Electromechanical Energy Conversion Systems (EECS),
Niroo Research Institute.
Vol. 1, Issue. 4. Winter 2019

Distributed Energy Resource Expansion Planning Considering Multi-Resource Regulatory Support Schemes

Alireza Sheikhi Fini

Power System Planning and Operation Research Department, Niroo Research Institute, Tehran, Iran

*****Corresponding author,*** *Email:asheikhi@nri.ac.ir*

Abstract

The goal of this paper is to achieve sustainable development. The most important way to achieve sustainable development is increasing the penetration rate of distributed energy resources (DER). A novel approach is presented in this paper for DER expansion planning problem considering multifarious support schemes. The intermittent nature as well as different uncertainties which are associated with the DER resources would cause investors to encounter risk in their investment decisions. Therefore, considering the supporting policies for increasing the penetration rate of DERs are known as an inevitable issue. The supporting policies for each of DERs technologies have remarkable impacts on investment strategy of other rivals. Under this condition, the system dynamics approach is employed in this paper for modelling of this multidimensional complex problem. System dynamics approach is known as an appropriate method for simulating the dynamics of power system and studying the effects of various factors on each other. Here, the supporting policies are contemplated in combined heat and power, wind turbine, PV and demand response resources. By using this method, the impacts of regulatory policies on market dynamics are modelled, which effect on market dynamics and investment policies of resource owners. Also, the robustness of achieving to sustainable development could be evaluated.

Keywords: Distributed energy resources; Expansion planning; Multi-resource support scheme; System dynamics.

1. Introduction

1.1. Motivation and incitement

International commitments on emission reduction, detour of fossil energy resources, new deregulated market environment, loss reduction, enhancing the power system reliability improvements and deferring the transmission and distribution expansion planning have been caused to increase the special interests in distributed energy resources (DERs).

DERs as small-scale generating units are usually located nearby the load points and consist of a wide range of technologies such as renewable energy resources, fossil-based technologies, storage energy devices and demand side management i.e. demand response (DR) programs [1].

One of the crucial issues in competitive electricity market is increasing and inclusion of several stochastic and uncertain parameters which is due to the dynamic nature of system inputs and elements. Capacity investment for satisfying the future demand is also an uncertain issue because of system uncertainties such as long-term expectation of profitability. In the competitive market environment, with a large number of capitals associated with its undertaken risks, the investors tend to minimize the aforementioned risks. In this case, more investment will be employed by investors with the aim of increasing the expected profitability whilst decreasing the expected risk.

From other point of view, high investment costs as well as intermittency and uncertainty of some resources cause to prevent development of these resources. Some regulatory support schemes can promote resources like renewable, DR programs and Combined Heat and Power (CHP) with the purpose of leading this technology to compete with some distributed generation (DG) such as gas engines.

1.2. Literature review

Many studies about DER expansion planning in deregulated environment have been conducted. In many researches, objective functions are focused on maximizing monetary profit through planning period. Several optimization methods have been utilized in order to allocate DERs optimally. A heuristic method beside economic analysis is addressed for optimal allocation of

DGs in Ref. [2]. Refs. [3-6] discuss DG expansion in the presence of uncertainties in which several single-resource support schemes have been considered.

Previous researches have utilized optimization methods based on equilibrium point for distributed resource expansion. The dynamic behaviour of investors and important market feedbacks are not taken into account in the above studies. Also, the aforementioned methods did not consider the deviation from long-term economic stability. Similar to many real economic systems, due to dynamic nature, generation resources do not encounter the required hypothesis that the system remains on long-run optimal trajectory at all the times. In order to overcome the aforesaid challenges, applying some effective and descriptive methodologies seems to be necessary. System dynamics method as a strategic decision making tool can be useful due to its inherent characteristics. As a result, more actual perspective for strategic designing of power system can be achievable.

The system dynamics approach is considered in bulk generation expansion planning [7-9], while it has not been addressed in DER expansion planning so far.

It is important for DERs investors to properly identify the behaviour of the market in long term in order to evaluate their expansion strategies and obtain a suitable strategy. System dynamics theory doesn't only simulate the actual behaviour of the market, but it can also represent the relationships between the main variables of the system in detail. Due to the existence of resources portfolio in the expansion planning with their own support schemes, the impact of each support scheme on penetration level of different resources should be investigated, which properly can be modelled through system dynamics concept.

1.3. Contributions and organization

In this paper, the impacts of regulatory policies on market dynamics are modelled, which effect on dynamic behaviours and investment policies of resource owners. The proposed model simulates investments in a set of distributed resource technologies, where each one owner is represented in the model as a separate decision maker to maximize its profit as its objective. Long-term price elasticity of demand is also included in the model. One of the contributions of this study is investigating the long term effects of multi-resource regulatory support schemes on distributed energy resources expansion planning. Also, existence of DR as a virtual demand side resource has not been investigated in previous researches. Entry of this resource along with other distributed energy resources have to be considered. The main contribution of this paper is presenting a model that comprehensively fulfil how to simulate the mutual effects of resources and their support schemes on each other. Therefore, it can be mentioned that the system dynamic approach is employed here for modelling the DER expansion planning problem considering multi-resource support schemes.

These support schemes ensure that achieving to the sustainable development, could be close. However, this modelling could show the amount of achieving to this development for each supportive policy and its stability.

The rest of the paper is organized in the following order. Section 2 describes DERs investment planning. Section 3 presents model requirements. Section 4 presents modelling DERs expansion planning. Numerical study is illustrated and also analyzed in Section 5. Finally, Section 6 concludes the paper.

2. DERs investment planning description

Long term behaviour of electricity market must be modelled for perfect investment decisions. In system dynamics approach, in each state of solving differential equation, investment decisions are taken based upon beneficial index. In fact, it describes relations between components which can evaluate the effects of policies and decisions on long-term behaviour of the system.

State variables of the investment system include capacity of each resource, forecasted load, production of rival investors and the support schemes. The behaviour of investments can be investigated through appropriate determination of variables in several time states. In this study, fuel cost, demand growth, investment costs, interest rate, support scheme, emission consideration and market type are external variables. Causal loop diagrams, which are sketches of the causal relations between different components of a system, are very useful tools for modelling the interactions between system variables. Fig. 1 represents the causal loop diagram of the problem.

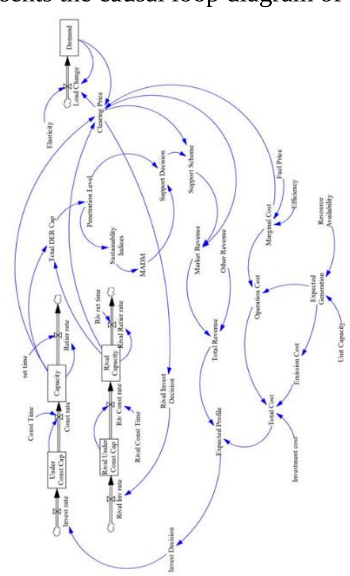

Fig. 1 Casual loop diagram of DER expansion decision

Major loops in DER expansion decision model are as following:

- Demand loop
- Capacity loop (self and rival)
- Support scheme loop

The demand loop is the most important loop. The electricity demand reacts in response to changes in electricity prices. As a balancing loop for the demand loop, a capacity acquisition loop is integrated in the model in the supply side.

This loop describes investments and construction of new generation capacities.

Moreover, the supply side is determined by the Operation scheduling loop. Using this loop, utilization of different capacities for each class of technology is coordinated as a function of electricity price. One of the important interactions of variable is the loop which determines the support scheme loop. It expresses the amount of needed support scheme that penetration level of each specified resource reach to its target.

3. Modelling requirements

3.1. DER uncertainties

When power system takes on complexity with growing levels of DERs, there are more uncertainties and variability to be considered. As wind generation is one of the considered DERs in this paper, the stochastic nature of wind power generation and its seasonal intermittency is modelled with a probabilistic approach. An ARMA function is used from Ref. [9] to capture the wind power generation uncertainty as well as the electricity demand uncertainty. In this paper, the uncertainty of fuel is not considered and the gas engine resources are considered as deterministic resources.

To model the main uncertainties of demand side reactions to the proposed DR program (DRP), here, the class of customers and their behaviours regarding DRP are considered. The customers are classified according to the regional climate of their living area. For each customer class, those important factors such as their participation in the program and drop out/enrolment rates are taken into account. The DRP has a magnitude of potential market. The potential market for each class of the customers should be estimated statistically. Here, b shows the regional climate. The participation of customers in DRP contract is considered based on historical data. The uncertainty at fairly high levels can have a dramatic impact on the capacity value [10]. Participation in DRPs may be changed year by year as some customers drop out and others enrol. Most demand response programs require a one-year commitment, and customers must re-enrol on an annual basis. Ref. [11] illustrates how participation can change over time. A factor must be obtained from historical data and be multiplied to utility benefit function. Hence, it is assumed that the participation factor is 30% and the dropout rate is taken 10% [12]. As a result, the actual number of participants can be calculated as follows:

$$\widetilde{N}_{b,t,h} = N_{b,t,h} \times PF_{b,t,h} \times (1 - drop_{b,t,h}) \qquad (1)$$

It should be noticed that the aforementioned model is a simple one and a more comprehensive model is going to be developed in future researches.

The uncertainties of other resources are not considered here.

3.2. DER support schemes

As it was described earlier, the characteristics of DERs such as the capital investment, primary resources, emission and uncertainty are different from each other; therefore, their regulatory may be different. DERs expansion program enormously depends to support schemes. Different mechanisms have been used to promote these resources worldwide [13]. In this paper, among various support schemes, the most applied one, feed in tariff (FIT), is used for wind and CHP generations and market based incentive mechanism for promoting DRPs.

3.3. Modelling of the demand

The differential equation of load is used in the system dynamics model. Therefore, two main terms are considered, the first term is annual load growth which, can be represented by normal distribution and in case of system dynamics model is shown as follows:

$$\begin{aligned} &d(t+\Delta t) \\ &= d(t) + \int_t^{t+\Delta t} DGR(\tau)d\tau \qquad \forall t \in T \end{aligned} \qquad (2)$$

The second term of the demand model illustrates its relation with the price, for taking into account the economic aspects of electric power consumption. Consumers are assumed to be able to modify their electrical energy consumption with price signal which depends to the price elasticity. Long-term price elasticity indicates the willingness to reduce electricity consumption (demand and/or time of use) over long period through investment on enabling technologies. Eq. (3) states the responsiveness of electricity consumption to long-term price variations:

$$d(t) = d_0(t) + \varepsilon \times \frac{d_0(t)}{\pi_0(t)} \times (\pi(t) - \pi_0(t)) \ \ \forall t \in T \qquad (3)$$

4. Modelling of DERs expansion planning

In the case of DER expansion planning, the impact of uncertainties and the regulatory policies on the market and investor's behaviour are modelled by system dynamics approach. For this reason, differential equations are utilized. The following assumptions are considered for the modelling of the problem:

- The DERs include fossil-based DG, wind generator, CHP and DR program (market-based).
- Uncertainties of DERs, the electricity price and demand are considered.
- The electricity market is completely competitive.

The investors should properly forecast the electricity price to make an optimum investment decision. In this regard, the profit of each investor can be calculated according to (4). The net present value method is applied in profit evaluation in lead time of the project.

$$Profit_j = \sum_{t\in T}\left(\frac{1}{1+IntR}\right)^t \times \left(B_j - Cvar_j\right) - Cfix_j \qquad \forall j \in J \tag{4}$$

For economic viability of an investment in a specific time interval, the expected profit should be positive. Solving the equation $Profit_j = 0$ for interest rate, gives a value which designate the internal rate of return (*IRR*), and then the dimensionless profitability index (*PI*) can be calculated as follows:

$$PI_j = \frac{IRR_j}{IntR} \qquad \forall j \in J \tag{5}$$

The greater profitability index, encourage investors more. An S-shaped function has been proposed by [13] to describe the aggregated capacity investment in each technology. A logistic function has been used to describe the investment factor m_j for each generation technology and is shown in (6):

$$m_j = \frac{m_j^{max}}{1+\exp(-\alpha_j \times PI_j - \beta_j)} \qquad \forall j \in J \tag{6}$$

The investment rate can be computed as follows:

$$\dot{I}_j(t) = m_j \times \dot{I}_{ref}(t) \qquad \forall j \in J, \forall t \in T \tag{7}$$

$$\dot{I}_{ref}(t) = \dot{D}_j(t) \times \dot{P}_j^{re} \qquad \forall j \in J, \forall t \in T \tag{8}$$

The capacity under construction for each technology is an accumulation depending to the construction accomplishment rate which is represented in (9).

$$P_j^c(t+\Delta t) = P_j^c(t) + \int_t^{t+\Delta t} \dot{P}_j^a(\tau)d\tau \qquad \forall j \in J, \forall t \in T \tag{9}$$

In other words, the accomplishment rate depends on the capacity under construction and the construction time and is illustrated in (10):

$$\dot{P}_j^a(t) = \frac{P_j^c(t)}{T_j^c} \qquad \forall j \in J, \forall t \in T \tag{10}$$

The benefit of DGs (gas engines, CHPs and wind generators respectively) from selling electricity as follows:

$$B_G(t) = \sum_{i\in N_{lb}} P_{G,i}(t) \times \pi(t) \qquad \forall t \in T \tag{11}$$

$$B_{CHP}(t) = \sum_{i\in N_{lb}} P_{CHP,i}(t) \times [\pi(t) + f_{CHP}(\pi)] \times Eff_{CI} + P_{CHP,i}(t) \times \pi_{heat} \times HTER \qquad \forall t \in T \tag{12}$$

$$B_W(t) = \sum_{i\in N_{lb}} Prob(i,t) \times P_{W,i}(t) \times [\pi(t) + f_W(\pi)] \qquad \forall t \in T \tag{13}$$

The aim of using CHPs is obtaining electric power; then, the income from sales of heat is converted to electricity. Therefore, its benefit function will be as (12). In this paper, the DR investor is assumed to be DISCO. Its benefit function is illustrated in (14). The infrastructure capacity deferral is important goal for utilization of DERs. The income from this deferral is considered as a DISCO reward and is shown by ΔPV in (14). The other income is from the penalty of consumer because of not responding to DRP and its cost is duo to the incentives given to customers for participating in DRP. Therefore, the benefit function of DISCO can be formulated as follows:

$$BDis(t) = \left[-Inc \times \pi(t) \times \left(d_0(t) - d(t)\right) + Pen \times \pi(t) \times Pcont(t)\right] \times \tilde{N}_{b,t,h} - Ptrade(t) - DRInv + \Delta PV \qquad \forall t \in T \tag{14}$$

The costs of each DG unit contains cost of investment (fixed cost) plus the cost of operation, the environmental cost and the penalty cost for loss proportion in feeders (variable cost) and are represented by (15)- (19) as follows:

$$Cfix_j = \sum_{i\in N_{lb}} IC_j \times P_{j,i} \qquad \forall j \in J, \forall t \in T \tag{15}$$

$$Cvar_j = \sum_{t\in T} C2_j(t) + C3_j(t) + C4_j(t) \qquad \forall j \in J, \forall t \in T \tag{16}$$

$$C2_j(t) = \sum_{i\in N_{lb}} C_{MWh,j} \times P_{j,i}(t) \qquad \forall j \in J, \forall t \in T \tag{17}$$

$$C3_j(t) = \sum_{i\in N_{lb}} P_{G,i}(t) \times \sum_{k\in K} \omega_k \times ER_k \qquad \forall j \in J, \forall t \in T \tag{18}$$

$$C4_j(t) = \pi_{loss}(t) \times P_{Loss,j}(t) \quad \forall j \in J, \forall t \in T \tag{19}$$

Active power line losses are obtained using generalized generation shift distribution factors (GGSDF) [14].

5. Numerical study

5.1. System under Study

The system under study is the IEEE 39 bus [19] with maximum demand of 7044 MW. Each period of time is a season and the planning horizon is considered to be 10 years, thus 40 time sequences are studied in this paper.

The probabilistic distribution functions of wind and PV power generations are evaluated in each season and their uncertainties are considered using the scenario method as well as the uncertainty of DR resources. Energy resources portfolio contain bulk nuclear and combined cycles and dispersed gas, wind, PV, CHP generation, and DR resources. Table 1 shows the load levels of the power system in different seasons and their periods.

Table 1. Load level in different seasons and its duration time.

Season	Load level (MW) and it's duration (h)		
	Min (duration)	Mean (duration)	Max (duration)
1	7748 (876)	9298 (986)	11622 (328)
2	8453 (876)	10144 (985)	12680 (329)
3	6340 (767)	7608 (876)	9510 (547)
4	7044 (876)	8453 (986)	10566 (328)

The interest rate is assumed to be 12.5 %. Demand annual growth is assumed to be 5%, the seasonal factors are assumed to be 1.0, 1.1, 1.2 and 0.9 for the four seasons, respectively.

Numerical studies are discussed to design support schemes for DERs to achieve sustainable energy expansion.

The profit of the investor will be affected by the fluctuation of electricity spot price resulting from elastic demand curve. The uncertainty function of wind power generation is evaluated in each season. Technical characteristics of the distribution system are available in [15].

5.2. Simulation results

The retail market is modelled with a supply and demand curve, and the electricity price is derived from the intersection of two curves. The time step is considered to be one season in the model. The results of energy resource expansion planning problem using the test model are illustrated in the following.

In this paper, eight support schemes are considered. The first scheme, is a market independent FIT and fixed over the next ten years (FIT1). The second support scheme is another market independent FIT (FIT5). The difference with the FIT1 is that the amount of this support decreases steeply and, even in some years is less than electricity price. The third support scheme is a market based incentive (FIT2) which is a coefficient of the electricity price. Fourth support scheme is another market based incentive (FIT3). The incentive in this policy is variable with the price of electricity, but in some years of study, there is no support. Fifth supportive policy (FIT4) is variable with the price of electricity, but the amount of this FIT is controlled, and in the years when the price goes up, there is no support. Type 6 of support policy is a green certificate. The seventh policy is quota, indicates that a certain amount of investment must be made on the desired resources. The eighth policy is to support the resources by reducing the bank's interest rate, down from 12% for large resources by 4% for the desired resources.

Fig. 2 to Fig. 6 illustrate the proposed FIT support schemes.

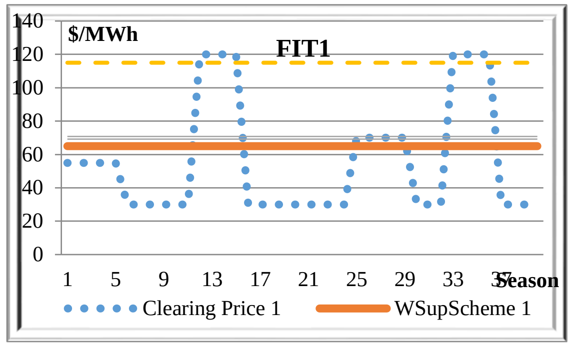

Fig. 2. The FIT1 support scheme.

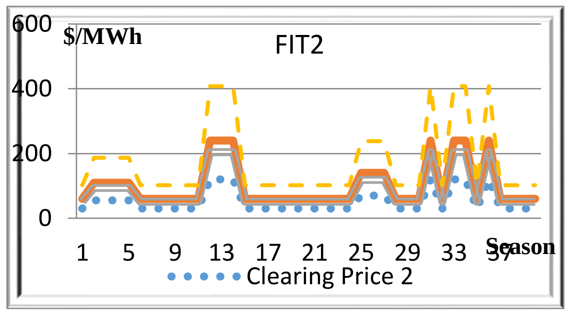

Fig. 3. The FIT2 support scheme.

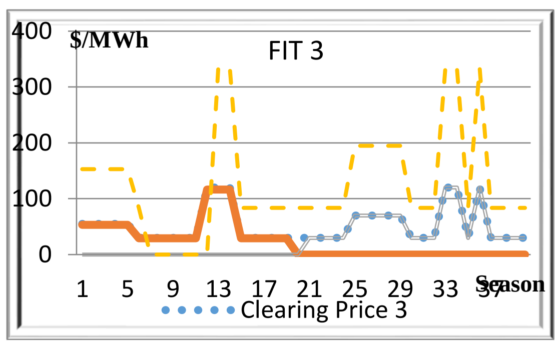

Fig. 4. The FIT3 support scheme.

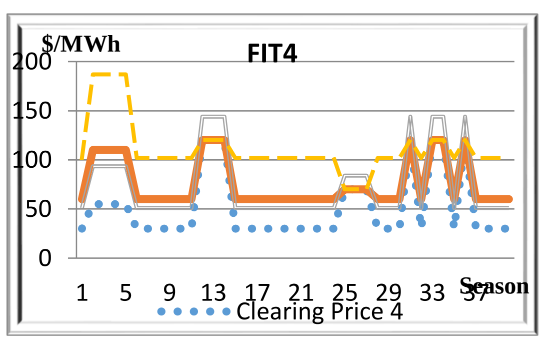

Fig. 5. The FIT4 support scheme.

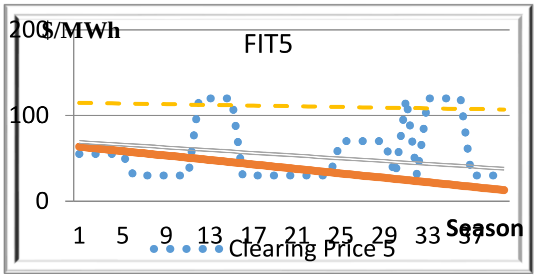

Fig. 6. The FIT5 support scheme.

The expansion capacity of each resource in the study year are shown in Fig. 7 to Fig. 13.

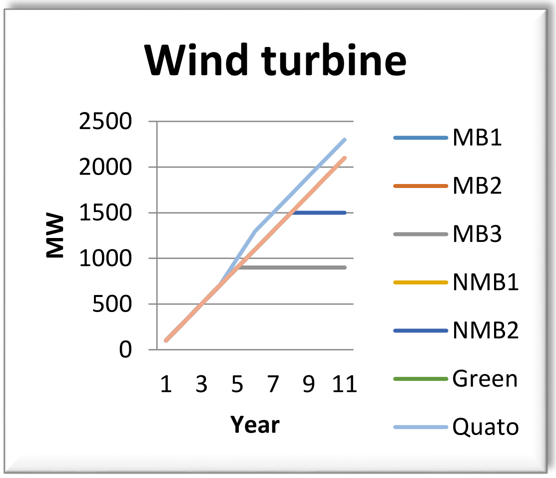

Fig. 7. The expansion capacity of Wind resources for support schemes.

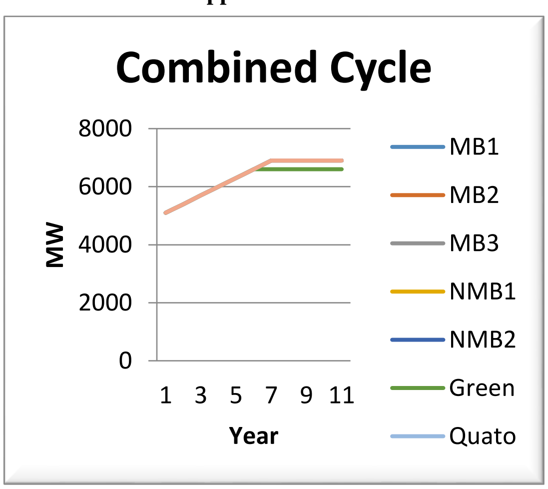

Fig. 8. The expansion capacity of Combined Cycle resources for support schemes.

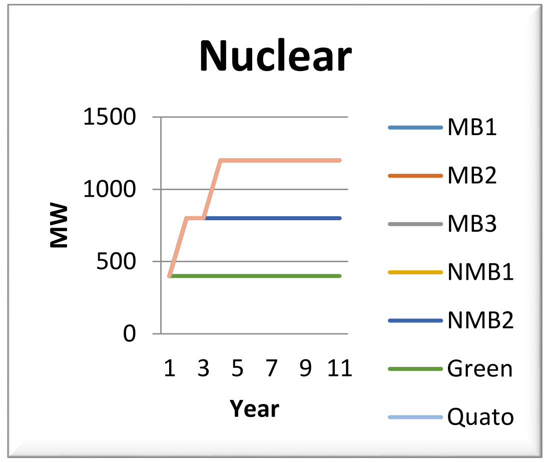

Fig. 9. The expansion capacity of Nuclear resources for support schemes.

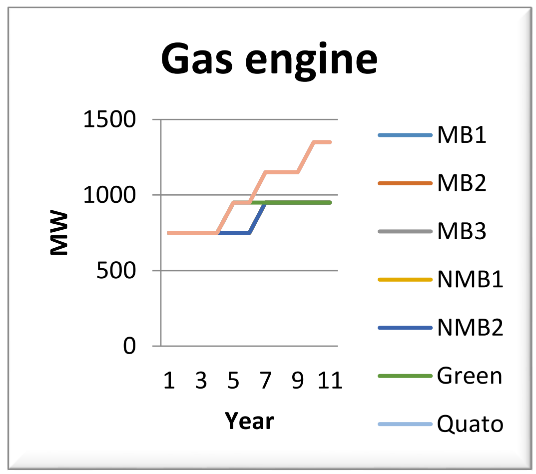

Fig. 10. The expansion capacity of Gas resources for support schemes.

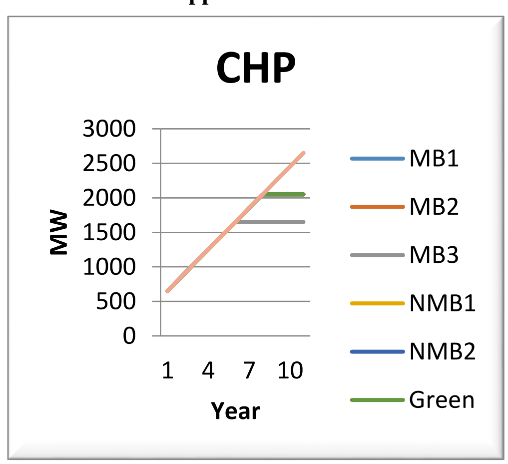

Fig. 11. The expansion capacity of CHP resources for support schemes.

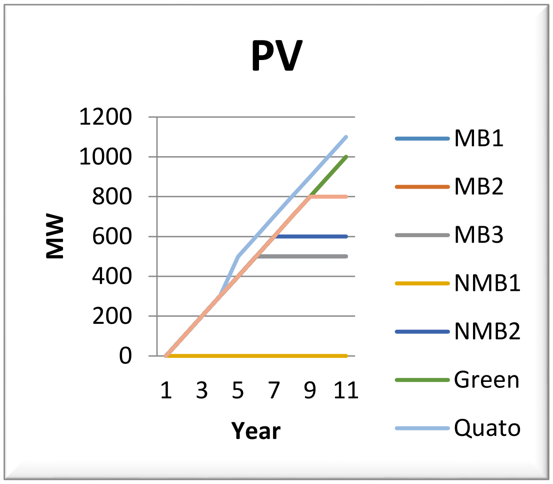

Fig. 12. The expansion capacity of PV resources for support schemes.

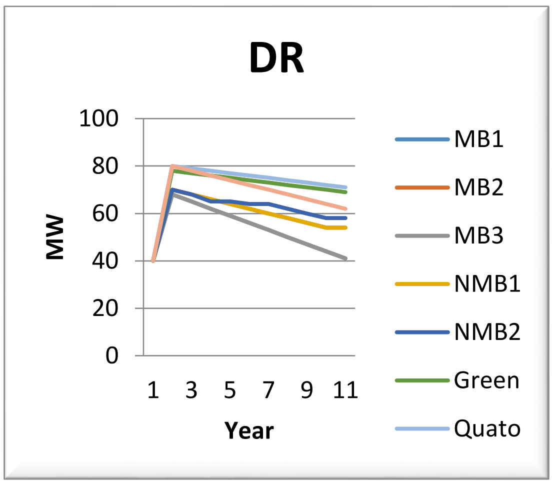

Fig. 13. The expansion capacity of DR resources for support schemes.

Table 2 shows the policies that have the greatest and least impact on the expansion of each resource. This analysis is suitable for planners who want to examine the impact of each policy on the penetration rate of each resource.

Table 2. Impact of strategies on the resources penetration rate.

Resource	Most impact strategies	Least impact strategies
Wind	Quota	All market based FIT incentives
PV	Quota	Market independent FIT1
CHP	Quota + Interest rate reduction	Market based FIT3
DR	Quota	Market based FIT1 and FIT3
Gas	Quota + Interest rate reduction	All FIT policies and Green certificate
Combined cycle	Other policies	Green certificate
Nuclear	Market based FIT1 + FIT3 + Quota + Interest rate reduction	Green certificate

The following analysis can be helpful, if we want to increase or decrease the penetration rate of a particular resource.

Among supportive policies, all FIT policies have the least impact on the growth of wind resources. The quota policy has the least impact on growth of combined cycle resources. Quota and interest rate reduction policies have the greatest impact on the growth of gas resources. Green certificate policy has the least impact on nuclear resources. Market based FIT1 and FIT3 have the least impact on the growth of nuclear resources but have the greatest impact on the growth of DR and PV resources. Since the quota policy has the greatest impact on the growth of clean resources, it has the most positive impact on indicators such as emissions.

Therefore, in order to achieve sustainable development, policies must be defined according the amounts necessary to increase the penetration rate of energy resources. Surely, the policies that support more growth and further diversification of energy resources, is more appropriate to achieve sustainable development.

6. Conclusion

A comprehensive model for distributed energy resource expansion decision has been addressed and dynamics of electricity market has been modelled using the system dynamics (SD) theory. The results illustrated that different structures of support schemes have different impacts on investment strategies. By means of SD, the mutual effects of resources as a consequence of admitting the support scheme on other resources growth are illustrated. In order to achieve the similar penetration rates of single resource support scheme, the amount of the incentive should be higher in case of multi resources. Price-based variable support scheme could lead to lower investment risks in comparison with the fixed one in case of single-resource support scheme. But, in case of multi-resource support scheme it is vice versa. Furthermore, the amount of DR resources needed to be called is determined to avoid price spike. Mutual effects of support schemes in multi-resource support schemes confirm that, regulators cannot count on superposition of results of several single-resource support schemes as same as the results of multi-resource support schemes. The aforementioned support schemes have different influence on sustainable development. Given the diversity and multiplicity of resources, a policy would be chosen that will make possible to achieve sustainable development.

Nomenclature

Sets

T_j	Set of life time of technology j.
T	Set of times.
J	Set of the generation technology.
N_{lb}	Set of DGs.
K	Set of pollutants.

Variables and parameters

$\tilde{N}_{b,t,h}$	Actual number of participants at regional climate b, season t and hour h (Number).
$N_{b,t,h}$	Enrolled number of participants at regional climate b, season t and hour h (Number).
$PF_{b,t,h}$	Customer participation factor at regional climate b, season t and hour h (Number).
$drop_{b,t,h}$	Dropout rate at regional climate b, season t and hour h (Number).
$d(t)$	Actual load at time t (kW).
Δt	Time interval (season).
DGR	Demand growth rate at time t (kW/year).
$d_0(t)$	Initial load at time t (kW).
ε	Price elasticity of demand.
$\pi_0(t)$	Initial electricity price at time t ($/kWh).
$\pi(t)$	Actual electricity price at time t ($/kWh).
$IntR$	Interest rate.
B_j	Benefit of technology j ($).
$Cvar_j$	Variable cost of technology j ($).
$Cfix_j$	Fixed cost of technology j ($)
$Profit_j$	Profit in lead time of the project for technology j ($).
PI_j	Profitability index of technology j.
IRR_j	Internal rate of return of technology j.
m_j	Investment factor of technology j.
m_j^{max}	S-shaped function coefficients of technology j.
α_j	S-shaped function coefficients of technology j.
β_j	S-shaped function coefficients of technology j.
$\dot{I}_j(t)$	Investment rate at time t for technology j.
$\dot{D}_j(t)$	Capacity addition rate plant at time t for technology j (kW/season).
$\dot{P}_j^{re}(t)$	Retired capacity rate at time t for technology j (kW/season).
$B_G(t)$	Benefit of gas engines at time t ($)
$P_{G,i}(t)$	Capacity of gas engine i at time t (kW)
$\pi(t)$	Electricity price at time t ($/kWh).
$B_{CHP}(t)$	Benefit of CHPs at time t ($)
$P_{CHP,i}(t)$	Capacity of CHP i at time t (kW)
$f_{CHP}(\pi)$	Support scheme function of CHP.
Eff_{CHP}	Efficiency of CHP.
π_{heat}	Heat price ($/BTU)
$HTER$	Heat to electricity ratio (BTU/kW)
$B_W(t)$	Benefit of wind turbine at time t ($).
$Prob(i,t)$	Probability of generation of the wind turbine i at time t.
$P_{W,i}(t)$	Capacity of wind turbine i at time t (kW)
$f_W(\pi)$	Support scheme function of the wind turbine.
$P_j^c(t)$	Capacity under construction at time t (kW)
$\dot{P}_j^a(t)$	Accomplishment rate at time t (kW/season)
T_j^c	Construction time (Season)
$BDis(t)$	Benefit function of DISCO at time t ($).
Inc	Incentive coefficient for participation of consumers in DRP.
Pen	Penalty coefficient for the consumers who do not contribute in their commitment in DRP.
$Pcont(t)$	Contracted amount of power which consumers would reduce through DRP at time t (kWh).
$Ptrade(t)$	Amount of purchase (sale) from (to) upper network at time t (kWh).
$DRInv$	DR capital investment cost ($/kW).
ΔPV	DISCO reward ($).
IC_j	Investment cost of resource j ($/kW)
$P_{j,i}$	Capacity of resource j in node i (kW)
$C2_j(t)$	Cost of operation ($/kWh).
$C3_j(t)$	Environmental cost ($/kWh).
$C4_j(t)$	Penalty cost for loss proportion in feeders ($/kWh)
$C_{MWh,j}$	Operation and maintenance cost for technology j ($/kWh).

ω_k	Weighting factor of pollutant k.
ER_k	Pollution rate of pollutant k.
$\pi_{loss}(t)$	Price of loss at time t ($/kWh)
$P_{Loss,j}(t)$	Active power line losses at time t for technology j (kW).

7. References

[1] A. Sheikhi Fini, M. Parsa Moghaddam, and M. K. Sheikh-El-Eslami, "An investigation on the impacts of regulatory support schemes on distributed energy resource expansion planning," *Renewable Energy*, vol. 53, pp. 339-349, 2013/05/01/ 2013, doi: https://doi.org/10.1016/j.renene.2012.11.028.

[2] A. Rezazadeh, M. Sedighizadeh, and A. Alavian, "Optimal sizing and sitting of distributed generation for power system transient stability enhancement using genetic algorithm," *IACSIT International Journal of Computer Theory and Engineering*, vol. 1, no. 5, pp. 387-390, 2009.

[3] H. Zakernezhad, M. S. Nazar, M. Shafie-khah, and J. P. S. Catalão, "Multi-level optimization framework for resilient distribution system expansion planning with distributed energy resources," *Energy*, vol. 214, p. 118807, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.energy.2020.118807.

[4] A. Ehsan, X. Chen, and Q. Yang, "Chapter 4 - Expansion planning of electric power distribution systems with microgeneration and EV charging stations," in *Renewable Energy Microgeneration Systems*, Q. Yang, T. Yang, and W. Li Eds.: Academic Press, 2021, pp. 69-105.

[5] M. Esmaeili, M. Sedighizadeh, and M. Esmaili, "Multi-objective optimal reconfiguration and DG (Distributed Generation) power allocation in distribution networks using Big Bang-Big Crunch algorithm considering load uncertainty," *Energy*, vol. 103, pp. 86-99, 2016/05/15/ 2016, doi: https://doi.org/10.1016/j.energy.2016.02.152.

[6] Y. Alinejad-Beromi, M. Sedighizadeh, M. Bayat, and M. Khodayar, "Using genetic alghoritm for distributed generation allocation to reduce losses and improve voltage profile," in *2007 42nd International Universities Power Engineering Conference*, 2007: IEEE, pp. 954-959.

[7] S. Wogrin, D. Tejada-Arango, S. Delikaraoglou, and A. Botterud, "Assessing the impact of inertia and reactive power constraints in generation expansion planning," *Applied Energy*, vol. 280, p. 115925, 2020/12/15/ 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115925.

[8] Z. Wang, J. Wang, G. Li, and M. Zhou, "Generation-expansion planning with linearized primary frequency response constraints," *Global Energy Interconnection*, vol. 3, no. 4, pp. 346-354, 2020/08/01/ 2020, doi: https://doi.org/10.1016/j.gloei.2020.10.005.

[9] H. T. Nguyen and F. A. Felder, "Generation expansion planning with renewable energy credit markets: A bilevel programming approach," *Applied Energy*, vol. 276, p. 115472, 2020/10/15/ 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115472.

[10] A. Bamshad and O. Safarzadeh, "Effects of the move towards Gen IV reactors in capacity expansion planning by total generation cost and environmental impact optimization," *Nuclear Engineering and Technology*, 2020/09/14/ 2020, doi: https://doi.org/10.1016/j.net.2020.09.005.

[11] Y. Lei *et al.*, "Multi-objective stochastic expansion planning based on multi-dimensional correlation scenario generation method for regional integrated energy system integrated renewable energy," *Applied Energy*, vol. 276, p. 115395, 2020/10/15/ 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115395.

[12] I. J. Scott, P. M. S. Carvalho, A. Botterud, and C. A. Silva, "Clustering representative days for power systems generation expansion planning: Capturing the effects of variable renewables and energy storage," *Applied Energy*, vol. 253, p. 113603, 2019/11/01/ 2019, doi: https://doi.org/10.1016/j.apenergy.2019.113603.

[13] A. S. Dagoumas and N. E. Koltsaklis, "Review of models for integrating renewable energy in the generation expansion planning," *Applied Energy*, vol. 242, pp. 1573-1587, 2019/05/15/ 2019, doi: https://doi.org/10.1016/j.apenergy.2019.03.194.

[14] S. Yu, X. Qing, and K. Chongqing, "Generation jointly shift distribution factor (GJSDF) and fast security analysis algorithm in economic dispatch [J]," *Automation of Electric Power Systems*, vol. 18, p. 002, 2003.

[15] V. Oree, S. Z. Sayed Hassen, and P. J. Fleming, "A multi-objective framework for long-term generation expansion planning with variable renewables," *Applied Energy*, vol. 253, p. 113589, 2019/11/01/ 2019, doi: https://doi.org/10.1016/j.apenergy.2019.113589.