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Combining game theory concepts and system dynamics for evaluating renewable electricity development in fossil-fuel-rich countries in the Middle East and North Africa

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ABSTRACT

Renewable electricity development is not a critical concern in fossil-fuel-rich countries in the Middle East and North Africa, where fossil fuels are abundant and accessible. As a result, the growth of fossil-fuel electricity generators reduces renewable electricity competitiveness and slows its development. Since renewable electricity has an insufficient market share (less than 5% of total electricity generation in these countries, according to global statistics), its development should become a priority due to fossil-fuel depletion and demand growth in the future. The present study investigates various scenarios to examine the energy sector's development in countries facing severe competitiveness challenges of renewable electricity. Then, it recommends the most appropriate policies through evaluating the proposed plans' effectiveness. In this regard, a comprehensive framework has been developed by integrating system dynamics modeling, agent-based modeling logic, and game theory concepts. This systemic modeling procedure has several advantages, including formation of a macro policymaking perspective, the analysis of renewable electricity development trends, and the simulation of competitors' and investors' reactions and decisions. In this case, Iran is chosen for the study due to being a representative of these countries, and its data have been used to validate the proposed model. Model validation showed less than 9% error between simulation results and real data. Besides, the simulation results indicated that establishing a competitive market and enacting targeted support policies could stimulate the development of renewable electricity up to the year 2060. A presumed combined policy based on efficient simulated scenarios could increase renewable electricity capacity and market share 5-fold and 6-fold by 2035, respectively. Also, it could improve capacity and market share 8-fold and 10-fold by 2060, respectively.

1. Introduction

Despite the critical nature of developing appropriate strategies for renewable energy development [1], planning for Renewable Electricity Development (RED) in fossil-fuel-rich countries (FFRCs) in the Middle East and North Africa (MENA), where fuel prices and its availability are not a critical concern, receives little attention (Fig. 1). Also, Low penalties, such as a tax on pollutant gas emissions, play a key role in this area. Certain countries' unique circumstances exacerbate the problem. For example, sanctions on oil, petroleum, and natural gas in Iran prevent their export, increasing the tendency for power plants to burn an excessive amount of fuel. The growth of fossil-fuel generation reduces the competitiveness and growth of renewable electricity sources.

The annual reports of the Energy Information Administration (EIA) in 2021 [3] and World Bank [4] revealed that 75% of the world's electricity was generated using non-renewable resources [3]. According to Table 1, this ratio reaches 95% in MENA's FFRCs. If hydroelectric power plants are excluded, it increases to 99%. These countries are mostly contributors to the production of greenhouse gases. Iran, for example, is one of the 20 countries that emit 75% of the world's greenhouse gas [6,7]. However, these countries have

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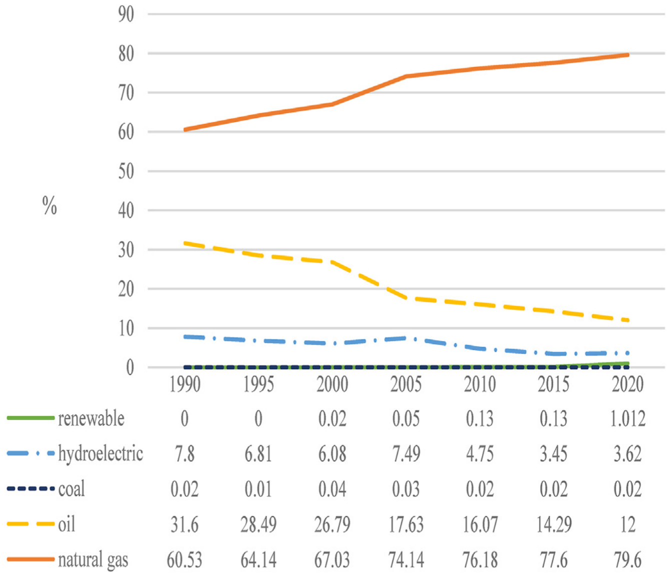


Fig. 1. The share of electricity generated by various sources in MENA's FFRCs [2–5].

Table 1
Renewable electricity market share in MENA's FFRCs [2–5].

Country	Electricity production from renewable resources (% of total)	Electricity production from hydropower resources (% of total)
Saudi Arabia	0.3	0
Iraq	0	3.7
Iran	0.28	7.5
United Arab Emirates	4	0
Qatar	0.2	0
Nigeria	0	18.2
Algeria	0.74	0.2
Oman	0	0
Libya	0	0
Egypt	4.6	6.6
Average	1.012	3.62

enormous potential for developing renewable electricity sources, such as proximity to the equator, direct sunlight, and connection to oceans.

Due to the future depletion of FFRCs in MENA and their high demand for alternative energy sources (the average annual growth rate of global energy consumption is above 1.5% [2,8], due to population growth and energy consumption trends in society [7]), the development of renewable electricity is a challenge that should be addressed immediately. Therefore, it is essential to implement a comprehensive analysis and find the most effective policies for renewable electricity development.

Renewable electricity development analysis requires a holistic approach to examine complex relationships and consider all critical parameters (e.g., dynamic environment, agents' interactions with one another and the environment, competition with other conventional electricity generation, and the shortcomings and conditions of the real world) while assuming price, supply, demand, and uncertainties as endogenous.

The lack of a framework that considers these factors is the primary motivation for the present study. Thus, a comprehensive framework is proposed to analyze renewable electricity trends and policymaking while considering its competition with conventional electricity generation in MENA's FFRCs.

Various approaches have been used for electricity generation expansion planning [9,10]. The three most frequently used methods for describing the long-term behavior of liberalized electricity markets are optimization, econometrics (time series), and simulation models [11,12]. Traditional modeling approaches that are based on the direct relationship between parameters deal with limitations, necessitating the development of new modeling approaches such as Agent-Based Modeling (ABM), System Dynamics (SD), game theory, financial risk modeling, and real options [9].

If the three mentioned dominant market models are distinguished [11], the complex, macro, and multidimensional problems (e.g., electricity market) can be modeled using the facilitation of simulation tools [13]. Selecting a simulation method as a solution has several advantages, including the creation of a long-term perspective, the flexibility of adding and removing variables, the presence of numerous nonlinear functions and constraints, consideration of consecutive impacts, interconnected relations, feedback effects, the absence of mathematical equations, considering time delays, and the ability to define multiple scenarios.

There are two types of simulation models: up to down macro vision with a high degree of integration (e.g., SD) [13] and bottom to up micro vision, with the ability to accept agents' behavioral heterogeneity (e.g., agent-based modeling) [14]. In recent years, various studies evaluated the relationship between these two perspectives and their combination, resulting in a more thorough and precise analysis [15–17].

Also, the planning techniques for the electricity generation expansion can be classified into two principal categories. The first category is the risks, scenario analysis, and real options (based on uncertainty analysis). The second category is the agent-based simulation and game theory (related to competitors' strategic analysis and system). These methods are complementary, which means that comprehensive generation development planning should consider both techniques. In addition, SD can be a supplemental tool for both approaches [9].

Since electricity generation expansion planning is a complex challenge, SD has been used to resolve various energy generation planning and policymaking problems [18], such as investment in renewable electricity capacity expansion [13,19] and evaluation of specific policies for renewable electricity investment growth [20,21] (e.g., feed-in tariffs (FIT) [10,22,23] and carbon tax [24]).

In the energy markets, establishing a competitive environment on price and quantity can encourage the development of a sustainable and renewable energy sector [25]. Recently, researchers have focused on models based on game theory as decision support tools.

The macro perspective causes fundamental micro-mechanisms to be neglected, such as cooperation, competition, sale, and trade between distinct agents [26]. Regardless of SD's effectiveness in establishing a macro vision, excessive integration and ignoring interaction mechanisms between individual agents can result in detail loss and thus model failure. It is self-evident that expanding a model in numerous dimensions introduces new constraints and variables, implying that algorithms cannot solve the model with limited vision [27].

The SD method has been combined with various concepts in other studies, increasing its flexibility and correspondence to reality [28,29]. For example, research has been published based on combining game theory with SD [30–32] and incorporating evolutionary game theory (EGT) into SD [33–36]. Additionally, some studies investigated other aspects, such as sensitivity analysis in SD [37–39], risk analysis in electricity generation investment decision-making [40,41], the analysis of uncertainty effects on alternative energy technologies through the SD and real options approach [42].

Some studies have multiple shortcomings in this area, such as omitting endogenous demand, supply, and price, neglecting

Table 2
A summary of the most recent research relating to policy vision.

Subject	Methodology	Type of energy	Location/ Period	Competition	Game theory	Considered variables				Uncertainty Sensitivity analysis	Support policy
						Technical	Economic	Environmental	Social		
Investigation on the main influencing dynamics in renewable energy development [1]	Simulation-CLD in SD	Renewable electricity				●	●	●	●		TGC
Study on the near future of wind power development [19]	Simulation-SD	Wind electricity	Iran 2004 to 2015			●	●	●	●	●	TGC FIT
Modeling and projection of primary energy consumption by the sources [8]	Econometrics (time-series)	Oil, natural gas, coal, nuclear energy, hydroelectricity	World 1965 to 2010							●	
Renewable energy investment risk evaluation model [40]	Simulation-SD	Renewable energy	China For 10 years			●	●	●	●	●	FIT
Effects of risk aversion on investment decisions in electricity generation [41]	Simulation-SD	Renewable and non-renewable electricity	France 2015 to 2035			●	●	●		●	
Forecasting electrical energy consumption [12]	Optimization Econometrics (time-series) Simulation	Electricity	Iran 1994 to 2005 (131 months)							●	
Modeling long-term dynamics of electricity markets [11,25]	Simulation-SD	Electricity	2000 to 2020	●		●	●			●	
Modeling sustainability of renewable energies [13]	Simulation-SD	Renewable energy	Iran for 50 months				●	●	●	●	Increasing traditional alternative energy prices Social acceptance
Model long-term investments in electricity generation [29]	Simulation (SD) Optimization	Companies that can invest in renewable and non-renewable electricity	Spain 2005 to 2025	●	●		●			●	
Assessment of the effects of capital subsidies and feed-in tariffs [20]	Simulation-SD	Solar PV	Taiwan 2001 to 2030			●	●			●	FIT Support in initial investment cost
Investment incentives in the electricity market [21]	Simulation-SD	Electricity (LNG, oil, coal, nuclear, and hydroelectricity)	South Korea 2006 to 2020	●		●	●			●	Capacity payment
Role of feed-in tariff policy [22]	Simulation-SD	Solar PV	Malaysia 2010 to 2050			●	●			●	FIT
A comparative study of FIT and renewable portfolio standard (RPS) policy [43,44]	Optimization	Renewable and non-renewable electricity		●	●		●	●		●	FIT RPS
Assessment of the dynamics of feed-in tariff policy [23]	Simulation-SD	Renewable electricity	Iran 2015 to 2035			●	●		●	●	FIT
Evaluating effects of feed-in tariff [10]	Simulation-SD	Renewable and non-renewable electricity	Malaysia 2010 to 2030	●		●	●	●		●	FIT
Performance of China's emissions trading scheme (ETS) [45]	Econometrics (time-series)	Electricity and other industries	China 2006 to 2015				●	●		●	ETS
Model of competing for electricity generation technologies [46] and exploration of the complexity and deep uncertainty [39]	Simulation-SD	Renewable and non-renewable electricity	Europe 2006 to 2100	●		●	●	●		●	Combination of different kinds of support programs
Analysis of the government and power producers [36]	Simulation (SD) Optimization	Power producers	China	●	●		●	●		●	Carbon trading market
Analysis of China's wind power development [47]	Simulation-SD	Offshore and onshore wind electricity	China 2012 to 2032	●		●	●			●	FIT

(continued on next page)

Table 2 (*continued*)

Subject	Methodology	Type of energy	Location/ Period	Competition	Game theory	Considered variables				Uncertainty Sensitivity analysis	Support policy
						Technical	Economic	Environmental	Social		
Analysis of renewable energy development [48]	Simulation-SD	Renewable electricity	USA 2010 to 2030			●	●				
Comprehensive a multi-stage decision support model for electricity planning [49]	Decision-making techniques Optimization	Renewable and non-renewable electricity	Iran 2013 to 2040	●		●	●	●	●		Incentive or tax policies Correcting the fuel price
Simulating price patterns for tradable green certificates [50]	Simulation-SD	Wind electricity	USA 2006 to 2020	●		●	●	●		●	TGC Carbon price
Investigation of the effects of subsidies [51]	Simulation-SD	Solar PV	Iran 2014 to 2050	●		●	●	●	●	●	Subsidy
Current research											
Evaluating renewable electricity development and presenting policy implications	Simulation-based optimization-SD and ABM concepts	Renewable and non-renewable electricity	FFRC in MENA 2010 to 2060	●	●	●	●	●	●	●	Combination of different kinds of support programs

competition between participants and energy generation technologies, omitting strategic games and logical behavior, ignoring technology growth, and disregarding combinations of different support policies [23]. Table 2 compares various aspects of the previous studies in this field.

The present study addresses these shortcomings through a novel combinational approach that utilizes SD and ABM concepts. This comprehensive framework has been developed to consider further aspects of the problem, such as competition and the problem's dynamics. This study illuminates the most influential dynamics in renewable and non-renewable electricity ecosystems, which informs policymakers and investors in this field through determining each one's market share. Although various uncertainties (e.g., technical risk, market risk, and regulatory uncertainty [40,41]) exist in electricity generation investments, the present study provides a more precise approximation of the current situation and the consequences of implementing various support plans, which result in the profitability and development of renewable electricity.

This paper is organized as follows. Section 2 expresses the research methodology. In this section, the problem modeling is carried out using the SD method and the principles of ABM. Then, the conceptual model of renewable electricity development is described in section 3. In this regard, the major effective dynamics of the problem are stated. Section 4 is focused on representing the proposed model considering the competition. After the validation process, the model results are extracted using market mechanisms in various scenarios in section 6. Finally, some recommendations regarding the development of renewable electricity are made in the policy implications section.

2. Research methodology

Expansion planning for electricity generation is a complicated issue, which involves many technical, economic, environmental, and social variables with mutual interactions. This complexity demonstrates the importance of developing a comprehensive framework to provide a realistic vision of the problem and analyze different scenarios. Solving this complex and multidimensional problem cannot be accomplished in a single step. The main steps of this research are depicted in Fig. 2. In the first step, the previous literature and reports are studied to identify the system and clarify the factors, variables, subsystems, and dynamics involved in developing renewable electricity. The second step identifies the problem's most influential variables through renewable energy industry experts. At the same time, the third step determines the most appropriate approach for resolving the problem.

As previously stated, SD serves as the solution's foundation due to its macro-level approach and feedback perspective. Despite its numerous advantages, it cannot simulate all aspects of the problem, including considering each agent's conditions, the effects of agent interactions, the agents' competitive behavior analysis, complex situations (e.g., electricity market [52]), and finding Nash equilibrium. As a result, it is necessary to use another simulation approach apart from the primary method. Thus, a framework is proposed by combining SD with the ABM concepts and considering sensitivity and uncertainty analysis tools. This procedure has been developed due to the high complexity of the interactions between players in the electricity market [53]. Also, it was based on considering a study on modeling approaches for integrated environmental evaluation and management and their corresponding application [54] and investigations on the possibility of combining SD and ABM [16,55,56]. This framework is applicable for a comprehensive analysis of RED trends in a dynamic competitive electricity market and assessing the effectiveness of development policies.

After defining the system's boundaries and selecting a comprehensive evaluation framework in the fourth step, it is possible to create a conceptual model containing mechanisms and balancing and reinforcing loops that affect the subsystems of RED. This procedure is performed through the Causal Loop Diagram (CLD) to demonstrate variables using the SD approach.

The developed model is run from 2010 to 2060 in Iran's oligopoly electricity market, as an example of an FFRC in MENA. In this case, the 2010 to 2021 period validates the model using the historical data, and the 2022 to 2060 period is considered to observe the effects of support policies. To this end, the fifth step collects data from 2010 to 2021 and formulates a dynamic hypothesis. Afterward, the proposed model is developed as a Stock Flow Diagram (SFD) based on the conceptual model. The model is verified and validated in the sixth step. Modeling is a recursive process, not a sequential one. In the seventh step, the development trends of the renewable and non-renewable electricity sources are simulated and evaluated using various scenarios during 2022–2060. In the final step, appropriate implications for RED are proposed based on real-world circumstances.

3. Conceptual model of renewable electricity development

In contrast to Refs. [20,22], which neglected environmental and social mechanisms and assumed some variables were exogenous, actions such as excessive integration, unnecessary simplification, disregarding the relationship between specific sub-sections such as demand and supply of electrical energy [31,32], omitting the market's effect on development [23,48], and failing to consider the mechanisms underlying the tendency to invest in power plant construction [48] cause failure or inefficiency of the model.

Following a review of the literature [23,24,41,57] and model boundaries [19,58], the dynamic variables and hypotheses affecting RED in FFRCs in the MENA have been identified. Besides, the subsystems and their dynamics were specified by consulting with renewable electricity experts. Fig. 3 depicts the causal relationships between path dependency [31,32,59], supply, demand, and price [25], investment based on benefit-to-cost ratio [10], learning effect [13,39,60], social acceptance [23,61], competition [25], uncertainty [40,62], resource depletion, and support policies.

The tendency to invest in renewable and non-renewable technologies is determined by their profitability and share of the total investment profit in the electricity industry (reinforcing loops R2 and R′2 in Fig. 3). This investment tendency increases by enhancing each power plant's revenue. Also, it decreases by increasing each power plant's cost (i.e., investment costs, maintenance, fuel, taxes, and fines). For example, appropriate pricing can win the electricity market, which increases profitability (balancing loops B2 and B′2 in Fig. 3). Also, the learning effect reduces initial investment costs. This situation results in increased profitability and improved willingness to invest. Consequently, increased development is attained (reinforcing loops R1 and R′1 in Fig. 3).

For simplicity, Wind Power Electricity (because of its maturity [63] and multiplicity [2]) and Combined Cycle Gas Turbine (CCGT) (because of its multiplicity [64]) are used as representative of renewable and conventional technologies respectively in Iran's electricity market.

The conceptual model (Fig. 3) includes three main balancing loops: resource depletion (B3 and B′3), price-demand interaction (B1 and B′1), and price-supply interaction (B2 and B′2). Also, it contains two main reinforcing loops: path dependence according to benefit to expenditure ratio (R2 and R′2), and learning effect (R1 and R′1), which affects the RED. In this regard, it is necessary to consider the existing uncertainties, social acceptance, and support programs that enhance or reduce the loops' effects.

4. Proposed model of renewable electricity development

As shown in Fig. 3, the dynamic hypothesis and CLD were formulated as SFDs in Vensim software. It is essential to develop mathematical functions between variables and numerical parameters in Vensim software. This procedure is performed to create a mathematical model using SFD. This section discusses the most important mathematical functions used in the proposed model, which were derived from previous studies [23,65,66]. In addition, the numerical data in Table 3 are used as system parameters during the simulation.

As mentioned in Section 3, path dependency [59] is one of the primary dynamics of the system (illustrated in R2 and R′2 in Fig. 3), affecting development of the power plants. This situation occurs in the MENA's FFRCs electricity market. Despite the benefits of

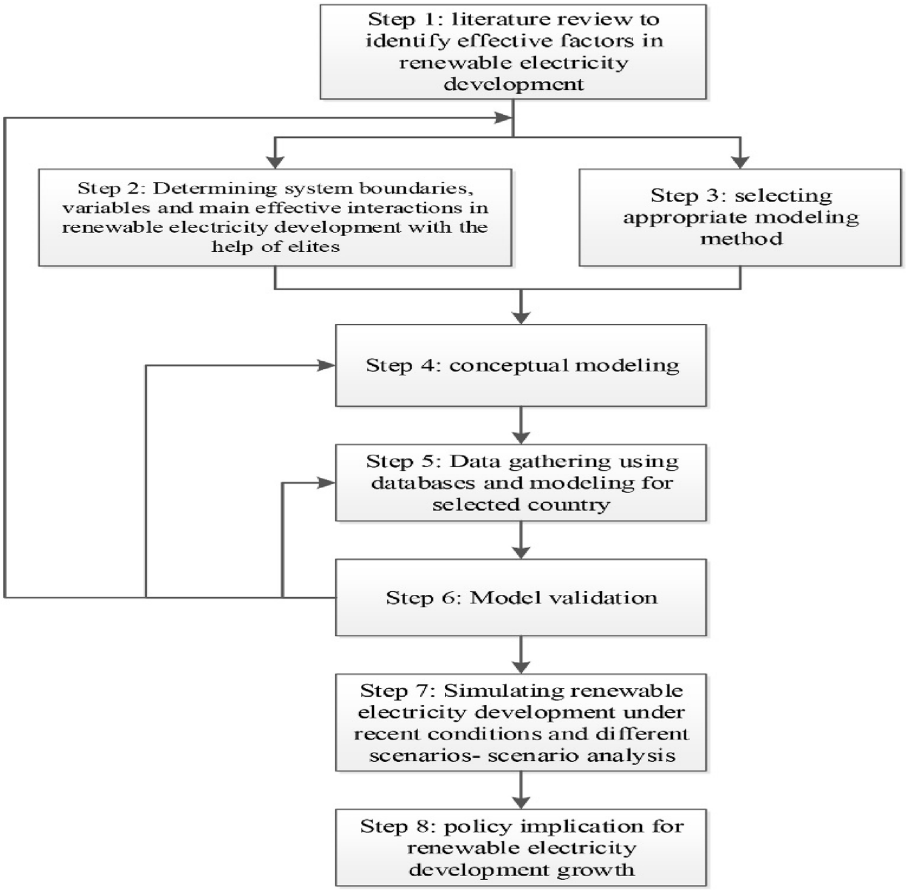


Fig. 2. The step-by-step procedure for the research methodology.

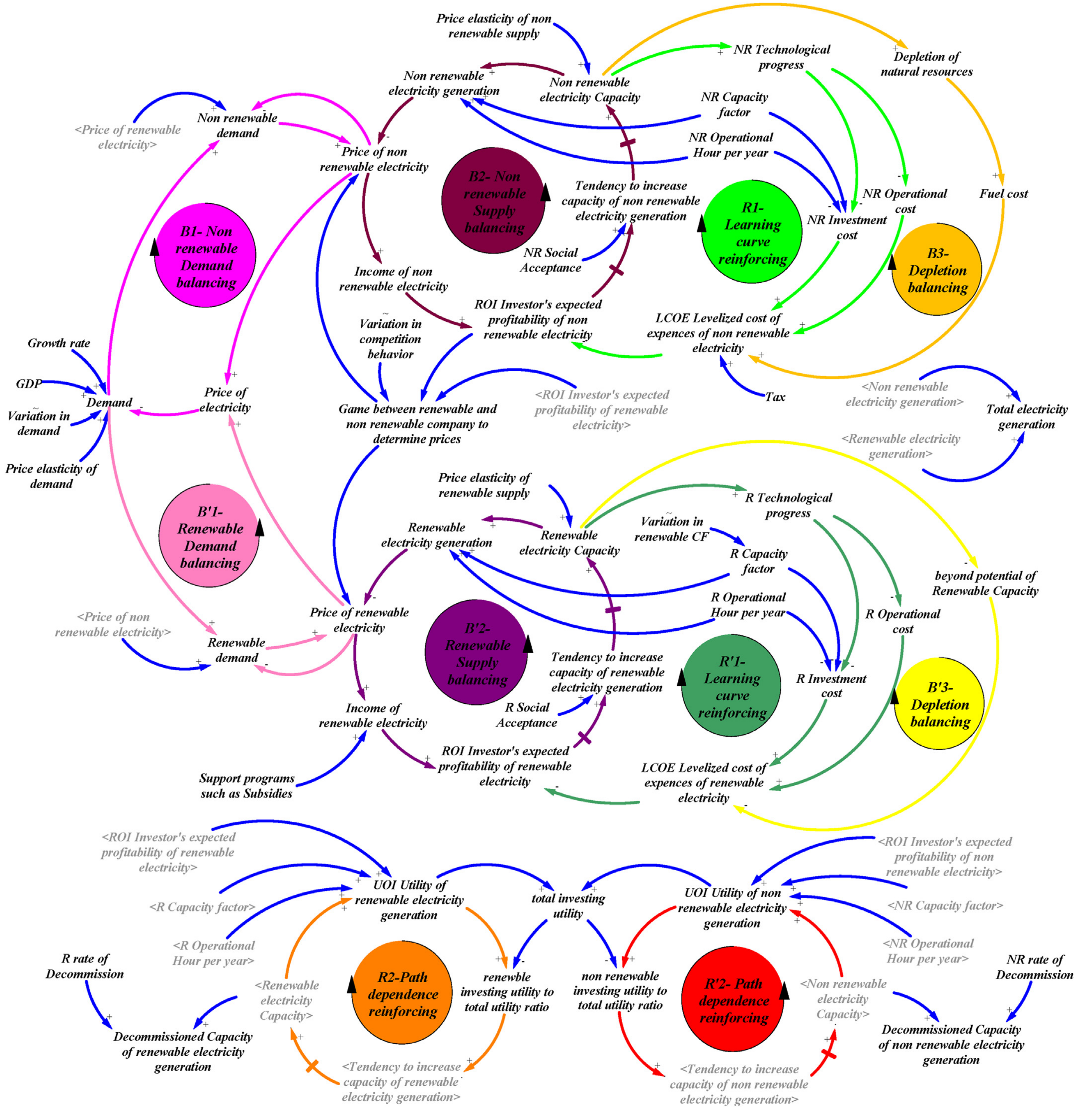


Fig. 3. Market dynamics and main effective loops in developing renewable and non-renewable electricity generation.

renewable energy, new fossil-fuel power plants are constructed year after year because of economic profit [49]. Indeed, path dependency depends on several factors, such as comprehension of the game's rules, market strength (market share), an adaptation with facilities and equipment, and complementary commodities.

The price of any type of power decreases by more generation (B2 and B′2 in Fig. 3). As a result, profit declines because of price and raises because of higher sales, and the other way around if power generation declines. Power plants appraise their electricity properly using logical rules to achieve a benefit and expenditure ratio (Return on Investment, or ROI) higher than their competitors due to price and generation volume. The annual ROI of power plants (Eq. (1)) is used as an index for Willingness for Investment (WFI). It is one of the most critical model variables for development investment [10,23]. WFI includes income, expenditure, and profit.

In this model, it is assumed that the total income generated by power plants comes from selling electricity so that service provision and reserve capacity are omitted. The Levelized Cost of Energy (LCOE) of a combined cycle gas turbine (CCGT) power plant is calculated using Eq. (2). Also, the LCOE of a wind power plant is

Table 3
Model parameters for wind and CCGT power plants (Ref. [64]).

Parameters	Value		Unit
	Wind Turbine	CCGT	
• Discount Rate (r)	15	15	%
• Escalation Rate (e)	2	2	%
• Depreciation Rate (DR) or Fixed Charge Rate (FCR)	5	5	%
• Plant Lifetime (PL)	30	30	year
• Physical Construction Lifetime/Delay (CL)	2	4	year
• Informational Construction Delay (time to adjust investment)	2	2	year
• Annual Initial Investment Cost for 2010 (IIC_{2010}) or Total Plant Cost (TPC)	1250	700	$\left[\$/_{KW}\right]$
• Fixed O&M Cost (FOM)	20	4	$\left[\$/_{KW\ in\ year}\right]$
• Variable O&M Cost (VOM)	0.001	0.0025	$\left[\$/_{KWH}\right]$
• Natural Gas Price (NGP) or Fuel Cost (FC)	0	0.3	$\left[\$/_{MMBTu}\right]$
• The Heat Rate (HR) for natural gas	–	0.00643	$\left[MMBTu/_{KWH}\right]$
• Emission Factor (EF)	–	$\begin{bmatrix} 60000 \\ 200 \\ 25 \\ 0.85 \\ 1 \\ 9 \\ 1.5 \\ 0.15 \end{bmatrix}$	$\left[gr/_{MMBTu}\right]$
• Unit Emission Cost (UEC)	–	$\begin{bmatrix} 0.0000178 \\ 0.00107278 \\ 0.00326289 \\ 0 \\ 0.000335222 \\ 0.00768789 \\ 0.000374222 \\ 0 \end{bmatrix}$	$\left[\$/_{gr}\right]$
• Initial Installed Power Capacity	92900	13983500	KW
• Capacity Factor (CF)	35	75	%
• Operational hours per year (HY)	8322	7728	hour
• Learning Factor ($\alpha_{learning}$)	10	10	%

computed using Eq. (3). In addition, the Levelization Factor (LF) is defined in Eq. (4), and the Externality Costs (EC) are formulated by Eq. (5) [65,66]. An industry that produces more pollution does not usually become accepted by society because of its damage and global attention. Initial Investment Cost (IIC) decreases with time due to the learning effect (R1 and R′1 in Fig. 3). IIC is proportional to Total Installed Capacity (TIC) and Decommissioned Capacity (DC) (Eq. (6)).

$$\%ROI = \frac{profitability}{Expence} = \frac{Income - Expence}{Expence} = \frac{Income - LCOE}{LCOE} \tag{1}$$

$$LCOE_{WT}\left[\$/_{KWH}\right] = \left[\frac{DR \times IIC(1+r)^{CL}}{HY \times CF}\right] + \left[LF \times \left(\frac{FOM}{HY \times CF} + VOM\right)\right] \tag{3}$$

$$\%LF = \frac{r(1+r)^{PL}}{(1+r)^{PL} - 1} \times \frac{1+e}{r-e} \times \left[\left(\frac{1+r}{1+e}\right) - \left(\frac{1+e}{1+r}\right)^{PL}\right] \tag{4}$$

$$EC\left[\$/_{KWH}\right] = EF \times UEC \times HR \tag{5}$$

$$IIC_t\left[\$/_{KW}\right] = IIC_{t-1} \times \left(1 - \alpha_{learning} \times \log_2\left(\frac{TIC_t + DC_t}{TIC_{t-1} + DC_{t-1}}\right)\right) \tag{6}$$

Iran's economic parameters in the electricity market are provided in Table 3. These parameters were derived from the country's energy balance sheet and used to run the simulation and extract final results.

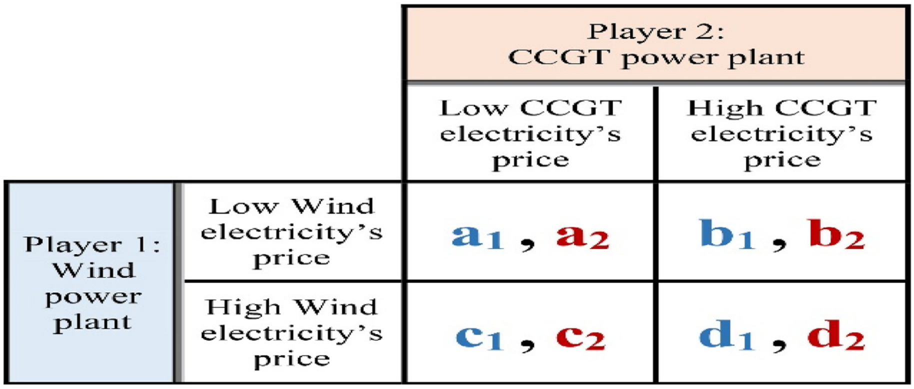
Due to the price elasticity of substitute goods, pricing and generation decisions affect both the player's ROI and the ROI of other competitors. As a result, an equilibrium point reaches if all players' ROIs maximize compared to all other competitors' strategies. The framework presented in this research can help answer the question of what price is acceptable for power plants to continue their growth trend, considering the problem's effective dynamics.

As previously stated, if wind and CCGT power plants are assumed to represent renewable and non-renewable electricity, respectively, two bidding strategies for two players can be considered. The first strategy is a low price to gain market share through increased sales, and the second strategy is a higher price to maximize profit, resulting in four distinct price situations. Thus, the ROIs of each player must be calculated for each situation. In this case, a_1, b_1, c_1, and d_1 are the wind power plant's ROIs, while a_2, b_2, c_2, and d_2 are the CCGT power plant's ROIs in four situations (Fig. 4). As a result, eight ROIs are calculated to determine the optimal strategy and a balancing point for two players in four situations. Modeling to calculate each ROI is possible in multiple views of the Vensim software. ROIs change dynamically, and their results are continuously incorporated into the competitive game to determine Nash equilibrium.

Incorporating ABM and evolutionary game theory (EGT) concepts into SD allows each component to have its own behavior and avoids the limiting assumptions of game theory. Although a precise solution of the game results only in discovering the balancing point, EGT not only dynamically converges to the balancing point, but also displays the path that leads there [67]. EGT is extremely useful for analyzing the long-term behavior of multiple players [34].

As illustrated in Fig. 5, the values of ROIs are calculated as outputs of SD simulation and entered into the agent-based model as inputs for the game. The game's outcome between agents (players), which is the output of ABM, varies according to the value of each ROI. Finally, players' behaviors are used as inputs for the SD model, altering its variables, and the loop is repeated. Each loop in the evolutionary game algorithm acts as a generation, bringing the

$$LCOE_{CCGT}\left[\$/_{KWH}\right] = \left[\frac{DR \times IIC(1+r)^{CL}}{HY \times CF}\right] + \left[LF \times \left(\frac{FOM}{HY \times CF} + VOM\right)\right] + [LF \times NGP \times HR] + EC \tag{2}$$



		Player 2: CCGT power plant	
		Low CCGT electricity's price	High CCGT electricity's price
Player 1: Wind power plant	Low Wind electricity's price	a_1 , a_2	b_1 , b_2
	High Wind electricity's price	c_1 , c_2	d_1 , d_2

Fig. 4. Player's payoff.

model closer to the Nash equilibrium. It is observed that a two-way data stream exists between SD and ABM.

The outcome of the game (probability of final bidding selection) is related to the reward. In this case, p and (1-p) represent the probability of selecting low and high wind energy prices, respectively, while q and (1-q) are the probability of choosing low and high CCGT energy prices, respectively (Fig. 6).

$$\begin{cases} E_p = q \times a_1 + (1-q) \times b_1 \\ E_{1-p} = q \times c_1 + (1-q) \times d_1 \\ E_q = p \times a_2 + (1-p) \times c_2 \\ E_{1-q} = p \times b_2 + (1-p) \times d_2 \end{cases} \rightarrow \begin{cases} \overline{E}_{p.\ 1-p} = p \times E_p + (1-p) \times E_{1-p} \\ \overline{E}_{q.\ 1-q} = q \times E_q + (1-q) \times E_{1-q} \end{cases} \tag{7}$$

$$\begin{cases} \dfrac{dp}{dt} = p \times \left(E_p - \overline{E}_{p.\ 1-p}\right) = coefficient\ p \times \left(E_p - E_{1-p}\right) = p \times (1-p)(q \times (a_1 - c_1) + (1-q) \times (b_1 - d_1)) = 0 \\ \dfrac{dq}{dt} = q \times \left(E_q - \overline{E}_{q.\ 1-q}\right) = coefficient\ q \times \left(E_q - E_{1-q}\right) = q \times (1-q)(p \times (a_2 - b_2) + (1-p) \times (c_2 - d_2)) = 0 \\ where\ coefficient\ p = p \times (1-p) \\ where\ coefficient\ q = q \times (1-q) \end{cases} \tag{8}$$

If the ROI of wind energy increases as the market price increases, the value of p decreases. Otherwise, this value increases. Additionally, if the ROI of a CCGT power plant increases with a high price offer, the q value decreases. Otherwise, this value increases. Each power plant's most suitable price offer is obtained at the equilibrium point.

In Fig. 6, E_P denotes the utility of a wind power plant if it chooses a low price, whereas CCGT can either choose a low or high price. E_{np} or E_{1-p} is the utility of a wind power plant if it bids at a high price, whereas CCGT either bids at a low or high price. Also, Eq is the utility of CCGT if it chooses a low price in the market, while the wind chooses either a high or low price. In addition, E_{nq} or E_{1-q} is the utility of CCGT if it selects a high price in the market, while the wind selects either a high or low price. These utility values represent each player's utility in each scenario. The variables $\overline{E}_{p.\ 1-p}$ and $\overline{E}_{q.\ 1-q}$ that characterize each player's average utility are calculated by Eq. (7).

Equilibrium exists when players have no intention of changing their bidding strategy to increase their profit [33–36] (Eq. (8)).

The SD method and ABM concepts are combined as a compound embedded model in the proposed framework to analyze competition through EGT, which necessitates running both models simultaneously. Thus, a comprehensive and integrated framework is created [16].

Array variables from the SD program are utilized to integrate SD and ABM in Vensim software [26,68,69]. These array variables are easy to use, but they have some drawbacks, such as fixed model structures and difficulties in simulating complex events. Thus, these issues can be resolved by presenting the model in multiple views in Vensim software or utilizing a module-oriented concept rather than the array tool [70].

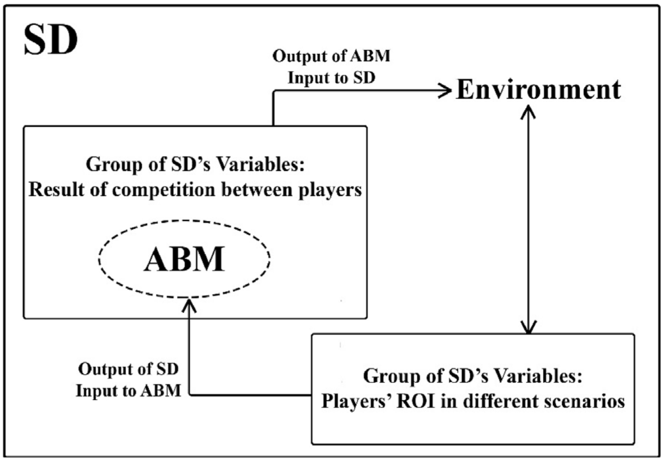


Fig. 5. Two-way information flow between system dynamics and agent-based modeling concepts.

According to Eq. (9), the Utility of Investment (UOI) in each power plant depends on the ROI of each player. It has been determined by the competition of players (EGT described in Fig. 6) and the power generated by the power plant. This generated power is calculated by multiplying Total Installed Capacity (TIC), Capacity Factor (CF), and operational hours per year (HY).

$$U[KWH] = ROI \times CF \times HY \times TIC[KW] \tag{9}$$

UOI is influenced by the phenomenon of path dependence (R2 and R′2 in Fig. 3). A greater UOI of a particular type of electricity compared to the overall UOI of the electricity industry attracts more investors, and thus the sector grows. All disincentives and incentives will affect renewable energy development by affecting the UOI variable.

In this research, the hybrid model can provide a novel and powerful tool to investigate the performance and consequences of development policies in a virtual environment while considering the influence of players' interactions. Also, this hybrid model can be utilized to evaluate the renewable energy industry's uncertainties and their impact on the energy sector's development process.

The present study is not focused only on an electricity market simulation or a game optimization between electricity market participants. Indeed, it is a simulation-based optimization that attempts to provide a comprehensive view of the problem. To this end, the simulation or exogenous part of the game, analyzes the dynamics of market processes and the relationship between supply, demand, and price. In contrast, the optimization part analyzes the finding process of the Nash equilibrium to determine the price in a competitive environment using EGT or the endogenous part of the game.

5. Model validation

Generally, validating the models presented in soft systems (e.g., SD method) is challenging and frequently depends on their ability to generate and improve an overall understanding of the dynamic interrelationships between problem subsystems. This procedure identifies trends instead of historical correspondence and accurate future predictions [59]. The model's validity is evaluated using several tests to ensure that the model's results are accurate. To this end, the proposed model is validated using the following techniques: boundary adequacy, structure assessment, dimension consistency, parameter verification, extreme conditions, sensitivity analysis, behavioral assessment, reproduction test, and comparison to historical data or integration error [58]. These tests were conducted on the consensus of a committee of renewable electricity industry elites. Also, the correspondence with other studies [23,24,48] has been admitted. The calculated error in the simulation results was less than 9% between 2010 and 2021 (see Fig. 7), which is an acceptable value because of the high complexity of the problem.

The system's behavioral validity was approved by the similarity between the model's behavioral trends and the most recent research conducted in similar conditions. Several studies (e.g., Mousavian et al. [23] and Eftekhari et al. [51]) investigated effects of various RED policies. According to Ref. [23], the installed capacity of renewable electricity in Iran (excluding hydropower) could reach 4.5–14 GW (GW) by 2035. In this case, the market share was between 4 and 13%. Since wind power accounts for approximately 35% of Iran's renewable electricity generation (excluding hydropower) [64], the proposed model's simulation results indicate that the total capacity of renewable electricity generation (excluding hydropower) can range between 2.2 and 12.7 GW with a market share of 1.3–8.8%. This finding is consistent with the range obtained in Ref. [23]. Also, the upward trend in the renewable electricity

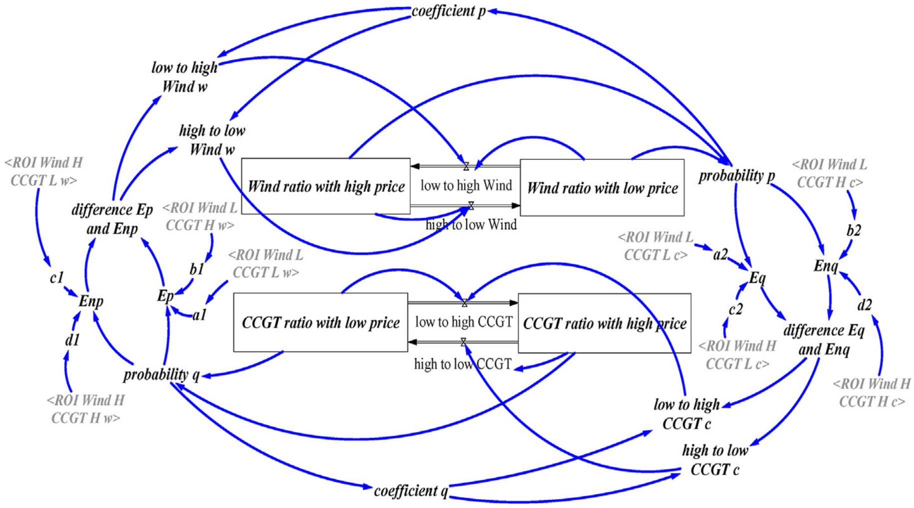


Fig. 6. SD model for the evolutionary game between wind and CCGT power plants.

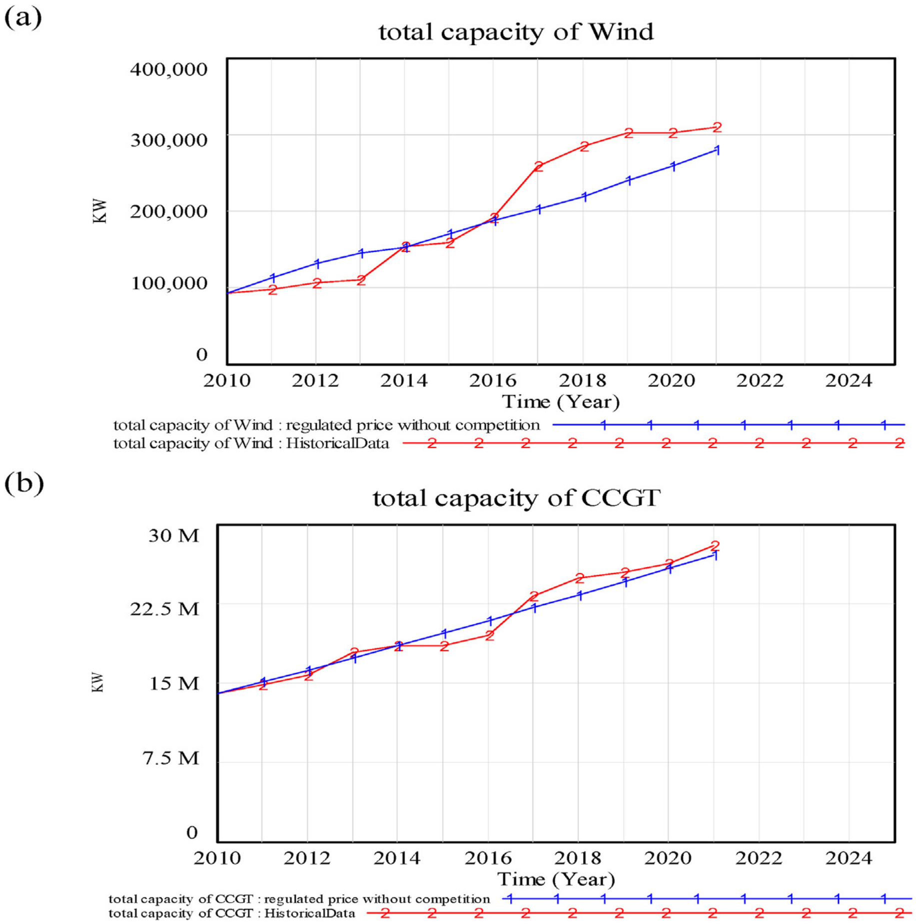


Fig. 7. (a, b). Historical data and simulated electricity capacity.

share is consistent with the upward trend estimated in Ref. [51]. The observed curvature of the CCGT market share in this study is matched with the curvature of greenhouse gas emissions between 2030 and 2040 reported in Ref. [51].

6. Result and discussion: simulation results under different scenarios

After validation, the model output has been used to analyze the wind power's electricity development trend in Iran using various scenarios and identify effective support policies. The LCOE of CCGT power plants is low in MENA's FFRCs, such as Iran, and the investment in CCGT power plants is profitable. In Iran, the electricity industry is dominated by fossil fuels. Other non-fossil electricity sources are less profitable and deal with significant challenges in the development path. According to the model's results, line 1 of Fig. 8 indicates that the results are consistent with other studies in Iran [19] and Iran's energy balance [64]. Wind power generation did not cover the gap between current conditions (310200 KW of installed wind energy by 2021) and defined goals (achieving 5 GW of renewable energy by 2021) under current trends and policies.

The results indicate that if the current situation with regulated prices and no support policies is maintained, wind energy growth will be deficient, while CCGT electricity growth will be rapid (line 1 of Fig. 8 (a, b)). If rational behavior prevails in the market and prices fluctuate in response to supply and demand, this factor favors wind power development (line 2 in Fig. 8 (a)). Also, this development occurs more quickly if the electricity market is competitive [71] (line 3 in Fig. 8 (a)). According to the lines in Fig. 8 (a), establishing a competitive market is beneficial for developing renewable electricity and accelerates its growth [71]. However, this level of development is insufficient. Thus, a combination of support policies along with market competitiveness or reasonable pricing is required to boost wind power generation [49].

6.1. Supporting policies

The modeling framework can perform sensitivity analysis, determine the equilibrium answer for each player, and simulate the decision variables and development trends of renewable electricity in different scenarios. Eight support policies are defined for RED based on the executive policies in various countries [19,23,49,71] and the support plans suggested in the Renewable Global Status Report (REN21) [2], which was proposed by the electricity industry experts. Assuming their implementation, and the possibility of renewable energy competition establishment in the competitive electricity market starting in 2022, their effects are examined through 2060. Each of these policies affects the UOI of every power plant. Also, the effects of each policy on wind power capacity and market share are depicted in Fig. 9 (a) and Fig. 9 (b), while their influences on CCGT power capacity and market share are displayed in Fig. 10 (a) and Fig. 10 (b), respectively. In addition, their impacts on wind energy and overall electricity prices are shown in Fig. 11 and Fig. 12, respectively.

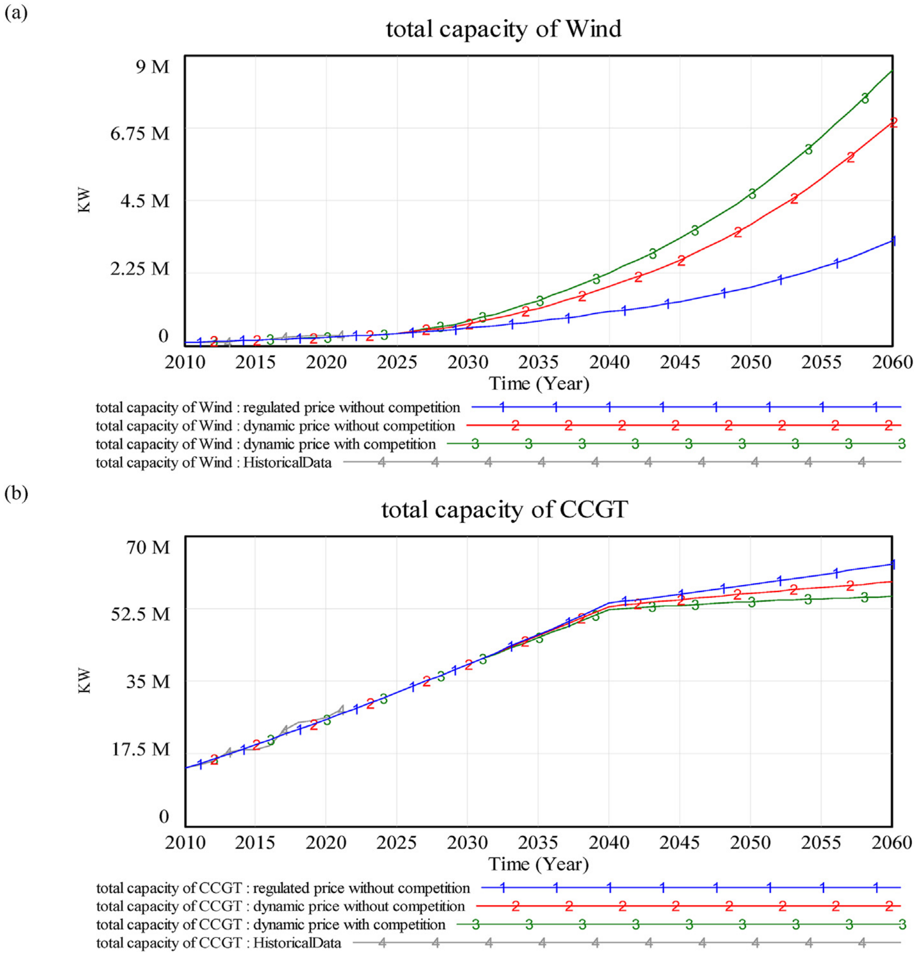


Fig. 8. (a, b). Wind and CCGT power plant capacity trends in Iran under current conditions and the effect of competition on wind electricity development in Iran.

- Direct renewable electricity generation subsidies

Under this policy, renewable energy producers are compensated a fixed amount per kilowatt-hour of electricity generated, which is gradually reduced as their market share increases. Besides, this policy is referred to as closeness to the goal [23] (line 9 in Figs. 9–12).

- Tax on pollution emission

This policy imposes a tax on polluting fossil-fuel power plants. The tax decreases the UOI of fossil-fuel power plants, and its effectiveness increases by enhancing the external and environmental costs of pollutants [24] (line 8 in Figs. 9–12).

- Tax on pollution emission and redistributing the revenue to wind energy production

This policy collects taxes from polluting power plants and invests them in renewable energy generation. The implementation of this policy avoids budget deficits associated with subsidy policies. Also, it has a more significant impact on development than taxing polluting power plants (line 7 in Fig. 9 (a, b)). This policy reduces the overall price of electricity, which benefits the consumer (line 7 in Fig. 12).

Tax revenue is proportional to the electricity generated by CCGT power plants under this policy. On the other hand, the amounts obtained from polluting power plants are divided by the amount of wind energy generated, yielding a subsidy for generating wind energy per kilowatt-hour. Due to the upward trend in wind energy generation, the subsidy per kilowatt-hour of generated wind energy will decrease. Although the subsidy initially exceeds the direct subsidy, it significantly decreases over time. From the development viewpoint, the effectiveness of this policy is considerably greater than the effectiveness of direct subsidy. (Fig. 9 (a, b)). This fact demonstrates the critical nature of the initial stage of the support measures in wind power development.

- Correction of power plant fuel costs

Since fuel has a low cost in FFRC in the MENA [49], this policy aims to bring the fuel price closer to the global average by doubling the price of fossil fuels used in power plants such as CCGT (line 6 in Figs. 9–12).

- Correction of power plant fuel costs and redistributing the revenue to wind energy production

This policy corrects fuel prices and spends the proceeds on the growth of renewable electricity. Besides, it does not result in a budget deficit and has a more impact on the power plants than the policy of fuel price correction (line 5 in Fig. 9 (a, b)). Overall, electricity prices will decline, benefiting the consumer (line 5 in Fig. 12).

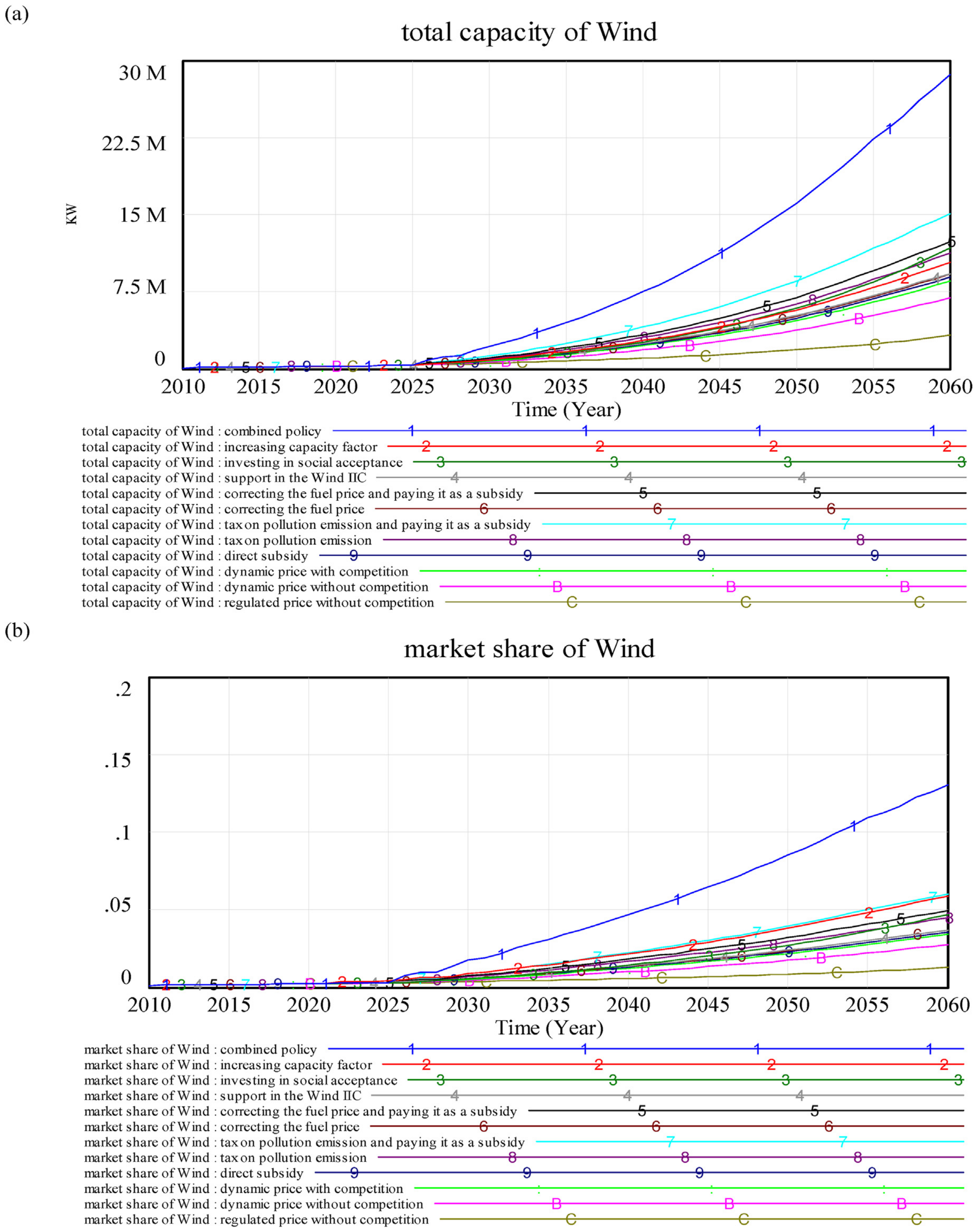


Fig. 9. (a, b). The impact of support policies on the wind power capacity.

- Support in wind power plant IICs

Due to the high IIC in renewable energy [23], the government can increase the profitability of renewable energy investments by accepting a portion of the IIC or facilitating its payment. This policy assumes that the government bears 50% of the IIC. Apart from the fact that it results in a budget deficit for the government, this policy is not acceptable because it has no discernible positive effect on renewable electricity growth (line 4 in Fig. 9 (a, b)) and provides no price benefit to the consumer (line 4 in Fig. 12).

- Investing in social acceptance and raising awareness of renewable power's importance

Social acceptance consists of three dimensions: sociopolitical, community, and market acceptance [61]. It results in a proclivity to

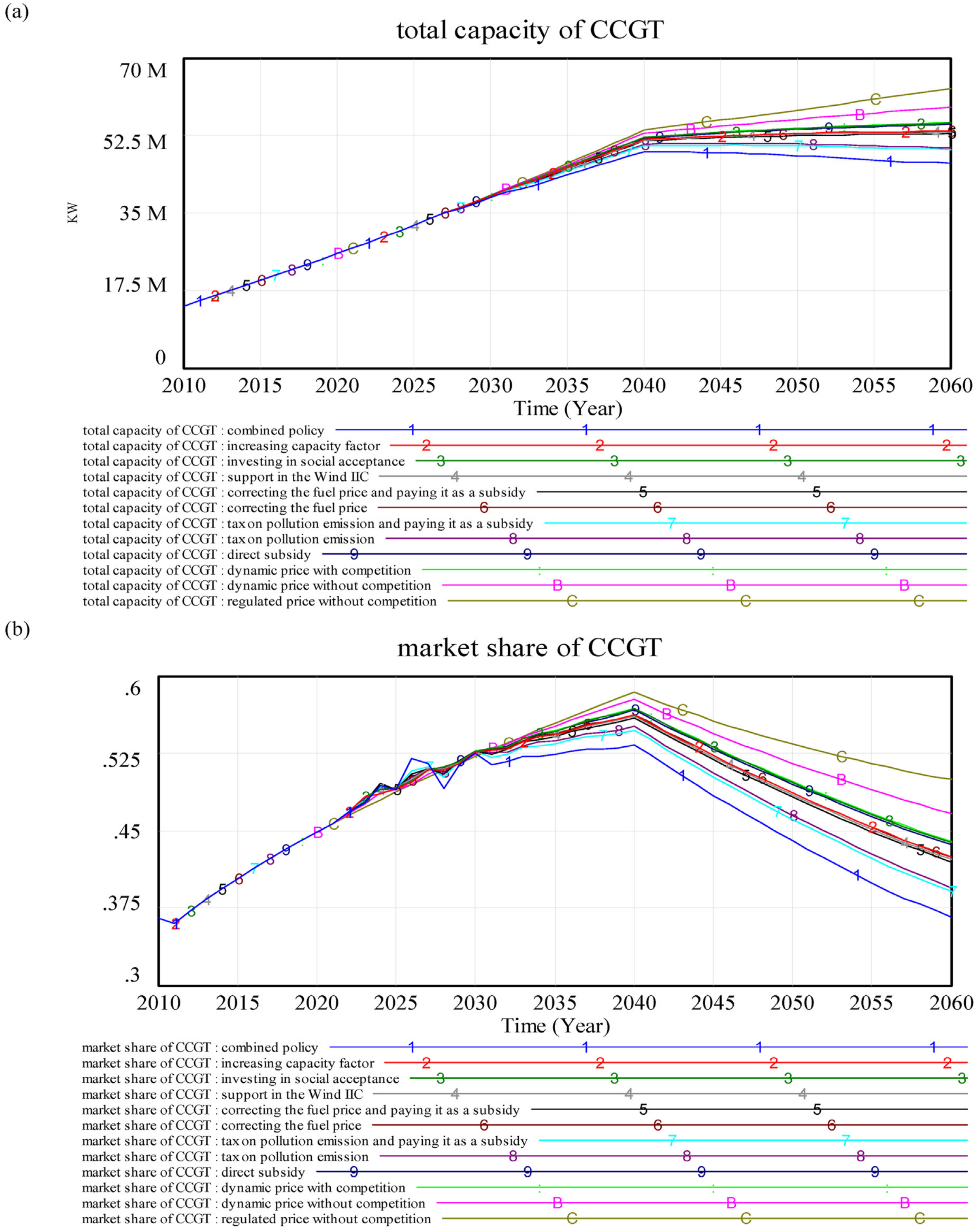


Fig. 10. (a, b). The influence of support policies on the CCGT power capacity.

invest in and consume clean energy, while increasing the social costs of fossil fuels (line 3 of Figs. 9–12).

- Increasing the capacity factor of wind power plants

The model assumes that wind farms' capacity factors increase from 35 to 50%. An increased capacity factor results in higher wind energy generation, improving the renewable energy sector's ROI and UOI. This situation causes increased installed capacity. As a result, the overall price of electricity is reduced, which benefits the consumer (line 2 of Fig. 12).

As shown in Fig. 11, implementing support measures (e.g., adjusting fuel prices and increasing pollutant emissions taxes) enhances the demand for renewable electricity and its price due to a lack of adequate infrastructure for renewable electricity capacity. An increase in profitability causes the development of renewable

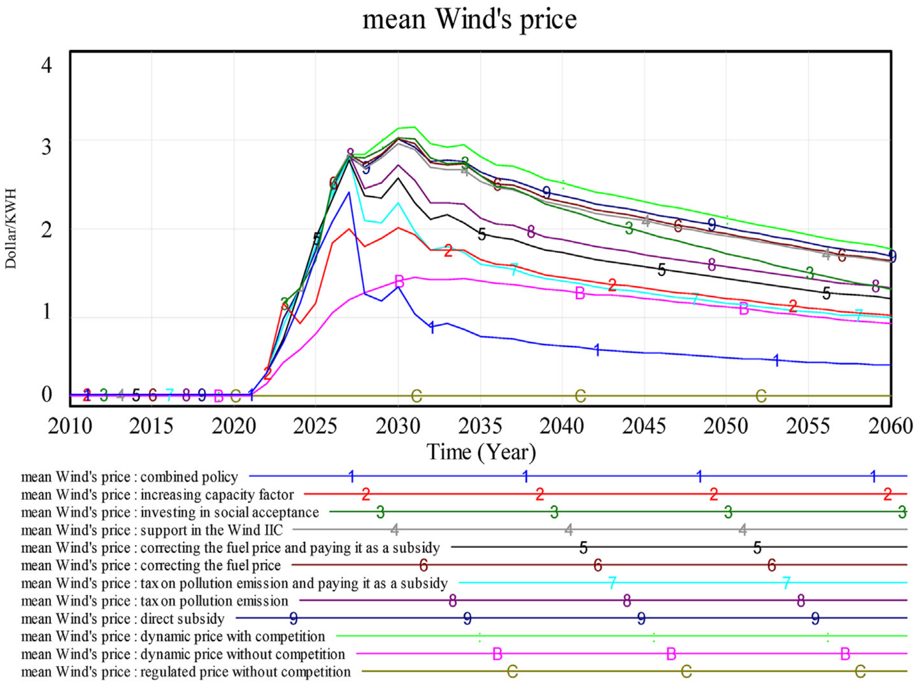


Fig. 11. The impact of support policies on wind power price.

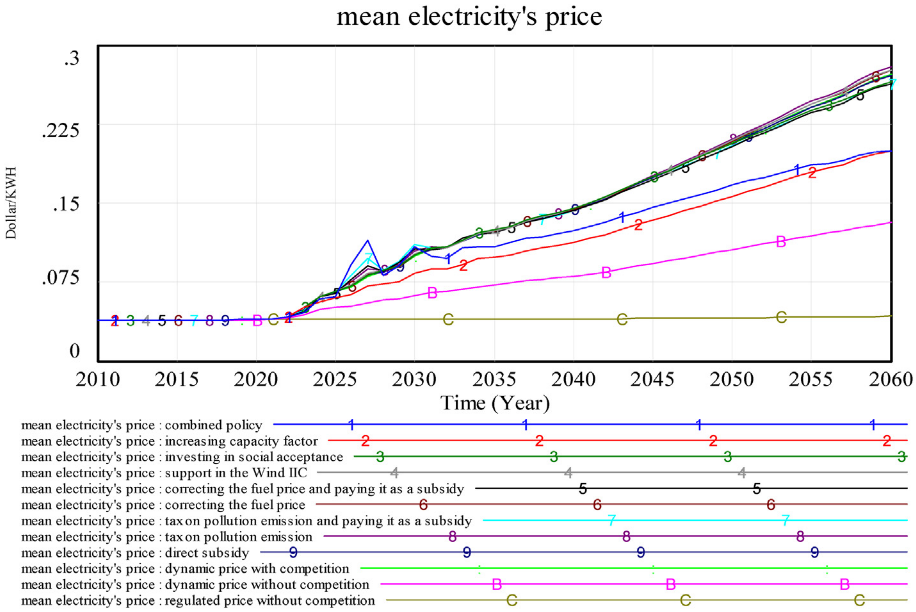


Fig. 12. The effect of support policies on total electricity price.

electricity capacity and pollution reduction (Figs. 9 and 10). Besides, renewable electricity prices are controlled by increasing their production. Developing more renewable electricity sources reduces the growth rate of fossil fuel power plants due to the path dependence phenomenon, and this growth may eventually cease. Also, if demand grows, fossil fuel power plants may continue to expand in the long run. However, this procedure does not carry out at the same rate as before. In addition, an increase in wind power prices occurs at the beginning of these countries' development paths, either directly through growth or indirectly through support policies.

Contrary to the widely held belief that electricity generation capacity always increases in proportion to the electricity price enhancement, however, Figs. 9 and 11 show that in a competitive market, the price of wind power gradually declines as the development path continues. Indeed, lower prices cause increased sales and market share (Fig. 9 (b)). Therefore, high competition results in lower prices and increased development.

Since a portion of Iran's electricity market is state-owned until 2021, large CCGT power plant capacities were installed in the early years of modeling (included in the model). This process has been accomplished without considering future studies or economic efficiency, just to satisfy the peak demand. If a competitive market is established, after the end of the life of CCGT power plants (nearly 30 years), this large capacity is subtracted from the total active capacity of CCGT power plants, resulting in a dip in the capacity diagrams for CCGT power plants in Iran's electricity market in 2040. Other fluctuations in certain sections of the diagrams result from investors' forecasting limitations and delays in obtaining permits and constructing new power plants [71,72].

6.2. Combined policy

According to the model's behavior under proposed policies, four policies are evaluated to be more effective in developing wind farms (Fig. 9), reducing their electricity prices (Fig. 11), and lowering the overall electricity price for consumer welfare (Fig. 12).

- Tax on pollution emission and redistributing the revenue to wind energy production
- Correction of power plant fuel costs and redistributing the revenue to wind energy production
- Increasing the capacity factor of wind power plants
- Investing in social acceptance and raising awareness of renewable power's importance

Additionally, support policies can be a hybrid of any of these policies. Suppose only half of the taxes collected from polluting power plants and half of the amounts collected from the modifying of the delivered fuel price to power plants are spent on wind energy development, and the capacity factor of wind power plants is increased from 35 to 40%, with only 1% additional investment in social acceptance. In that case, the results indicate a highly positive effect on development of wind power, its price reduction, and the overall price of electricity (line 1 in Figs. 9–12). This combined policy could increase RED in Iran five times by 2035 compared to the current electricity development trend and reach 4.5 GW of wind power, conforming to other studies [19,23]. Under this policy, the consumer's overall electricity price will increase by no more than threefold.

6.3. Policy implications

Efficient policy recommendations for the development of renewable electricity in Iran's competitive market, as an example of an FFRC in the MENA region, are derived based on the sensitivity analysis as follows:

1. As illustrated in Figs. 9 and 10, pollution taxes increase wind farm capacity while decreasing the CCGT power plant capacity [24]. However, subsidies for wind power funded by polluting power plant tax revenue have a far more impact on wind power development than the tax of polluting power plants alone.
2. According to Figs. 9 and 10, correcting the price of fuel delivered to power plants in FFRCs increases the cost of fossil-fuel electricity against the cost of renewable electricity, encouraging consumers to demand renewable electricity. However, subsidies for wind power generated from the income collected via correction of fuel price delivered to power plants are far more effective than a policy of solely correcting the delivered fuel price to power plants.
3. According to the results of various subsidies to wind energy production (directly, through collecting taxes from polluting power plants or adjusting the fuel price for power plants), the starting stage of development is critical for the growth of wind power capacity. The more resources dedicated to wind power development at the outset, the more success will occur, and the need for future aid will decrease.
4. It is necessary to determine the right price in a competitive market or increase the price of wind power in non-competitive markets to compete with other electricity. This situation leads to profitability and WFI in renewable energy. Also, increasing electricity prices encourage investment as long as demand declines are negligible [73,74].
5. As illustrated in Fig. 11, although raising wind power prices are unavoidable for development, the lines in Fig. 9 demonstrate that a policy that results in a lower increase in wind power prices is more conducive to development due to the more competitive wind power market.
6. Although the Feed-In Tariff (FIT) policy (a form of direct subsidy for renewable energy) benefits development, but it increases the government's fiscal deficit, and it results in only a temporary increase in RED [10,23]. As a result, any supporting policy that emanates from the system avoids creating a budget deficit while simultaneously reorganizing the system's structures in favor of renewable energy, which is deemed a more appropriate policy.

7. Conclusion

Due to the depletion of fossil fuels and the essential need of FFRCs in the MENA region for future electricity sources, as well as the importance of renewable electricity growth in these countries, the present study assessed the development trends under current and alternative scenarios to propose effective policies for RED in countries with challenging conditions for competition and growth of renewable electricity. Following a review of prior research in this field, the primary critical factors and variables influencing RED have been identified to foster systemic thinking.

A comprehensive framework has been developed to investigate this issue. This framework is established by combining system dynamics and agent-based modeling concepts. The significant correlation between the simulation results and historical data demonstrated that the proposed framework effectively studied the development process and assessed the effects of implemented policies. Indeed, the model simultaneously considers both micro and macro perspectives. Then, this model has been used to evaluate support policies and compare the long-term consequences of each plan, assisting policymakers in determining which scenario is the most logical option for their country's renewable energy development, given their particular circumstances and constraints.

The simulation results indicated that market competitiveness, combined with the implementation of targeted support programs for renewable electricity, provided a five-fold increase in the development of this energy by 2035 and an eight-fold increase by 2060 compared to continuing current policies in Iran, which is an example of FFRCs in the MENA region.

The proposed modeling framework can simulate the development process of additional FFRCs with different amounts of each decision variable, equilibrium answer, and player behavior in an oligopoly market with more players and varying decision variables. In this study, the electricity market's pricing mechanism was designed to maximize power plants' ROI. The following section contains recommendations for future research:

- Assuming alternative pricing mechanisms with different objective functions, such as pollution reduction or decreasing the government's fiscal deficit
- The sustainability of electricity generation development can be assessed using a variety of policymakers' scenarios
- Prioritizing support programs based on their effectiveness through the use of Multiple-Criteria Decision-Making (MCDM) methods

- Utilizing the model to determine the optimal values for variables in the combined policy via optimization algorithms

CRediT authorship contribution statement

Fateme Dianat: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft. **Vahid Khodakarami:** Investigation, Writing – review & editing, Supervision, Project administration. **Seyed-Hossein Hosseini:** Conceptualization, Software, Validation, Writing – review & editing, Supervision. **Hamed Shakouri G:** Writing – review & editing, Supervision.

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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