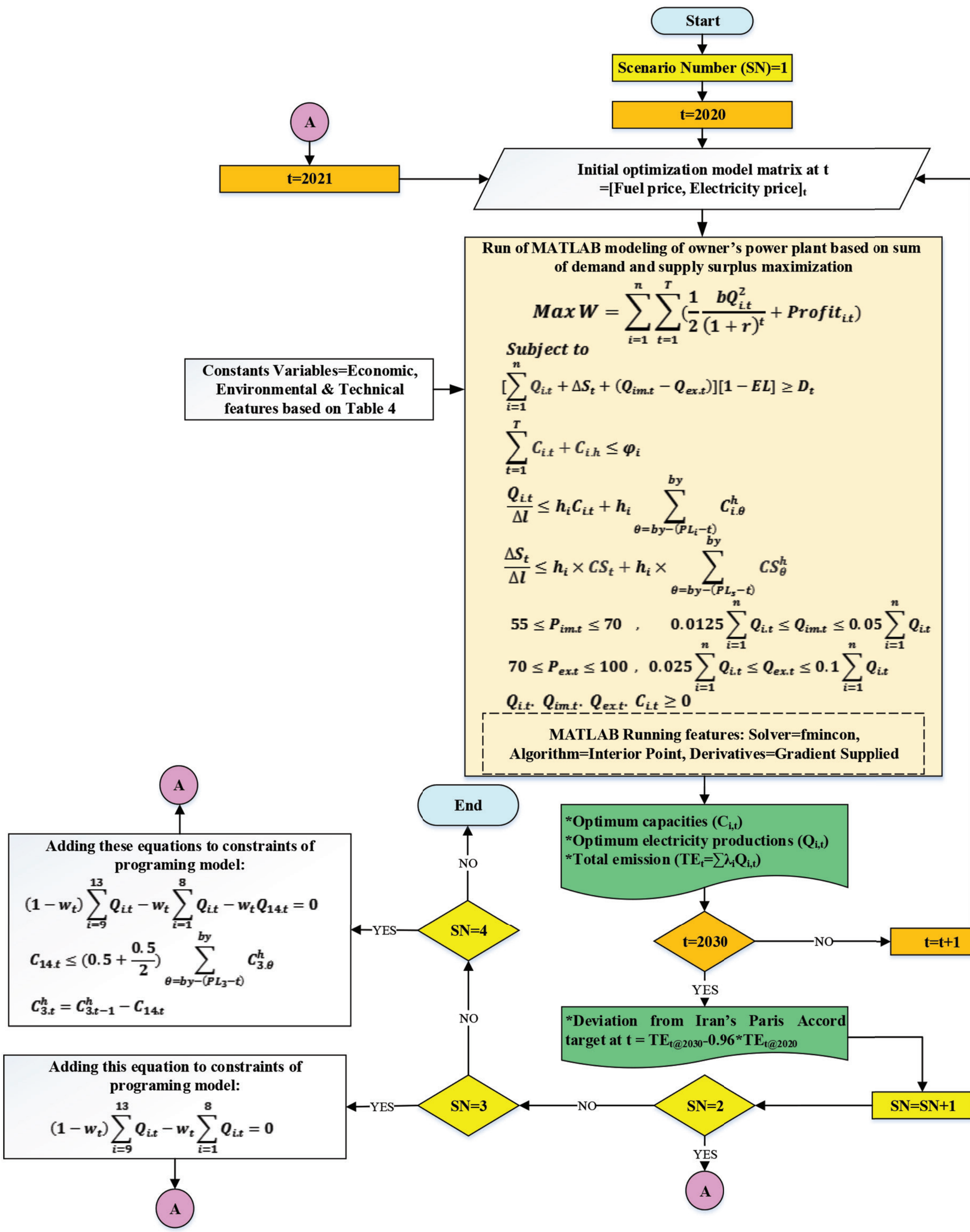

Figure 2: Methodology flowchart schematic of this investigation

them are investigated on the deployment of low emission technologies such as renewables. Each scenario has special driving forces (Table 2) that described these conditions of Iran's energy system. These scenarios cover current status and possible status which will occur in future. Based on expert's expertise in the management and planning organizations of Iran, these driving forces were identified and were combined with each other to develop scenarios. Import and export quantity changes are considered based on share of them in total net electricity production and Iran's energy security. Renewable share changes from 10% (low limit of renewables diffusion) to 20% (high level of it) [22]. Furthermore, based on Iran's renewable energy policy, solar power plants are implemented locally in small scale for distributed regions and their prices are considered 4000 USD/kW [23].

This section describes these scenarios analyzed in this paper: Reference, Carbon Tax-1, Carbon Tax-2, and Combined Cycle Diffusion scenarios. In this paper, the base year, time of scenario implementation, and time horizon are selected at 2017, 2020, and 2020–2030, respectively. Time step and load modeling parameter (l) are based on yearly value.

All scenarios have identical assumptions on population growth and electricity consumption which have a determined growth rate. Electricity consumption is related to energy demand in categorized sections and is dependent on macro-economic variables such as population, GDP, and electricity cost [17]. For Iran, demand forecast is taken from long-term development plan of the country's energy sector. The annual electricity demand and the peak demand are assumed constant based on the reference demand growth scenario (3.4%) and are given to the prepared mathematical programing model (shown in Figure 3) [24].

3.1. Reference scenario

The reference scenario serves as a benchmark for comparison and builds on various data sources and assumptions. So, this scenario includes the energy policies that are currently announced. Energy intensity index did not change on time horizon 2017-2030 and no new optimization pattern took place on demand side for consumption decrement.

This scenario did not include supportive policies to promote renewable energy technologies, and installation of these power plants (especially on-grid wind turbine and solar photovoltaic) will remain at the same level as in the past, with only 5% to 7% share of the net electricity production in energy supply system. All the capacity under construction will become operative and fossil fuel

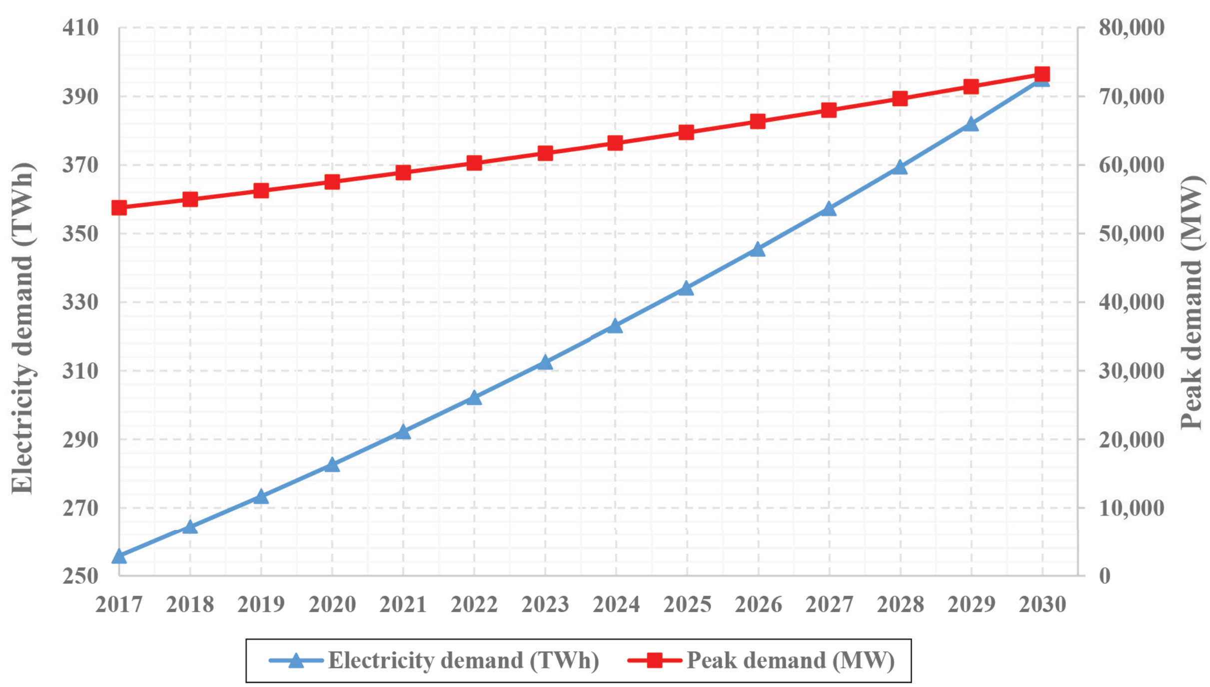

Figure 3: Electricity demand curve until 2030 of Iran [24] (Reproduced by permission from the original publisher)

consumption in power plants remains the same as the base year (2017). Furthermore, the price of electricity import and export vary from 55 to 70 and 70 to 100 USD/MWh, respectively, at this paper's time horizon [24], [25].

3.2. Carbon Tax-1 scenario (CT1)

Two alternative scenarios are designed against the reference case to reflect the impact of carbon taxes on the transition process from conventional towards renewable power plants. In the second scenario, a carbon tax of 25 USD/tonneCO_2 was applied to the mathematical programming model based on IEA Deployment scenario presented in the World Energy Outlook 2019 as a driving force for increasing renewable energy diffusion in energy supply system [26].

So, we hope that high-pollutant power plants such as diesel and coal power plants would only be constructed in response to remote needs and their total share in energy supply system will decrease. All fuels used in gas turbines (GT) and combined cycle power plants (CCPPs) in all seasons will be natural gas, and it will also replace oil in steam power plants.

3.3. Carbon Tax-2 scenario (CT2)

In the carbon Tax-2 scenario, another driving force, increasing the diffusion of renewable power plants, has been incorporated into the mathematical programming model. Iran has diverse and abundant resources of renewable energies whose compatibility with the environment and interminability are their main benefits for electricity production in various regions.

Creating macroeconomic revenue from the available and free renewable resources of the country, increasing GDP, reducing the effects of sanctions, enhancing self-reliance with native non-fossil production, and decreasing GHG emissions are the benefits of accomplishing this scenario.

3.4. Combined Cycle Diffusion scenario (CCD)

In the Combined Cycle Diffusion scenario, in order to increase the driving force of GHG emission minimization, accelerating the increase in the efficiency of GTs is intended with the help of technological changes such as making them combined cycle. These changes have been applied by installing of steam unit in traditional gas turbine power plants. According to technological basics of power plants design, by adding one steam unit to two capacities of gas turbines in MW, three MW of CCPPs are created [27].

So, in modelling this driving force, only 5% (annually) of the existing gas turbines will be converted to combined cycle power plant. One of the main advantages of this scenario execution is that the capital cost of installing combined power plants will decrease and be limited to the installation cost of steam units.

The detailed description of the four mentioned scenarios is summarized in Table 2.

In this paper, electricity subsidy variations are not considered as a driving force, with its value assumed about 6cents/kWh in different scenarios [23]. Changes in the electricity subsidy is related to the political behavior of Iran's government, which is shown to be negligible in the time horizon of this paper by experiences in the past decades. Fuel prices and technological characteristics considered in the RES of this article are shown in Table 3 and Table 4, respectively. It should be noted that combined cycle plant-2 (14th power plant technology in this table) is the GTs capacity which were converted to the combined cycle in Combined Cycle Diffusion scenario.

In this article, accurate estimation of emission costs is crucial and effective on the final results. So, this estimation has been done based on real data collected from various installed power plants in Iran (as shown in Table 5).

Rational prediction of electricity price has been done by Tavana et al. for 2017-2050 [16], whose results are employed in the mathematical programming model in this study and are shown in the Figure 6. Electricity price estimation is a complex process that is needed to simulation of electricity market and it discussed in previous papers. This modeling is investigated in reference [16], and we applied this parameter as exogenous variable. Although more accurate electricity price modeling can present in future works that improve the accuracy of our paper results.

According to Figure 4, price of electricity and fuel are applied as exogenous variables and each scenario must be run by these variables and considering driving forces. On the other hand, CO_2 tax was determined by IEA Deployment scenario presented in the World Energy Outlook 2019 that is the most effective value in increasing renewable energy diffusion in energy supply system and removing gradually subsidy from fossil power plants.

Table 2: Scenarios features and their assumptions

Scenario	Driving forces	Import quantity changes[b] (%) (see Eq.10)	Export quantity changes[b] (%) (see Eq.12)	Supplementary constraint[a]
Reference	–	1.25–5	2.5–10	
Carbon Tax-1	1. Imposing Carbon tax (25 USD/ tonneCO_2)	1.25–5	2.5–10	
Carbon Tax-2	2. Imposing Carbon tax (25 USD/ tonneCO_2) Applying Renewable share (10-20%)	1.25–5	2.5–10	$(1-w_t)\sum_{i=9}^{13} Q_{i.t} - w_t \sum_{i=1}^{8} Q_{i.t} = 0$ $where\ 0.1 \le w_{t@2017-2030} \le 0.2$ (Eq. 13)
Combined Cycle Diffusion	1. Imposing Carbon tax (25 USD/ tonneCO_2) 2. Applying Renewable share (10-20%) 3. Acceleration in technological changing of GTs to CCPPs	1.25–5	2.5–10	$(1-w_t)\sum_{i=9}^{13} Q_{i.t} - w_t \sum_{i=1}^{8} Q_{i.t} - w_t Q_{14.t} = 0$ $where\ 0.1 \le w_{t@2017-2030} \le 0.2$ (Eq. 14) $C_{14.t} \le \left(0.5 + \frac{0.5}{2}\right) \sum_{\theta=by-(PL_3-t)}^{by} C_{3.\theta}^{h}$ (Eq. 15) $C_{3.t}^{h} = C_{3.t-1}^{h} - C_{14.t}$ (Eq. 16)

[a] This equation will be added to Eq. 5–Eq. 12 as supplementary constraint
[b] These values are the share of Import or export in total net electricity production [25], [26]

Table 3: Fuel prices in the base year (cent USD/kWh) [28, 29, 30, 25]

Natural gas	Diesel	Liquid fuel	Nuclear fuel	Thermal coal
1.47	4.46	3.74	0.39	0.79

About energy subsidy, despite Iran's government attempts to decrease this subsidy in recent years, fuel price of power plants in Iran is lower than global average, and their pricing are done based on heat value of fuels. So, it is assumed that fuel price will reach Free On Board (FOB) cost of the Persian Gulf by the year 2030.

4. Results and discussion

This section presents the results of the mathematical programing model which are obtained from the four prepared scenarios. The first part discusses the impact of these scenarios on the composition of the energy supply system. Next, we zoom in on the greenhouse gas emission paths by total emission and by emission intensity.

4.1. Installed power plant capacities and electricity generation

As shown in Figure 5-a, the total installed capacity in Reference scenario for providing the demand will reach 103.69 GW in 2030. This amount will be 114.76 GW for the Carbon Tax-1 scenario, 131.84 GW for the Carbon Tax-2 scenario due to low energy density of renewable energy, and 141.63 GW for Combined Cycle Diffusion

Table 4: Techno-economic data of power plants in electricity supply system [28, 29, 30, 25, 31, 23]

NO.	Technology	Capital cost (USD/kW)	Fixed O&M (USD/kW)	Variable O&M (USD/MWh)	Efficiency (%)	Plant lifetime (year)	Plant factor (%)	Self-consumption (%)	Decreasing rate of investment cost(%/year)	Upper limit on new capacity additions[a] (MW/yr)	Maximum capacity (MW)
1	Steam power plant	1100	9.4	0.48	41.2	30	75	6.8	0	0	0
2	Reciprocating engine (DG)	800	8	5	40–45	10	80	0.7	0	119	3000
3	Gas turbine	550	4.4	0.64	34.3–38.9	12	70	0.8	0	0	0
4	Combined cycle plant	760	4.3	0.41	50–55	30	80	1.9	0	0	0
5	Diesel generator	550	3.8	0.74	33	10	70	6.5	0	0	0
6	Conventional coal plantb	1600	64	0	35.3	30	85	5.5	0	0	0
7	Advanced supercritical coal	3700	88	0	46–50	40	85	5.6	0.7	0	0
8	Light water reactorc	4800	92	0.5	31	40	80	10	0	0	0
9	Small-scale solar photovoltaic	4000	50	0	0	25	25	0	3	48	900
10	Small hydropower	2000	14	0	0	40	50	0.5	0	192	2600
11	Large hydropower	1500	10.8	0	0	50	15	0.5	0	1080	26000
12	Wind turbine (on-grid)[d]	1500	48	0	0	20	30	1.4	1.5	3055	40000
13	Expansion turbine	780	30	0.45	0	15	70	0	0	115	1500
14	Combined cycle plant-2e	1140	4.3	0.41	50-55	30	80	1.9	0	0	0

[a] An upper limit of a technology for maximum capacity of its power plant that is imposed on the model.
[b] The country will construct capacity of this technology about 650 MW until 2030.
[c] According to nuclear sanctions that were imposed on country, it could be only install 1000 MW capacity of this technology similar to Bushehr's nuclear power plant until 2030.
[d] Based on capacity fluctuations of wind turbine in the country, capacity of this technology will be five time until 2030.
[e] Capacity value of this technology until 2020 was assumed zero and it will be had value after this time (only in CCD scenario).

Table 5: Pollutant and GHG emissions factors in Iran power sector by power plant types for the year 2017 (g/kWh) [7]

Ownership	Type of Plant	CO_2	C	N_2O	CH_4
Governmental Sector	Steam	684.874	186.784	0.002	0.015
	Combined Cycle	493.708	134.648	0.001	0.010
	Gas	832.395	227.017	0.002	0.016
	Diesel	811.159	221.225	0.007	0.033
Private Sector	Steam	680.974	185.720	0.001	0.012
	Combined Cycle	497.376	135.648	0.001	0.011
	Gas	752.758	205.298	0.002	0.015

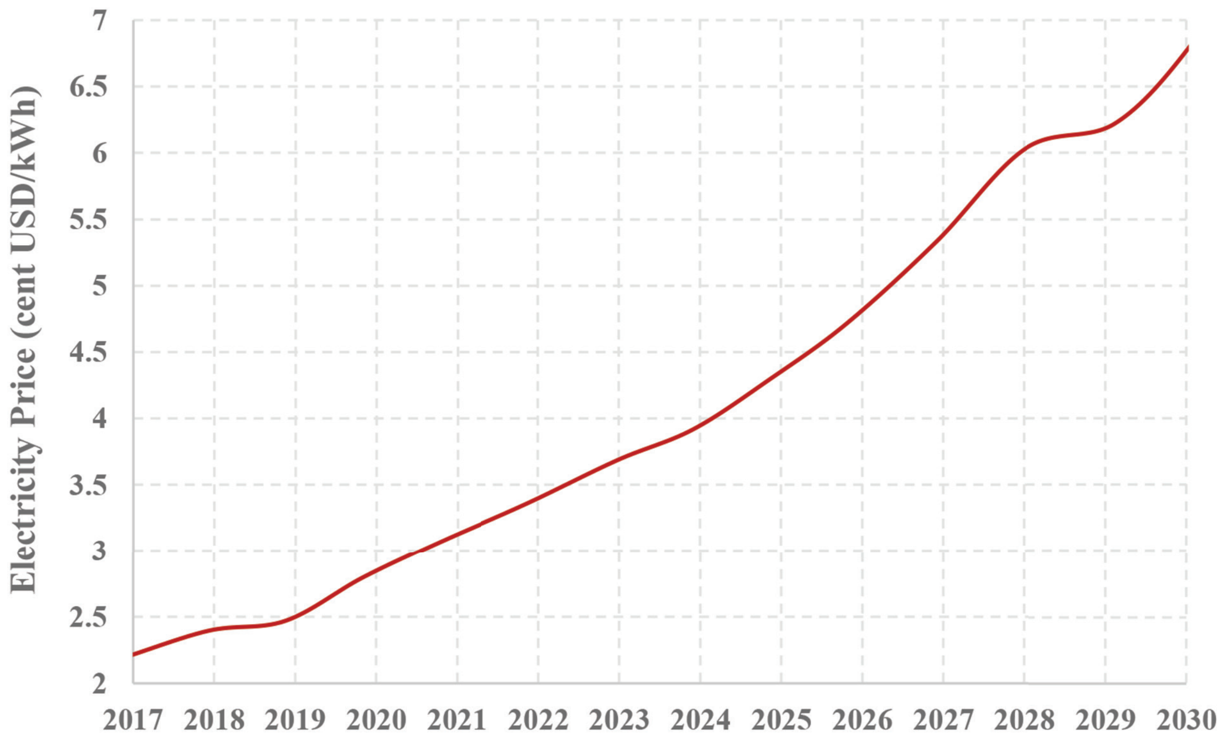

Figure 4: Electricity price changes in Iran energy supply system [16]. (Reproduced by permission from the original publisher)

scenario because of the increased capacity of combined cycle power plants in energy supply system and their high electricity efficiency (Figure 5-b to Figure 5-d). The dependence of Iran's electricity sector on fossil fuels will continue in these scenarios. Although this dependency decreases from 93% in Reference scenario to 81% in the CCD scenario, it will not be diminished.

During the planning horizon, the total capacity grows at an annual rate of 1.8% in Reference scenario. This rate ranges from 2.7% to 4.63% in the alternative scenarios. The growth differences mainly stem from the utilization of renewable technologies that normally have a lower capacity factor, the diffusion of high-efficiency power plants such as combined cycle, and the reduction of the share of high-pollutant technologies such as steam power plants. Indeed, in these scenarios, the key role of combined cycle power plants in Iran's electricity supply system is evident, which is due to the abundance of gas resources and their low emission rates.

On the other hand, the capacity of steam power plants should be preserved to supply the demand until 2030 and even later. The government must invest in renewable

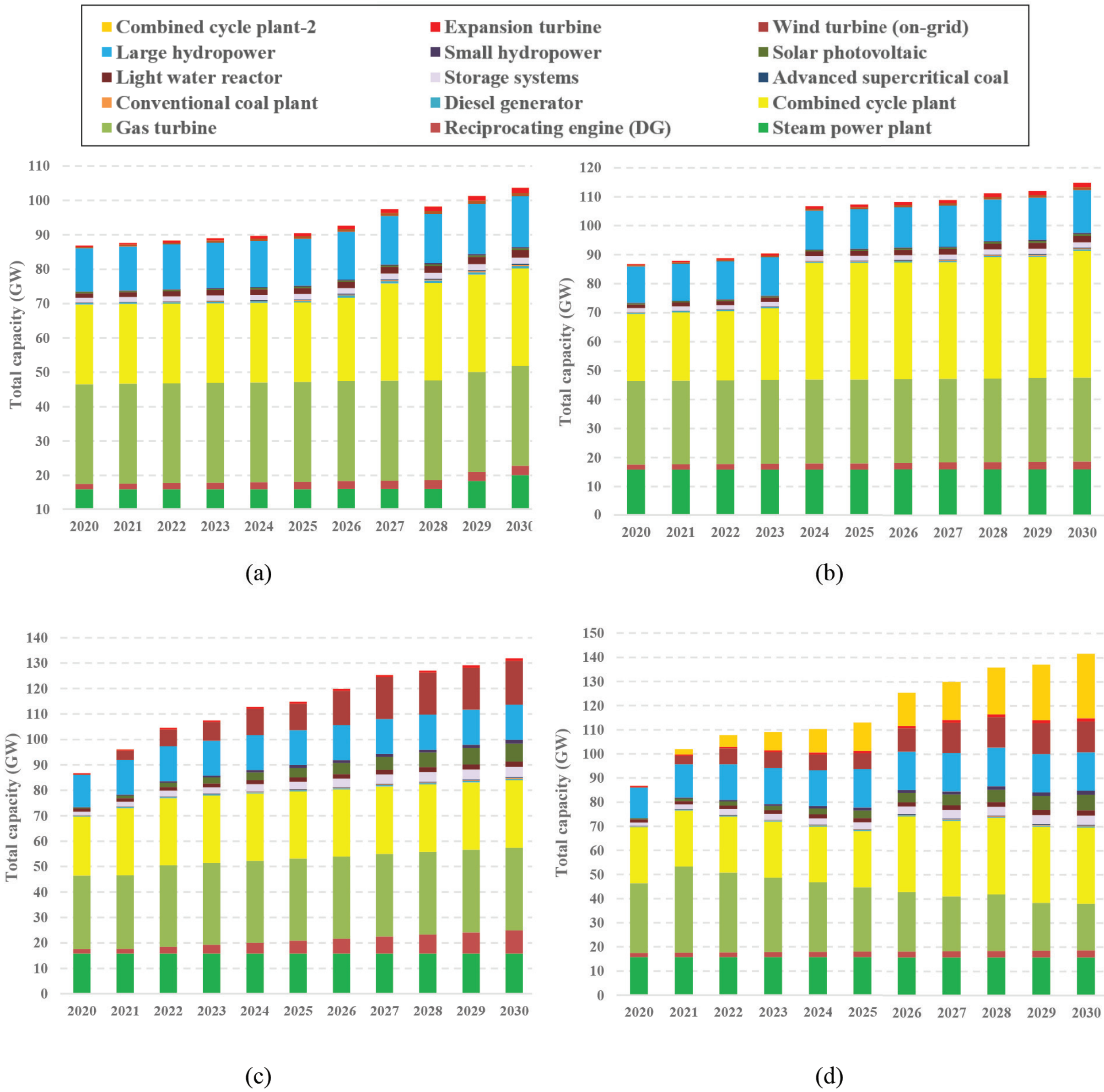

Figure 5: The total capacity installation in different scenarios (a: Reference, b: CT1, c: CT2, and d: CCD)

energy (because of using distributed renewable resources) and combined cycle (for using abundant gas resources to reduce emissions) to decrease GHG emissions. Nevertheless, in Reference scenario, shares of the fossil and renewable technologies in electricity production are 4428 TWh and 318 TWh, respectively (cumulative 2020-2030). The difference between these values in other scenarios has decreased, which are shown in Figure 6 and Table 6).

According to the above figures and table, the share of steam power plants gradually decreases until 2030 (except for the Reference scenario), and it disappears at 2030, 2028, and 2029 in CT1, CT2, and CCD scenario, respectively. Therefore, the model will attempt to reduce the share of pollutant power plants in electricity production in order to meet the Paris Agreement targets in the specified time window of this pledge (2020-2030).

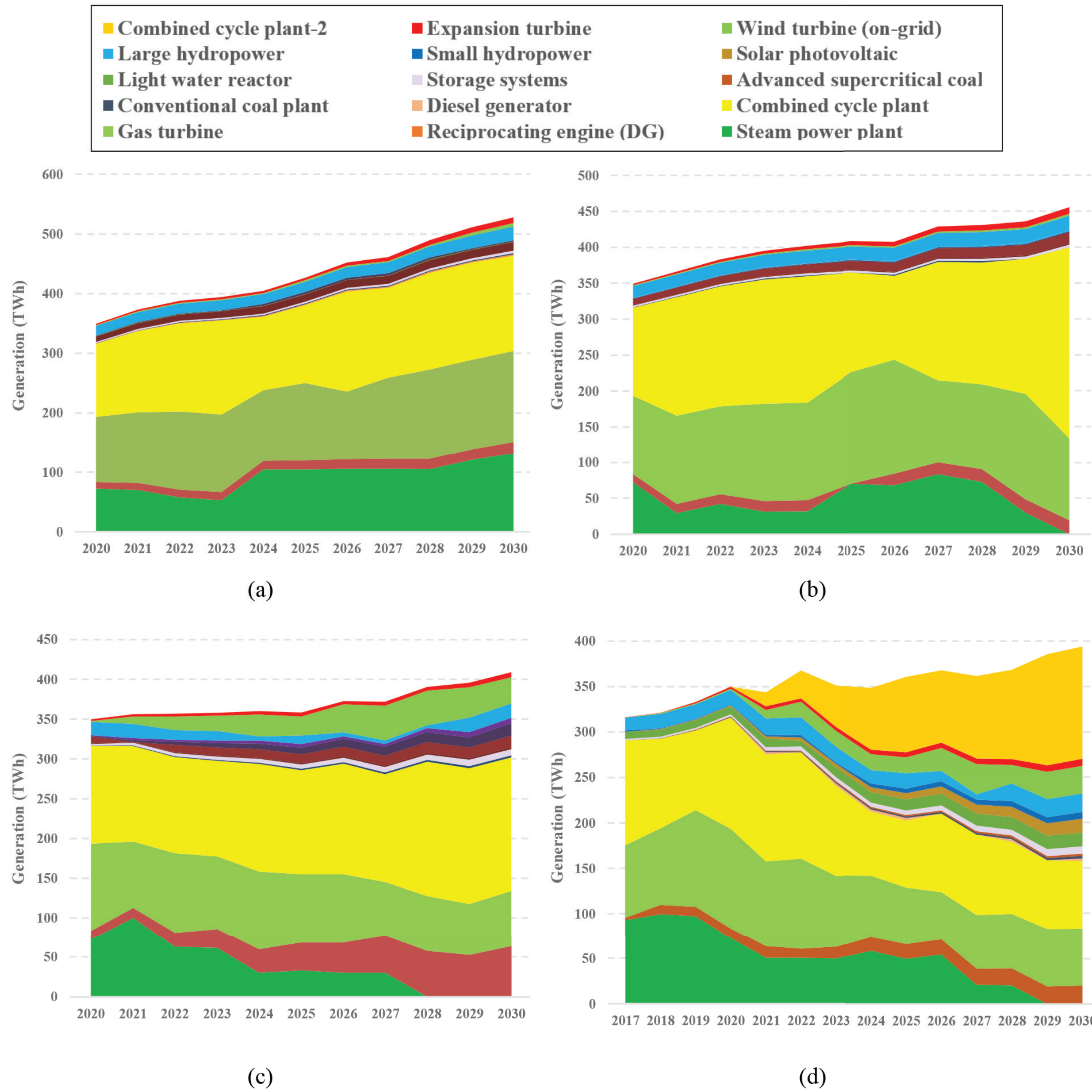

Figure 6: The electricity generation mix in different scenarios (a: Reference, b: CT1, c: CT2, and d: CCD)

Table 6: Comparison between fossil and renewable power plants in total electricity generation (cumulative of 2020-2030)

Scenario	Fossil power plants in TWh (F)	Renewable power plants in TWh (R)	R/F ratio (%)	Difference (R-F)
Reference	4428	318	7.18	4110
Carbon Tax-1	4127	305	7.39	3822
Carbon Tax-2	3424	594	17.34	2830
Combined Cycle Diffusion	2617	587	22.43	2030

The reserve margin is an important metric used in mid-term planning models to certify the resource adequacy of projected power systems is estimated by following equation,

$$Reserve\ margins_t(\%) = \frac{\sum_{i=1}^{n} h_i (C_{i.t} + CS_t) - PD_t}{PD_t} \quad (17)$$

This endogenous variable was estimated in various scenarios and its results were shown in Figure 7.

As shown in above figure, because of imposing 3 driving force simultaneously, reserve margins in CCD scenario have the best value rather than other scenarios and their value will attain to 54.78% in 2030.

4.2. Greenhouse gas emissions

Still dependent on fossil fuels, the growing electricity demand clearly plays a key role in the upward trend of GHG emissions. So, we should present scenarios to not only supply the growing demand but also constrain these emissions under Paris Agreement limitations. In the base year (2017), the amount of greenhouse gas emissions is 174.14 Mt of CO_2 equivalent. In Reference scenario, it will reach 292.01 292.01 Mt of CO_2 equivalent with an average growth rate of 4.07% until 2030.

Due to greenhouse gas emissions reduction policies, GHG emissions are expected to decrease to 213.92, 195.01, and 180.67 Mt of CO_2 equivalent in CT1, CT2, and CCD scenarios, respectively. If these scenarios are accomplished by the government, meet the Paris Agreement targets would be accessible. Trend of emission variations in the four scenarios investigated are shown in Figure 8-a and Figure 9.

According to the above figures, GHG emission in Reference scenario is rising dramatically over time, caused by the high share of fossil fuels in electricity production. So, if this trend continues until 2030 and the government does not take any action against it, meeting the Paris Agreement targets will not be possible.

In this scenario, the deviation from the COP21 criteria is about 106.02 Mt of CO_2 equivalent, highlighting the importance of focusing on decreasing the share of pollutant technologies such as steam power plant and increasing the share of combined cycle and renewable resources. In Carbon-Tax1 scenario, GHG emission deviation has decreased to 27.92 Mt of CO_2 equivalent but did not meet the COP21 criteria. Indeed, applying carbon tax to this scenario could decrease the emission of high-GHG-emitter power plants, but this policy action

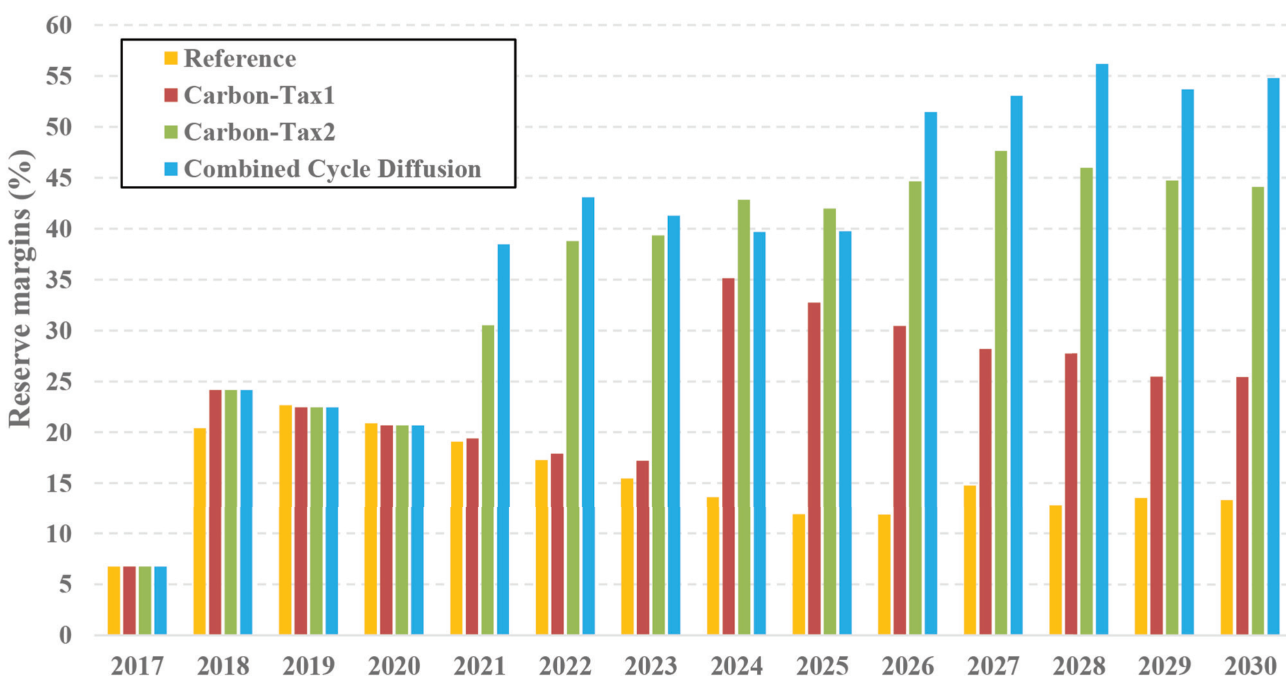

Figure 7: Reserve margins in different scenarios

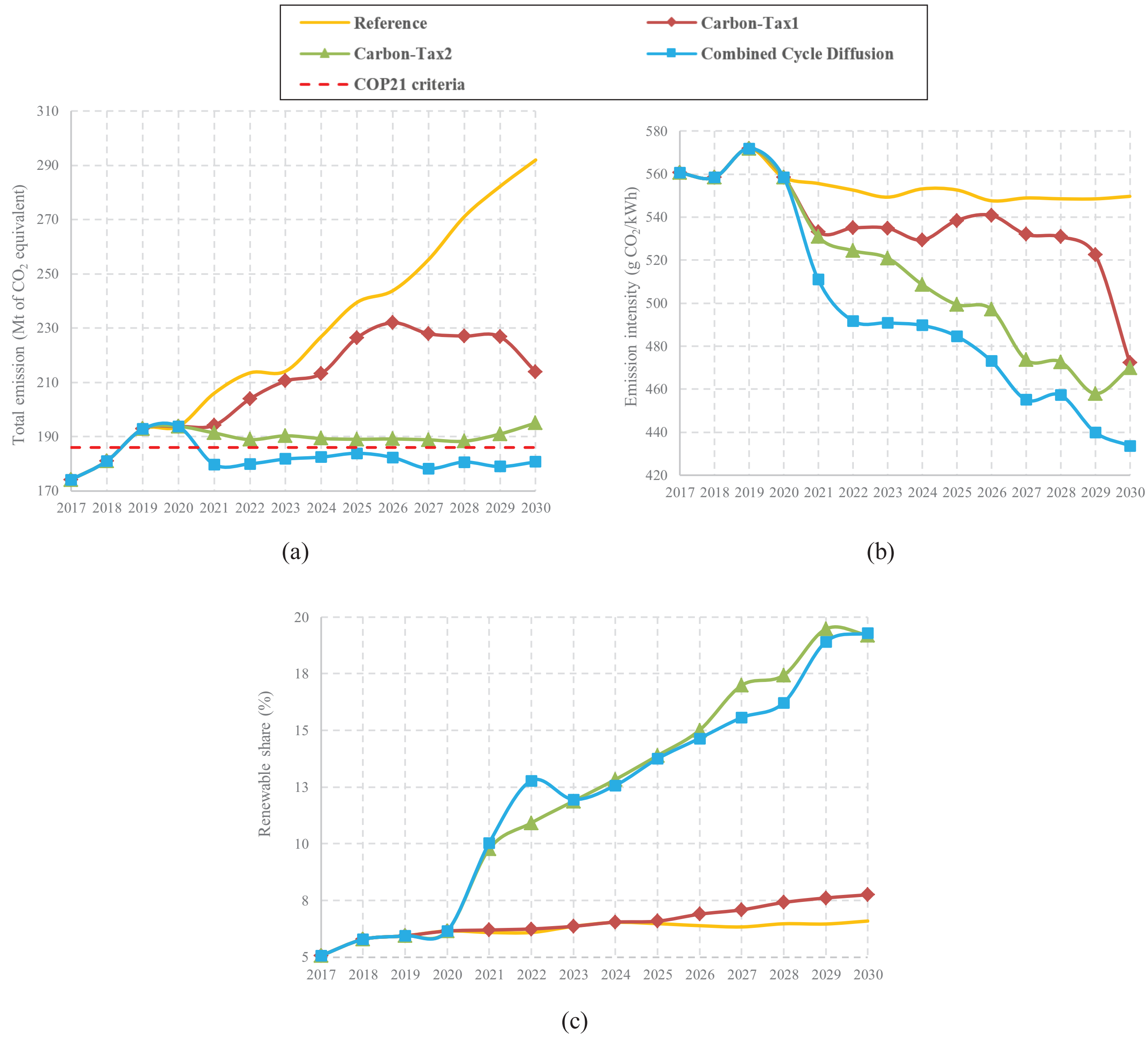

Figure 8: Variations of total GHGs emissions (a), emission intensity (b), and renewable power plants share in electricity production of supply energy system (c) in different scenarios

was not enough to satisfy the Paris Agreement targets; the owners of power plants were willing to pay carbon tax and not participate in decreasing more GHG emission.

In the Carbon-Tax2 scenario, the deviation from targets optimistically decreases to 9.02 Mt of CO_2 equivalent upper than COP21 criteria, which proves that the two driving forces, limiting emissions of pollutant power plants by applying carbon tax and increasing the share of renewable resources in electricity production, almost could aid governments in meeting Paris Agreement targets. However, after 2028, total emissions soar, possibly higher than COP21 criteria after Paris Agreement deadline in 2030.

Therefore, another scenario was developed for sustainable reduction of emissions by increasing the diffusion of combined cycle as the 3rd driving force. This

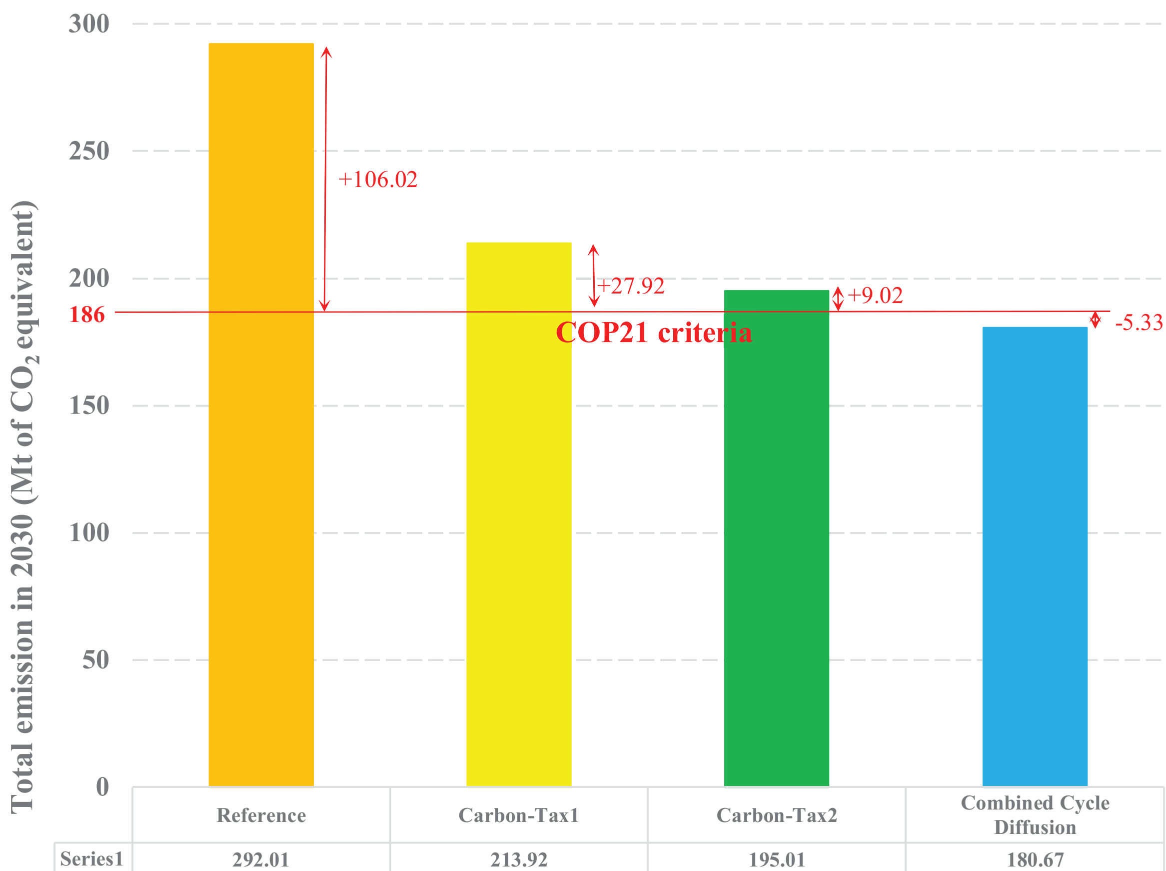

Figure 9: Deviation GHGs emission from Paris Agreement (COP21) in different scenarios

final scenario is Combined Cycle Diffusion. In this scenario, the deviation from COP21 criteria will decrease to 5.33 Mt of CO_2 equivalent under Iran's Paris Agreement targets, with its trend dropping until 2030.

Furthermore, emission intensity is one of the main indicators of the amount of electricity production versus GHG emissions, determining the amount of GHG that will be emitted for increasing electricity production to supply demand. In Figure 8-b, different emission intensities are shown in different scenarios.

The reduction in emission intensity appertains to many factors the main ones of which are: (1) increasing the efficiency of fossil fuel power plants, (2) decreasing the share of high emitter fuels in electricity production such as liquid fuels, and (3) increasing the share of low or zero-emission power plants such as combined cycle and renewable resources (Figure 8-c).

The fluctuated reduction in the Reference scenario until 2030 comes from the temporary behavior of the government in fuel pricing and supplying the high growth rate of electricity demand with high-pollutant technologies. However, in other scenarios, because of higher diffusion of renewable resources and CCPPs, emission intensity will have a downward trend. It can be observed that this trend in the CCD scenario is strictly descending, indicating that this scenario has a sustainable behavior over time, from which the government can benefit for the power plant sector to meet the country's Paris Agreement targets.

4.3. Cost analysis

Net present value of total costs in the Reference scenario is equal to 46.56 billion USD in 2030, including non-renewable capital cost (16%), renewable capital cost (6%), fuel cost (72%), and O&M cost (7%). The biggest share of the cost in this scenario belongs to fuel cost due to the high contribution of fossil fuel power plants to electricity production. Moreover, because of the dominant availability of fossil technologies, this cost has the highest value in the Reference scenario compared to other scenarios (see Figure 10).

As shown in Figure 11, in the other scenarios, emission cost is added to total cost, which is related to

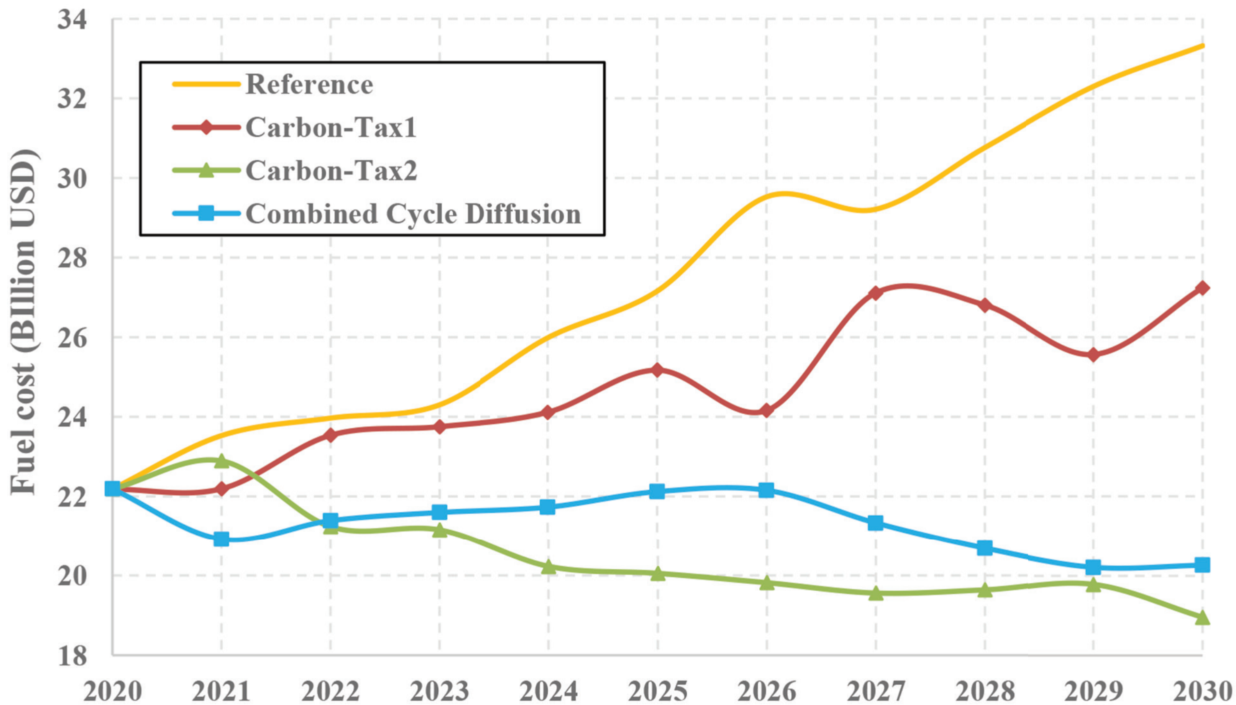

Figure 10: Net present value of fuel cost in different scenarios

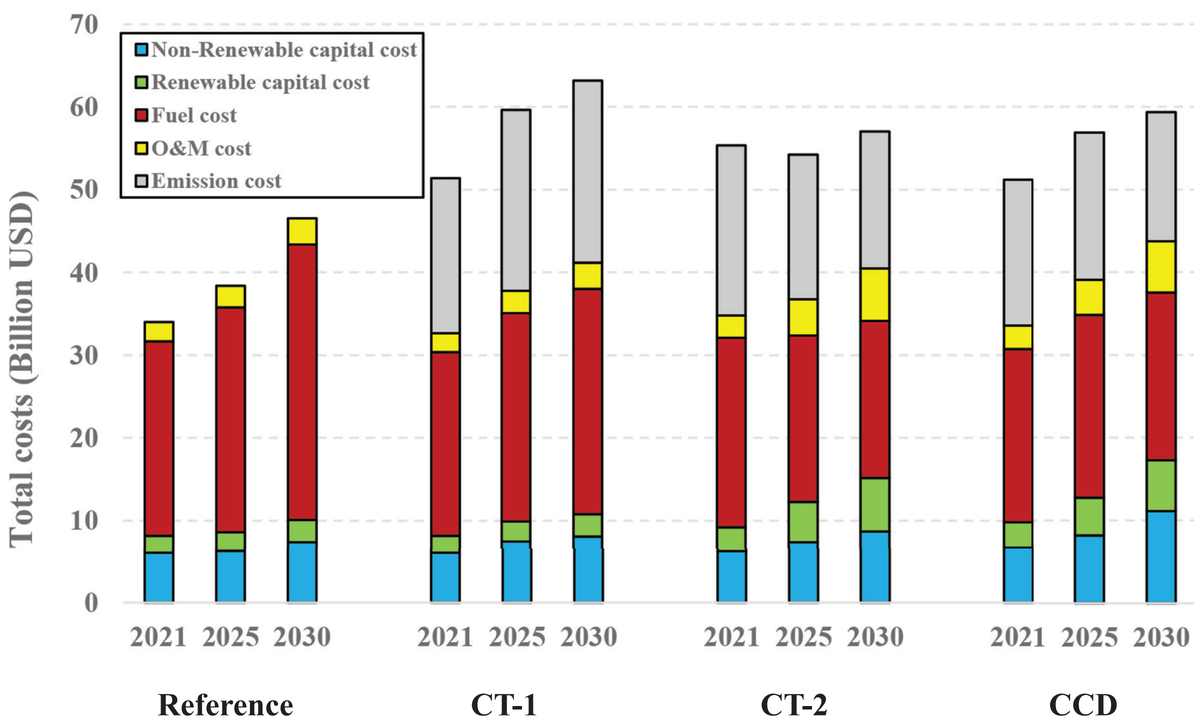

Figure 11: Net present value of total cost of electricity supply in different scenarios

imposing carbon tax on these scenarios as a driving force. Furthermore, the Reference scenario has the lowest total cost compared to other scenarios.

In the Carbon Tax-1 scenario, net present value of total costs will be 63.20 billion USD, and the share of non-renewable capital cost, renewable capital cost, fuel cost, O&M cost, and emission cost will be 13%, 4%, 43%, 5%, and 35%, respectively. Also, fuel cost has the highest percentage of the total cost in this scenario, followed by emission cost which is ranked second.

Net present value of total cost in Carbon Tax-2 scenario is equal to 57.04 billion USD in 2030. Because of the low efficiency and low power density of renewable resources, capital and O&M costs will be 6.47 and 6.32 billion USD higher than Carbon Tax-1 and Reference scenario (see Figure 12-a), but due to the increase in renewable to fossil fuel capacity ratio in Carbon Tax-2 scenario (38%), the fuel and emission cost will fall to 18.95 and 16.56 billion USD lower than previous scenarios.

In the Combined Cycle Diffusion scenario, due to capacity conversion of GTs to CCPPs, non-renewable capital cost will rise to 11.13 billion USD higher than other scenarios. Detailed variations of this cost were

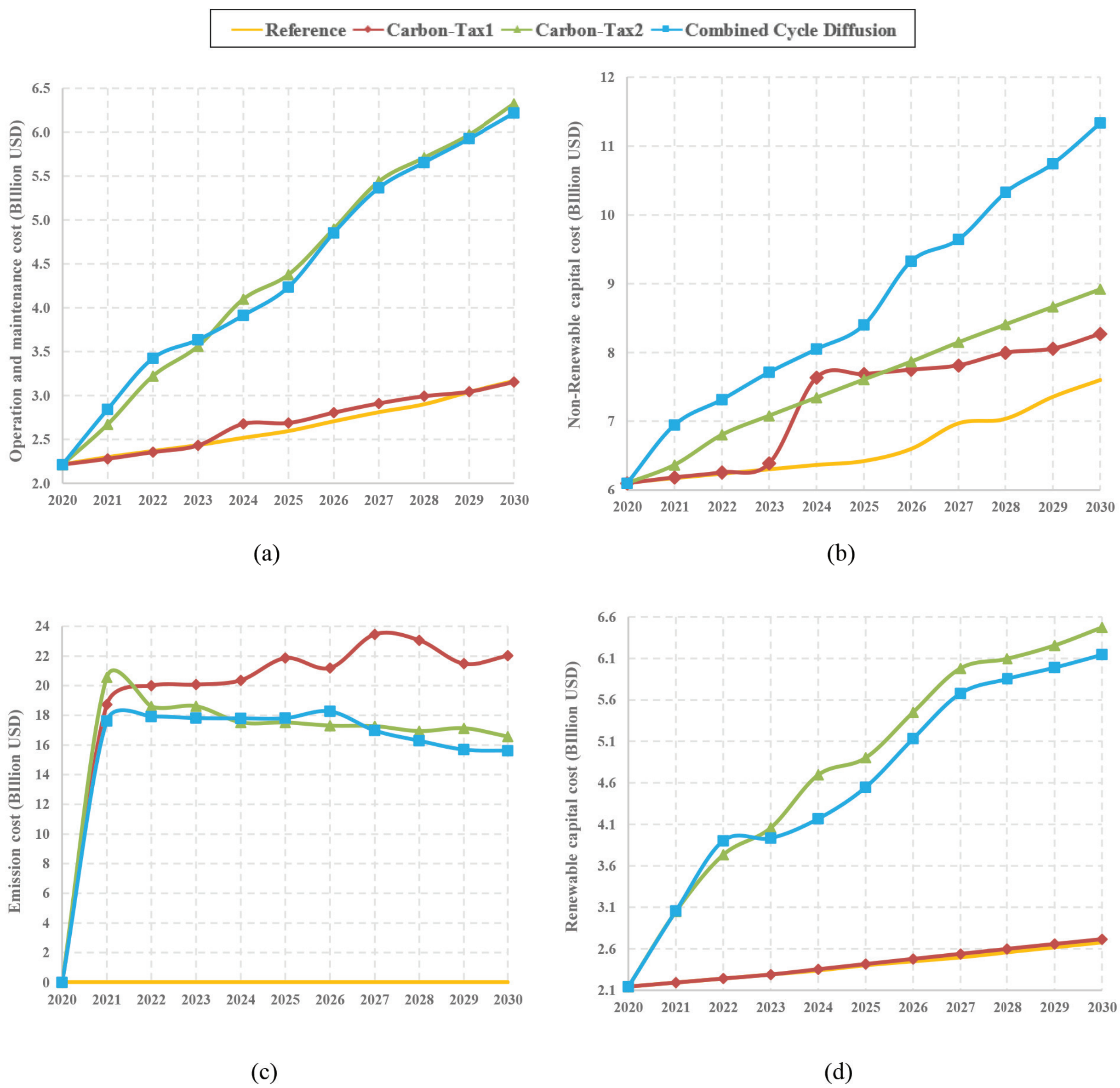

Figure 12: Variations of total GHGs emissions (a), emission intensity (b), and renewable power plants share in electricity production of supply energy system (c) in different scenarios

Table 7: Final economic values of different scenarios in billion USD

Economic parameter	Reference	CT-1	CT-2	CCD
Profit	9.31	12.01	11.98	13.66
Total cost	46.56	63.20	57.04	59.39
Welfare	11.18	14.29	14.49	16.80

shown in Figure 12-b which presented its highest value in this scenario in 2030.

On the other hand, this scenario has the lowest GHG emission, so it is expected to have lower emission cost than previous scenarios, which is about 15.62 billion USD in the CCD scenario (see Figure 12-c). Also, the government can support renewable power plants by increasing feed-in tariff (FIT), lower-interest loans, and increasing their production share in electricity supply system to 10-20% which were considered in CT-2 and CCD scenarios. Exerting the following driving force has extra expenditure in the form of renewable capital cost that were demonstrated in Figure 12-d.

Finally, three economic values that have various trends in implantation time horizon were calculated in 2030 and were presented in the following table.

As presented in Table 7, CCD scenario has the maximum value of economic parameters rather than other scenarios. Although, CT-1 and CCD scenarios have higher costs rather than other scenarios, but their total revenue and the amount of energy production regarding to each technology are higher than reference and CT-2 scenarios. On the other hand, with adding each driving force, welfare grows in each scenario and energy system will close to ideal conditions in order to welfare maximization.

5. Conclusions

In this paper, we present three ways to prevent increasing GHG emissions in power plant sector each of which has driving forces such as imposing carbon tax on fossil power plants, increasing the share of renewable resources, and improving current technologies using CCPPs.

If the government can encourage the private sector to invest in low-carbon power plants by reforming the electricity market and considers the mentioned driving forces, Carbon-Tax2 scenario is a suitable solution for the mid-term development of power plants in decreasing GHG emission and meeting to Iran's Paris Agreement targets; this scenario can reduce GHG emissions to 195.01 Mt of CO_2 equivalent which is 9.02 units higher than the COP21 criteria.

On the other hand, Combined Cycle Diffusion scenario reduces GHG emissions to 180.67 Mt of CO_2 equivalent (5.33 units lower than COP21 criteria) with a decreasing trend that will be sustainable in the long run even after 2030. So, this scenario is suggested for the sustainable development of the generation sector in Iran. As a result, carbon tax is considered as a driving force to reduce GHG emissions (the only driving force in CT1 scenario), but it is not enough for successfully decreasing the emissions of energy supply system under the COP21 criteria. However, the carbon tax (25 USD/tonne CO_2) is directly coupled with increasing the share of renewable energy production (20% is suggested), especially at low fossil fuel prices.

Nevertheless, at higher fossil fuel prices, this driving force does not significantly affect the share of renewable production. This is because the model already finds optimal use of renewable instead of fossil fuel, and additional penalization trough carbon tax is not needed to reach 20% of renewable share set by the Iranian policy

Indeed, the country can attract international investment by the efficient development of a structure for the reduction of the power plant emissions. However, many barriers currently exist against these scenarios (CT1, CT2, and CCD) in Iran the main ones of which are: the underpricing of natural gas, the absence of environmental taxes, and low FITs of renewable energy.

However, in the current mathematical programing model, variability and natural dynamics of electricity price were not considered, but considering them can improve final results in future investigations. Moreover, using shorter time steps increases modelling complexity and its results can be compared with outputs of operational simulation energy models such as EnergyPLAN [32], which can be considered in future works.

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