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CASE STUDY

A bi-level multistage distribution network expansion planning framework with the cooperation of residential private investors (A case study in Iran)

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Abstract

In recent years, supporting schemes have been legislated by several governments to encourage private investors in installing renewable energy resources (RER). In such cases, the supportive policies are mainly enacted based on the either investor or distribution companies' standpoint. In this paper, a distribution network expansion planning (DNEP) framework with the cooperation of residential private investors (RPI) is proposed. Due to the presence of a couple of main participants, the proposed framework is arranged in a bi-level framework, where the RPI participation is optimized at the upper level, and the system structure is determined at the lower level. In order to assess the profitability of the project from the investors' attitude, payback period years (PBY) is utilized. Meanwhile, due to the presence of uncertainty resources, fuzzy clustering method (FCM) is developed to catch the intermittency of the problem. The proposed framework is implemented on a real 81 bus distribution test system in Iran. Moreover, the existing scheme in Iran and also a modified plan are investigated to make cost-effective decisions. Finally, sensitivity analysis is performed to reach a more beneficial result. Obtained results demonstrated how distribution companies can utilize the potential of residential customers in long-term planning.

1 | INTRODUCTION

1.1 | Motivation

Over the past few decades, the concept of distribution network expansion planning (DNEP) has been changed due to basic modifications such as the presence of renewable energy resources (RER). Although these resources bring various benefits to the power systems, including greenhouse gas reduction, increasing system reliability, and the capability of working as a standalone system, they can make challenging issues for the network system [1]. High penetration of RERs or installing resources without any investigation may cause voltage raising, reverse power flow, and protection problems [2].

Another barrier to installing such resources is the high investment cost of them since they are costly technologies. To overcome this problem, many countries have legalized incentive policies and offered investment plans to attract private investors' attention [3, 4]. In such conditions, the benefit of private investors is assessed through economic indices such as payback period years (PBY), internal rate on return (IRR), and net cash flow. Among different supporting schemes, Feed-in Tariff (FiT), net metering (NM), and net billing (NB) are well-known strategies that are now utilized by many governments [5].

Although the enacted incentive policies by governments have attracted numerous investors to participate in the DNEP problem, the potential of private investors in the long-term network planning concerning the aim of planners and investors' profits is not addressed as well as possible. In other words, in some studies, just the benefit of investors is considered irrespective of their technical impact on distribution networks. On the other hand, some articles consider the role of distributed generation (DG) and RERs in the system regardless of the economic consideration of these resources. Planning a distribution system regarding both investor and distribution company's targets is an important issue that should be considered.

It is noteworthy that some studies conduct private investors into the power system targets. But there are two main subjects concerning such studies. Firstly, installed resources by investors are mainly supposed as large plans, starting from some hundred kilowatts to some megawatts. Secondly, these problems are considered either from the investors' or distribution companies' standpoint, and the interactions of these participants are neglected. This problem becomes worsen for the problem with small-scale resources. Because in the case of small-scale resources, for instance, a 5 kW PV plant installed by a residential customer, the planner generally focuses on persuading investors to participate in the project to provide a part of the energy by themselves. As a consequence, the role of small-scale investors in long-term planning is not well investigated. Therefore, here, a framework to consider the cooperation of residential investors and distribution companies in long-term planning is suggested. Since both operation and planning condition has to evaluate, the problem is presented as a bi-level model. Meanwhile, the long-term contraction between the company and investor convinces the authors to model the problem as a multistage one.

1.2 | Literature review

DNEP problem regarding the potential of RERs and private investors has been addressed in plenty of studies. These studies can be categorized based on several subjects such as the planning horizon, type of renewable resources, private investor status, network asset planning, and solution techniques. Meanwhile, the battery as an instrument that can support the peak load of the system and therefore offer the opportunity of deferring the need of the system in expansion system components are considered here as well.

As mentioned before, the enacted rule in supporting private investors is investigated in many studies, while in some studies the benefit of investors is more highlighted than the technical issues. In [6], a compound model is presented to evaluate PV and energy storage subsidy. In the study, social welfare as a substantial target is also considered. The impact of national subsidy retraction on wind power investment decisions is assessed in [7]. The uncertainty of the investors' decision based on a realistic approach for the case in China is carried out in the study. In [8], the influence of subsidy policies and operational strategies on the photovoltaic supply chains and the overcapacity problems is assessed. Similar to these studies, the assessment of FiT and NM schemes on the grid-connected renewable resources and network conditions is also considered in some articles [9–12].

In mentioned studies and more ones like this, the impact of RERs on the power network is neglected. However, some others consider the role of RERs in either planning problems or evaluating operational conditions. The optimal integration of battery energy storage and RERs in the distribution network is presented in [13]. To reach the optimum structure, a planning-operation decomposition methodology is used. In [14], the optimal distribution network planning employing DGs and storage to minimize energy not supplied and reduce power losses is offered. In [15], a multi-level framework for distribution network expansion planning in the presence of DGs is provided. In the framework, the stochastic parameter of the system is caught through different levels. A bi-level framework for the DNEP problem in the presence of RER is presented in [16]. The bi-level structure helps the planner to co-ordinately plan different types of content and reach more precise results. An approximate dynamic programming approach used in a flexible DNEP problem is suggested in [17]. Multiple energy resources of the study are modelled via the Markov decision process and the economy comparison is also performed.

In the case that the private investors contribute to the planning problem, the condition is a little different, while the economic indices should be evaluated to assess the benefit of investors. A private investor-based DG expansion planning is proposed in [18], where economic analysis is performed to evaluate the investors' benefit. The main objective function of the study is based on the investors' target and technical problems are considered as planning constraints. In [19], an incentive-based multistage DNEP model is proposed, where the subsidy prices for candidate buses are evaluated to reach the same economic results. In order to support the evening load of the system, conventional and fossil-based DGs are hired in the study. Another bi-level framework to model the operational condition and the system structure in long-term network planning is presented in [20]. The profitability of the investors is guaranteed through the operational evaluation of the lower levels. A summary of considered work and comparison concerning planning options is presented in Table 1. Furthermore, the specification of the proposed work is shown in the last row of the table.

Table 1 denotes that the joint consideration of private investors and distribution companies has been considered in some studies. But a missing issue in the studies is guiding small-scale investors in long-term planning. In fact, these kinds of investors are mainly evaluated to provide self-energy usage, and their cumulative impact on the total system requirements such as installing HV/MV substations and MV feeders is neglected. But these small-scale investors can make a significant impact on the power system if they conducting properly. More specifically, installing both PV and battery system by investors not only supply a main part of their energy but also helps the system operator to shave the total peak load of the system and then postpone the need for system upgrading. However, in such conditions, the benefit of the investors should also be well satisfied to persuade them in contributing to the project. Here, the cooperation of private investors and distribution companies in long-term planning is proposed, while both participants' targets are investigated.

1.3 | Aims and contribution

By taking into account the above literature, it is revealed that the DENP problem in the presence of RER has been

TABLE 1 Summary of literature review regarding DNEP and private investors' participation

Ref. no.	Planning stages	Network asset planning: feeder	Network asset planning: substation	Renewable resources: PV and/or wind	Renewable resources: battery	Scale of renewable resources	Private investor participation	Subsidy policies	Solution method
[13]	single	–	–	☐	☐	large	–	–	Decomposition method
[14]	single	–	–	☐	☐	large	–	–	Evolutionary algorithm
[15]	single	☐	–	☐	☐	large	–	–	Evolutionary algorithm
[16]	single	☐	–	☐	–	large	–	–	Evolutionary algorithm
[17]	multi	☐	☐	☐	☐	large	–	–	Approximate dynamic programming
[18]	single	–	–	☐	–	large	☐	☐	Evolutionary algorithm
[19]	multi	☐	☐	☐	–	large	☐	☐	Mathematical based programming technique
[20]	multi	☐	–	☐	☐	large	☐	–	Karush—Kuhn–Tucker model
This study	multi	☐	☐	☐	☐	small	☐	☐	Bi-level framework using evolutionary algorithm

considered in many studies. But based on the best of the authors' knowledge, none of the existing papers concentrate on developing a long-term DNEP with the cooperation of small-scale private investors. Although in our previous study [21] the joint implementation of PV and battery in DNEP problem is considered, the potential of RPI in deferring the system requirements and their impact on total planning costs has not been considered yet. Therefore, here, a bi-level multi-stage DENP framework conducting residential investors into the technical targets is proposed. It should be noted that proposed problem is considered as a multistage problem due to several reasons. Firstly, in the distribution scale, loads that here are considered as private investors, are normally gradually added to the system, more specifically for long-term planning. Therefore, the planning period can be divided into some stages to consider new loads in the system. Secondly, in expansion problems that need to either install or upgrade HV/MV substations, planning stages should be divided to prevent installing all substations at the first stage. Finally, for such long-term problems, installing network instruments, as well as contributing private investors, are distributed on the planning horizons. So, it would be better to evaluate them at every year or every stage, instead of considering all of them at the beginning of the project.

The major contributions of this study are as follows:

- Residential customers as potential investors are engaged alongside the technical aims. Therefore, both planner and RPIs targets are addressed and the benefit of investors is evaluated via a popular economic index. Furthermore, the possibility of RPI participation in the project is assessed based on the behaviour of investors in the past years.
- A bi-level framework is developed to consider both technical and economical evaluation. The network structure including the status of HV/MV substations and MV feeders as well as the RPIs' status are determined through the upper and lower levels respectively.
- Iranian's new regulation related to guarantee purchase agreement, revised in 2021, is investigated since there are some remarkable modifications in the new instruction. Meanwhile, instead of installing just PV systems, joint implementation of PV and battery is suggested and the assessment is performed to reach a better technical performance from the planner's standpoint. To reach this target a new FiT pattern concerning the injected power by batteries is introduced and the system planning costs regarding this new FiT are calculated.

The remainder of this paper is organized as follows:

The methodology of the proposed framework including the structure of the bi-level model, RPI modelling, and the uncertainty modelling are introduced in Section 2. In Section 3, the problem formulation, upper and lower-level objective function, and planning constraints are presented. In Section 4. The solution framework and the structure of candidate particles are suggested. The case study system and the simulation results are provided in Section 5. Moreover, a sensitivity analysis is carried out in this section as well. Finally, the paper is concluded in Section 6.

2 | METHODOLOGY

Network planners are responsible for designing a system with the lowest investment and operation cost while the technical issues are properly satisfied. In the case of the presence of other participants like private investors, their target should be taken into account as well as their impact on the planning procedure. Meanwhile, these participants turn the problem into a more complex problem since different targets are merged in the planning problem. Another factor that may influence the planning

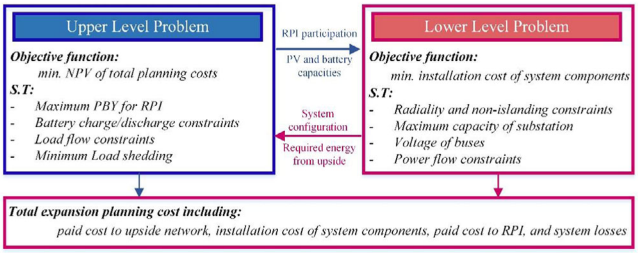

FIGURE 1 The proposed framework for bi-level DNEP problem considering RPI.

problem is the planning horizon and project duration. For long-term DENP problems, a multi-stage type is more precise than a single-stage one, which is employed in this study.

2.1 | Bi-level distribution network planning

The single-level planning, which is frequently used in many studies, is most appropriate for a system with limited decision variables. However, in a multi-contributor planning scheme with high decision variables, a multi-level framework may be more effective and leads to a more precise result [22]. Here, however, the problem faces different situations including planning calculations, operational evaluation, and economic assessment. Therefore, as depicted in Figure 1, a bi-level framework is introduced in this study. In the proposed structure, the planning problem is divided into two optimization subproblems; upper level and lower level problems.

The upper level dedicates to the operational evaluations and net present value (NPV) of planning cost. Meanwhile, the benefit of both private investors and the distribution company are also calculated at this level. But it should be mentioned that to compute the planning cost, the system configuration is required that can be determined via the lower level. In other words, the number of private investors and installed resources by them is firstly suggested at this level. Then, the possible load shaving is calculated and the system reconfiguration based on the load levels is determined in the lower level. Finally, the total operational costs are assessed at the upper level. To reach the total planning cost, an hourly load flow is required at this level. Through load flow calculation, the benefit of RPIs and implement the charging/discharging strategy of batteries would be achievable. In order to persuade the private investors, the PBY of investing PV and battery are considered as the constraint of this level. The status of batteries and load flow constraints should be well addressed throughout this level. Additionally, a minimum load shedding is supposed since peak shaving is one of the former aims of employing batteries. This is a soft constraint that makes the planner sure about a minimum load shedding by installing PV and battery and here, it is supposed to five percent of the total load. By determining the initial outcomes of this level, the RPIs' participation, the number of PV and batteries installed in the system, and the total planning costs are determined.

Once the total capacity of PV and batteries is determined in the upper level, the total peak of the system and the ability of the system in load shedding would be calculable at the lower level. Therefore, at this level, the planner is seeking the best system structure with the lowest investment cost. The status of MV lines and HV/MV substations are also determined at this level. To reach this aim, load flow calculations should be performed to be sure about the satisfaction of technical constraints such as voltage constraints and thermal capacity of MV lines. Moreover, the constraint regarding the maximum capacity of substations should be satisfied as well. Radiality and non-islanding constraints are other important limitations that play a vital role in such problems. Eventually, this level specifies the total system structure and therefore the energy bought from the upside and other planning parameters could be assessed then at the lower level.

It is noteworthy that all mentioned procedures comprising upper level and lower-level problems are adopted for one stage of planning. By running this procedure for the first stage, the system structure and the total investors who should participate in the problem are determined. Then, these series of steps are implemented for the next stage, while the system structure is adjusted concerning the output of the first stage. These steps are repeated for all stages of planning to reach the final structure and total planning results.

2.2 | RPI participation and uncertainty

The encouragement policies enacted by governments subject either the large-scale plants or the small scale ones which can be invested by private investors. But it should be noted that small-scale investors need a limited investment cost that is almost accomplishable for all residential customers. Meanwhile, residential customers are usually dispread all over the distribution system. Therefore, these customers are potential points to install renewable resources close to the consumption places.

In 2014, the Iranian ministry of energy started an instruction to engage private investors in investing RERs. This instruction covers a wide range of investors starting from some kilowatts to some megawatts. After more than seven years, this rule has attracted a considerable tendency in installing renewable resources. More specifically, residential customers represented remarkable participation in this project, which right now many applicants are now waiting to approve their permission in connecting to the network.

Private investors just participate in the projects with the proper economic justification. In Iran however, this condition is properly satisfied, since the PBY of the project is less than the investor's expectation. But according to the present plan offered by the ministry of energy of Iran, just PV systems are feasible for the residential customer. These installed PV systems can help the system operator to supply a portion of the day peak of the system; however, they could not be fruitful for the evening peak of the system. As a consequence, the total peak of the system is not changed in the presence of PV systems. Therefore, in this study, the impact of simultaneous implementation of PV and battery systems is supposed. Nonetheless, the probability of the presence of investors may change due to the economic conditions of the problem. Therefore, a possibility function regarding the PBY of the project is defined to model the uncertainty of participation. With this function, the total planning results can be assessed from both the planer and investors' standpoint.

2.3 | Data clustering

Every power distribution system shows a stochastic treatment due to the fluctuation in the load of the system. But the level of the system uncertainty can be increased in the presence of RERs such as PV plants. This condition requires an effectual method to catch the uncertainty of the problem. However, in the case of the system equipped with battery storage, the uncertainty modelling method should let the planner implement the charging/discharging strategy of the batteries. In other words, a series of daily information should be produced as the outcome of the uncertainty modelling method. By taking all these considerations into account, the fuzzy clustering method (FCM) as a powerful categorizing technique is engaged here [23].

Through employing FCM, the data related to solar irradiation and the load of the system over a period of time are summarized in specific clusters. The FCM is a data clustering method that employs the membership degree of data to classify them [24]. This method starts with random data as the initial cluster centres. Then, the membership of each data is updated through an iterative procedure until the stopping criteria are satisfied. This membership is located within 0–1 interval. The objective function of FCM is to minimize the distance of each data from a cluster centre can be presented as (1).

$$J_b(U.\Gamma) = \sum_{\Gamma_b \in \Gamma} \sum_{x_j \in \Gamma_b} \mu_{bc}^m d\left(x_j.\lambda_b\right) \tag{1}$$

Meanwhile, the membership degree is updated via (2) and the cluster centre is determined by (3).

$$\mu_{bc} = 1 / \sum_{r=1}^{C} \left[d\left(x_c.\lambda_b\right) / d\left(x_c.\lambda_r\right)\right]^{\frac{2}{m-1}} \tag{2}$$

$$\lambda_b = \sum_{c=1}^{n} \mu_{bc}^m x_c / \sum_{c=1}^{n} \mu_{bc}^m \tag{3}$$

3 | BI-LEVEL MULTI-STAGE PLANNING FORMULATION

3.1 | Upper-level formulation

In the upper level of the proposed framework, the contribution of RPI in the planning problem is evaluated, while the lower level is concentrated on the structure of the whole system. Therefore, at the upper level, the planner is looking for the minimal operation cost, losses cost and paid costs to the RPI as well. Accordingly, the objective function of the upper level which is presented in (4) consists of three main parts; paid cost to upside network (PUN), paid cost to RPI ($PRPI$), and losses cost (LC).

$$\min \sum_{t \in T} \left(PUN(t) + PRPI(t) + LC(t)\right) / (1 + dr)^{(t-1)Y} \tag{4}$$

The total paid costs to buy energy from the network is presented in (5). This cost is calculated based on the energy received from the upside network subtracted by energy injected from RPI into the network. As a consequence, a higher produced energy by RPIs can decrease this item; however, the paid cost to RPIs would be inversely increased as represented in (6). $PRPI$ is also comprised of two parts concerning the produced power by PV during day hours, and injected power by batteries during evening hours. It is worth noting that due to technical issues such as voltage rising and reverse power flow, the batteries are charged from the PV system. Thus, the net produced power by PV should be considered in this section. The losses cost is the last part of the upper-level objective function as formulated in (7). In all mentioned equations, the calculation is performed for every hour of the daily scenarios created by data clustering method. This procedure is repeated over all hours of scenarios and the result are multiplied by the probability of the mentioned scenario ($\rho_{sci.h}^{LV}$ and $\rho_{sci.h}^{SI}$). By gathering all these evaluations, the total result of a year is then assessed. These probabilistic parameters are also considered for the lower level formulation, whenever a PV or load is employed in the relations.

$$PUN(t) = \sum_{y \in Y} \left(\left[\sum_{s \in \psi_{sub}} \sum_{sci \in \psi_{sci}} \sum_{h \in [1.24]} \left(P_{h.sci.s}^{sub} * \rho_{sci.h}^{LV} * MP_{h.y} * 365\right) \right] / (1 + dr)^{(y-1)} \right) \tag{5}$$

$$PRPI(t) = \sum_{y \in Y} \left(\left[\begin{array}{l} \sum_{cu \in \psi_{cus}} \sum_{sci \in \psi_{sci}} \sum_{h \in [1.24]} \left(\left(P_{cu}^{PV} * \rho_{sci.h}^{SI} - Pr_{cu}^{bat} * \chi_{cha}\right) * 365\right) \\ * FiT_{PV}(y) + \sum_{cu \in \psi_{cus}} \sum_{sci \in \psi_{sci}} \sum_{h \in [h_{dis}.24]} \left(Pr_{cu}^{bat} * \chi_{dis} * \rho_{sci.h}^{SI} * 365\right) \\ * FiT_{bat}(y) \end{array} \right] / (1 + dr)^{(y-1)} \right) \tag{6}$$

$$LC(t) = \sum_{y \in Y} \left(\left[\sum_{sci \in \psi_{sci}} \sum_{h \in [1.24]} \sum_{f \in \psi_{fee}} \left(PLoss_{f.\ sci.\ h} * MP_{h.y} * \rho_{sci.h}^{LV} * 365\right) \right] / (1 + dr)^{(y-1)} \right) \tag{7}$$

In Equation (6), there are two parameters that determine the total paid cost to RPIs, FiT_{PV} and FiT_{bat}. These two parameters are explained in the upcoming subsection in detail.

3.2 | Lower-level formulation

The lower level of the proposed method is organized to determine the status of HV/MV substations and MV feeders as well. These statuses are affected by the percentage of customers who participated in the problem which is determined at the upper level of the problem. Higher participation of RPI causes supplying a higher value of load by customers and therefore a lower power from HV/MV substations is needed. Consequently, the objective function of the lower level consists of the installation cost of HV/MV substations (IC_t^{sub}) and installation cost of MV feeders (IC_t^{feeder}) as shown in (8). It should be mentioned that a fully yearly data is not required to consider at this level, since the maximum load of the system has the main influence on the status of the system structures. Thus, the worsening cluster of the last year of each stage is merely evaluated at this level.

$$\min \sum_{t\in T}\left(\sum_{s\in\psi_{sub}} IC_s^{sub} * \alpha_{s.t} + \sum_{f\in\psi_{fee}} IC_f^{feeder} * \gamma_{f.t}\right) / (1+r)^{(t-1)Y} \tag{8}$$

In this study, it is supposed that the planner has to install a new HV/MV substation either if the maximum load of the existing substation reaches its maximum value or if the operator would not be able to supply all nodes under voltage constraints. The latter condition is due to long MV feeders that mainly have a long distance from the existing substation and therefore the voltage of the system exceeds the permitted interval. In such conditions, although the total load of the substation is not reached to the maximum value, the system needs a new substation.

3.3 | Economic evaluation for the investors

As mentioned previously, in the upper-level formulation, there is a parameter that affects both the investor's decision and the total planning cost. The FiT_{bat} that is relevant to buying energy from injected power by batteries is computed based on the total planning cost. In other words, the presence of batteries in the network can defer the requirement of installing a new substation, paid costs to the upside network, and paid costs to RPIs. This causes to save costs over the planning horizon which is dedicated to buying energy from injected power by batteries. Therefore, three items affect the FiT_{bat}; difference cost in installing substations (dif_{tot}^{sub}), the difference in paid cost to upside network (dif_{tot}^{PUN}), and the difference in paid cost to RPIs (dif_{tot}^{PRPI}).

$$FiT_{bat} = \frac{dif_{tot}^{sub} + dif_{tot}^{PUN} + dif_{tot}^{PRPI}}{\sum_{cu\in\psi_{cus}}\sum_{sci\in\psi_{sci}}\sum_{h\in[h_{dis}.24]}\left(Pr_{cu}^{bat} * \chi_{dis} * \rho_{sci.h}^{SI} * 365\right) * T * Y} \tag{9}$$

The dif_t^{sub} is relevant to the investment cost of the HV/MV substations. Join implementation of PV and battery can postpone the requirement of installing substation which finally causes to save installation cost. This parameter can be evaluated as shown in (10). In all the following equations, the indices *wob* and *wb* denoted the system with private investors who just install PV (existing plan), and the system with private investors who install both PV and battery (modified plan), respectively.

$$dif_{tot}^{sub} = \sum_{t\in T}\frac{\left(\sum_{s\in\psi_{sub}} IC_s^{sub.wob} * \alpha_{s.t}\right)}{(1+r)^{(t-1)Y}} - \sum_{t\in T}\frac{\left(\sum_{s\in\psi_{sub}} IC_s^{sub.wb} * \alpha_{s.t}\right)}{(1+r)^{(t-1)Y}} \tag{10}$$

The dif_{tot}^{PUN} depends on the differences of paid costs to upside network. When the RPIs participate in the project, a portion of the energy is supplied by investors. As a consequence, a lower amount of energy should be bought from the upside network which increases the saved cost according to (11).

$$dif_{tot}^{PUN} = \sum_{y\in Y}\left(\frac{\left[\sum_{s\in\psi_{sub}}\sum_{sci\in\psi_{sci}}\sum_{h\in[1.24]}\left(P_{h.sci.s}^{sub.wob} * \rho_{sci.h}^{LV} * MP_{h.y} * 365\right)\right]}{(1+dr)^{(y-1)}}\right) - \sum_{y\in Y}\left(\frac{\left[\sum_{s\in\psi_{sub}}\sum_{sci\in\psi_{sci}}\sum_{h\in[1.24]}\left(P_{h.sci.s}^{sub.wb} * \rho_{sci.h}^{LV} * MP_{h.y} * 365\right)\right]}{(1+dr)^{(y-1)}}\right) \tag{11}$$

The dif_{tot}^{PRPI} is the difference of paid cost to the investors for just their produced energy by PV systems. In the existing plan, all produced energy by PV systems is directly injected into the system; however, in the modified plan, a part of produced energy by PV is dedicated to charging the battery, and the surplus produced power is then injected into the system. This difference is also added to other saved costs as (12) which helps the system operator to offer a higher FiT_{bat}.

$$dif_{tot}^{PRPI}=\sum_{t\in T}\frac{\sum_{cu\in\psi_{cus}}\sum_{sci\in\psi_{sci}}\sum_{h\in[1.24]}\left(\left(P_{cu}^{PV.wob}*\rho_{sci.h}^{SI}\right)*365\right)*FiT_{PV}(y)}{(1+r)^{(t-1)Y}}-\sum_{t\in T}\frac{\sum_{cu\in\psi_{cus}}\sum_{sci\in\psi_{sci}}\sum_{h\in[1.24]}\left(\left(P_{cu}^{PV.wob}*\rho_{sci.h}^{SI}-Pr_{cu}^{bat}*\chi_{cha}\right)*365\right)*FiT_{PV}(y)}{(1+r)^{(t-1)Y}} \tag{12}$$

According to the Iranian instruction in supporting private investors, the FiT_{PV} and FiT_{bat} are increased over the contract duration. Based on the Iranian new instruction enacted in 2021, these parameters vary as presented in (13).

$$FiT_{rer}(y)=FiT_{rer}(1)\times\left(AC(y)\times C(y)\times\left(1+C_{np}\right)\right)\ .\ rer\ \forall\ PV\ \&\ bat \tag{13}$$

As this relation shows, the FiT is affected via three factors, including the adjustment coefficient ($AC(y)$), the yearly coefficient ($C(y)$), and the national production factor (C_{np}). The yearly coefficient is a factor to prevent a high growing pattern of FiT over the planning period and alleviate it in the eighth, twelfth, and sixteenth years of the project. This item however had a different value in the former instruction of Iranian instruction where the yearly coefficient just reduced the FiT in the tenth year by a factor of 0.7. National production is also a factor that is imported into the formulation to support the national companies that manufacture PV system components such as panels, inverters, and structures. Nonetheless, this factor is not considered in the practical evaluation and we ignored it in this study as well. But the most important factor is the adjustment coefficient which is varied concerning retail price index and Euro exchange rate as shown in (14). In this equation, α has a number between 0.2 and 0.3. It is worth mentioning that EER used in this formula is presented as a ratio, while according to the central bank of Irans' information, the USD ratio can cause the same result. Since Iran is a developing country, the accurate prediction of retail price index and Euro exchange rate is not feasible, and the variation of the FiT in the last years proved this fact. Therefore, here, an average value obtained from the variation of FiT over the last years is investigated as the adjustment coefficient.

$$AC(y)=\left(\frac{RPIF(y-1)}{RPIF(1)}\right)^{\alpha}\times\left(\frac{EER(y-1)}{EER(1)}\right)^{(1-\alpha)} \tag{14}$$

Once the FiT for different years is determined, the economic indices are now calculable. Among different economic indices, the PBY may be the most prominent one, especially for investors in Iran. Thus, the PBY as a critical decision variable for RPIs is evaluated in this paper as presented in [25] (15).

$$PPY=Y_{ln}+\frac{|CCF_{ln}|}{CCF_{ln+1}+|CCF_{ln}|} \tag{15}$$

Based on the above equation, the PBY depends on the year of the project with the last negative amount of net cash flow (Y_{ln}), and the cumulative cash flow at that year (CCF_{ln}). The cumulative cash flow is also related to the net present value (NPV_{cu}) which depends on the net present benefit (NPB_{cu}) the net present cost (NPC_{cu}) as shown in (16).

$$NPV_{cu}=NPB_{cu}-NPC_{cu} \tag{16}$$

The net present benefit for each customer determines by selling energy to the network as illustrated in (17). Customers' income is divided into two parts including produced energy by PV and injected power via battery.

$$NPB_{cu}=\sum_{y\in Y}\left(\sum_{sci\in\psi_{sci}}\sum_{h\in[1.24]}\left\{\begin{array}{l}\left(\begin{array}{c}P_{PV}(h)*(1-(y-1)*d)\\-\chi_{cha}*(E_{bat}(h)-E_{bat}(h-1))\end{array}\right)\\ *365*FiT_{PV}(y)+(\chi_{dis}*(E_{bat}(h)\\-E_{bat}(h-1)))*365*FiT_{bat}(y)\end{array}\right\}\right)/(1+dr)^{(y-1)} \tag{17}$$

The net present cost of the system for each customer is also comprised of three parts; investment cost of PV and battery (IC_{cu}), replacement cost of instruments (NPR_{cu}), and operation and maintenance cost of the system ($NPOM_{cu}$). These parameters are described as (18)–(21) as follows.

$$NPC_{cu}=IC_{cu}+NPR_{cu}+NPOM_{cu} \tag{18}$$

$$IC_{cu}=N_{PV}\times IC_{PV}+N_{bat}\times IC_{bat}+IC_{inv} \tag{19}$$

$$NPR_{cu}=\sum_{y\in Y}\left(N_{bat}\times IC_{bat}\times\vartheta_y\times\left(\frac{(1+i)^{(y-1)}}{(1+dr)^{(y-1)}}\right)+IC_{inv}\times\xi_y\times\left(\frac{(1+i)^{(y-1)}}{(1+dr)^{(y-1)}}\right)\right) \tag{20}$$

$$NPOM_{cu}=\sum_{y\in Y}\left(N_{PV}\times OM_{PV}\times\left(\frac{(1+i)^{(y-1)}}{(1+dr)^{(y-1)}}\right)+N_{bat}\times OM_{bat}\times\left(\frac{(1+i)^{(y-1)}}{(1+dr)^{(y-1)}}\right)\right) \tag{21}$$

3.4 | Problem constraints

Either in the upper level or lower level, some technical and economic constraints should be well addressed. However, some constraints are similar in both levels such as the load flow and active and reactive power balance as shown in (22)–(25).

$$P_h^{sub} + \sum_{cu\epsilon\psi_{cus}} P_{h.PV} + \sum_{cu\epsilon\psi_{cus}} Pr_{h.cu}^{bat} * \chi_{dis} = \sum_{f\epsilon\psi_{fee}} PLoss_{h}.f + \sum_{i\epsilon\psi_{bus}} Pload_{h.i} + \sum_{cu\epsilon\psi_{cus}} Pr_{h.cu}^{bat} * \chi_{cha}\ \forall\ h \in [1:8760] \tag{22}$$

$$Q_h^{sub} = \sum_{f\epsilon\psi_{fee}} QLoss_{h}.f + \sum_{b\epsilon\psi_{bus}} Qload_{h.b}\ \forall\ h \in [1:8760] \tag{23}$$

$$P_{ij.t} = V_{i.t}^2 G_{ij} - V_{i.t}V_{j.t}G_{ij}\cos\left(\delta_{i.t} - \delta_{j.t}\right) - V_{i.t}V_{j.t}B_{ij}\sin\left(\delta_{i.t} - \delta_{j.t}\right)\ \forall ij \in \psi_{fee}\ .\ t \in T \tag{24}$$

$$Q_{ij.t} = -V_{i.t}^2 B_{ij} - V_{i.t}V_{j.t}G_{ij}\sin\left(\delta_{i.t} - \delta_{j.t}\right) + V_{i.t}V_{j.t}B_{ij}\cos\left(\delta_{i.t} - \delta_{j.t}\right)\ \forall ij \in \psi_{fee}\ .\ t \in T \tag{25}$$

The voltage constraint is another important constraint that should be considered on both levels as follows:

$$V_{min} \le V_{i.t} \le V_{max}\ \ \forall i \in \psi_{bus}\ .\ t \in T \tag{26}$$

At the upper level, there are some constraints concerning the operational condition of PV and batteries. The capacity of PV systems is constant according to the Iranian rules, therefore this parameter is set to 5 kW per customer as (27). The capacity of batteries however should be less than a maximum value as (28). Meanwhile, the capacity of batteries installed by customers should be evaluated so that the minimum load shedding of the upper level is satisfied. This constraint is denoted in (29).

$$N_{PV} * p_{PV} = 5\ \text{kW} \tag{27}$$

$$0 \le ca_{cu}^{bat} \le ca_{cu}^{bat.max} \tag{28}$$

$$\frac{\sum_{cu\epsilon\psi_{cus}} P_{h.PV} + \sum_{cu\epsilon\psi_{cus}} Pr_{h.cu}^{bat} * \chi_{dis} + \sum_{cu\epsilon\psi_{cus}} Pr_{h.cu}^{bat} * \chi_{cha} + \sum_{f\epsilon\psi_{fee}} PLoss_{h}.f + \sum_{i\epsilon\psi_{bus}} Pload_{h.i}}{\sum_{i\epsilon\psi_{bus}} Pload_{h.i}} \le LSH_{max} \tag{29}$$

Moreover, the hourly stored energy in the batteries should be relevant to the stored energy of the last hour as (30). Meanwhile, the state of the charge (SOC) of batteries should be located within the interval shown in (31).

$$E_{cu}^{bat}(h+1) = E_{cu}^{bat}(h) * (1-\omega) + \left(Pr_{h.cu}^{bat} \times \eta_{bat}\right) * \chi_{cha} + \left(\frac{Pr_{h.cu}^{bat}}{\eta_{inv}} \times \eta_{bat}\right) * \chi_{dis}\ \forall h \in [1-8760] \tag{30}$$

$$E_{cu}^{bat.max} * (1-DOD) \le E_{cu}^{bat}(h) \le E_{cu}^{bat.max}\ \forall h \in [1-8760] \tag{31}$$

An important constraint regarding the radial structure of the system should be investigated at the lower level as well. To reach this aim, the graph tree theory is supposed as shown in (32) [19]. According to this theory, the subtraction of total buses and total substations should be equal to the total number of feeders.

$$\sum \psi_{fee.sub} = \sum \psi_{bus.sub} - \sum \psi_{sub} \tag{32}$$

Finally, the relation for evaluating the presence of investors in the project is shown in (33). Although this equation is not a constraint in the planning procedure, it is utilized to evaluate the possibility of participation. In this hypothetical relation, it is assumed that in the project with a PBY of less than 5.5 years, all applicants for participation would be completely fulfilled. This is a fact acknowledged by experiences of enacting the rule in Iran. For the project with PBY higher than 5.5 years, an exponential function is supposed that displays a severe negative tendency on participation.

$$Pos\ (PBY) = \begin{cases} 1\ if\ PBY \le 5.5\ years \\ exp\left(\frac{PBY}{10} + 10\right)\ if\ PBY > 5.5\ years \end{cases} \tag{33}$$

4 | SOLUTION FRAMEWORK

The flowchart of the proposed method to solve the bi-level multi stage planning is depicted in Figure 2. As this figure shows, the program is started by importing data such as system configuration, solar irradiance, and data clustering information. Then the solving procedure for the upper level is started in order to determine the best location, the number of customers, and the characteristic of batteries in the system. However, through

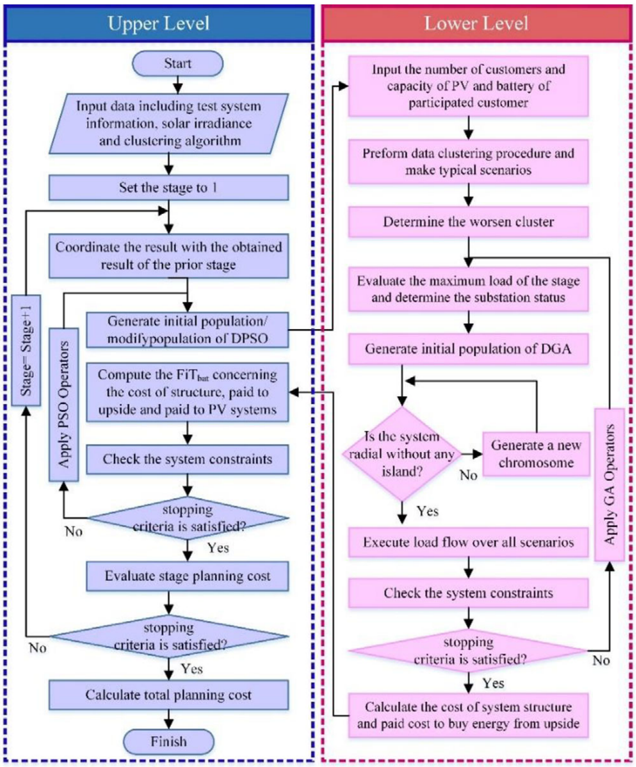

FIGURE 2 Flowchart of the proposed Bi-level multi-stage planning model.

solving the upper level problem, the optimal system structure including the status of HV/MV substations and MV feeders is also determined by the lower level problem. The result of the lower level then returns to the upper level to evaluate total planning costs and complete the solving procedure.

All aforesaid procedure is repeated for the whole stages to reach the total system structure. Due to adding new loads at each stage, the network structure should be updated at each stage. This structure depends on the result of the last stage. In other words, it is required to install new lines or install new HV/MV substations to supply all loads of the stage. Furthermore, the number of investors who participated in the stage also should be evaluated. Then, these results are considered as the existing structure for the next stage and the optimization for the new stage is repeated. After evaluating all stages, the total system structure as well as the number of private investors are determined.

It should be mentioned that due to the presence of nonlinear equations, the proposed framework is an inherently mixed integer nonlinear programming problem. In this study, evolutionary algorithms are employed to reach the optimal solution for each level. At the upper level, particle swarm optimization (PSO) is utilized to reach the optimal result. The genetic algorithm is also hired to solve the lower-level problem and determine the system structure. Both of these algorithms are powerful evolutionary algorithms that have been frequently employed in many studies. The structure of the particle of the upper level and the chromosome of the lower level are illustrated in Figure 3. It should be

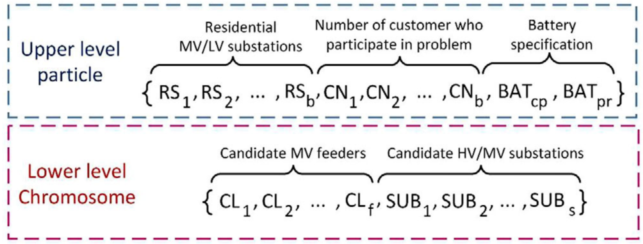

FIGURE 3 Proposed structure for the particle and chromosome of upper and lower levels.

noted that all residential buses are supposed as candidate buses to install PV and battery by RPIs.

5 | CASE STUDY AND TEST RESULTS

5.1 | Test system specification and assumption

Since assessing the real instruction of the ministry of energy of Iran in supporting investors is one of the main targets of this study, a real distribution test system of Iran is selected to evaluate the effectiveness of the proposed bi-level model. The test system is located in the east of Iran and contains 81-bus at the last stage of planning. The voltage of the system is 20 kV and the power factor of the system is supposed to be 0.9 lag. The MV busses are divided into two parts; residential buses and non-residential buses, where 46 buses at the horizon year are from residential ones. Moreover, an existing HV/MV substation and a suggested one at bus 81 are proposed to supply all load nodes as depicted in Figure 4. Detailed information on the real test system is presented in the appendix (Table 9). Meanwhile, the suggested feeders for expansion of the system in the stages are also present in the appendix (Table 10).

According to the Iranian instruction, the duration of the contract with the private investors is set to 20 years [26]. Therefore, the planning horizon of this study is also supposed to be 20 years, divided into four stages with 5 years per stage. The load growth is assumed to be 2%/year as well. Since Iran is a developing country, economic parameters like interest rate and the discount rate did not have a constant value in the past years. Therefore, the average value of the last 20 years is computed and employed in this study [27]. The life span of PV panels, battery banks, and inverters is supposed to be 20, 5, and 10 years, respectively. The real data related to the existing system verify these values and make the planner sure about the inserted data. More information concerning the simulation results is listed in Table 2. it should be mentioned that all prices presented here all the real value in Iran in 2022 and these values are transferred to the US dollar based on the exchange rate offered by the central bank of Iran [27]. The possibility function of private investor participation in the project is also displayed in Figure 5. This function is utilized to assess the planning results regarding the possibility of investors' participation.

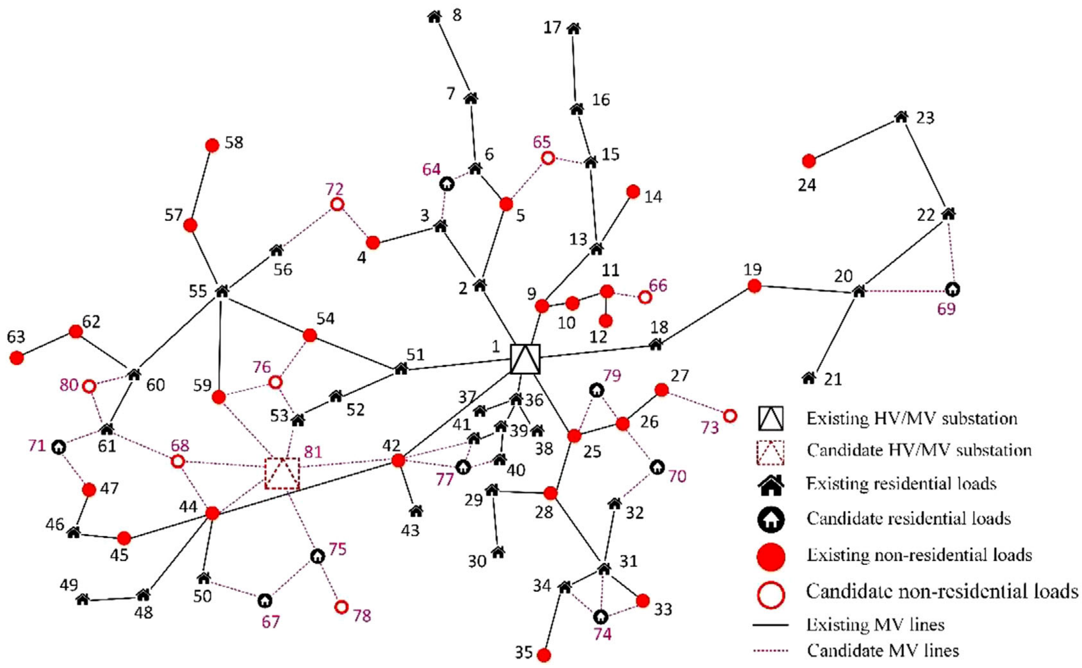

FIGURE 4 Real 81-bus distribution test system of SKEDC.

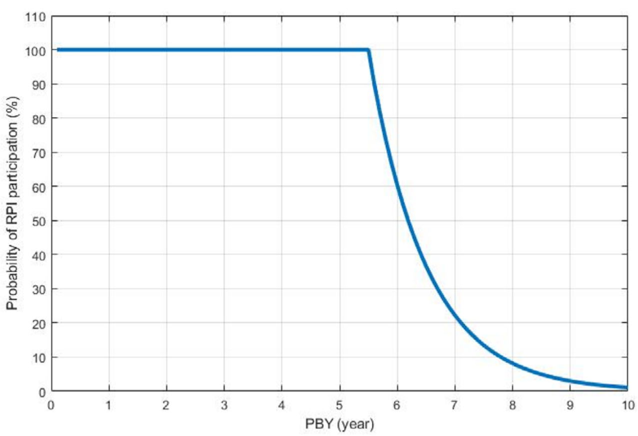

FIGURE 5 The possibility of RPI participation with respect to PBY.

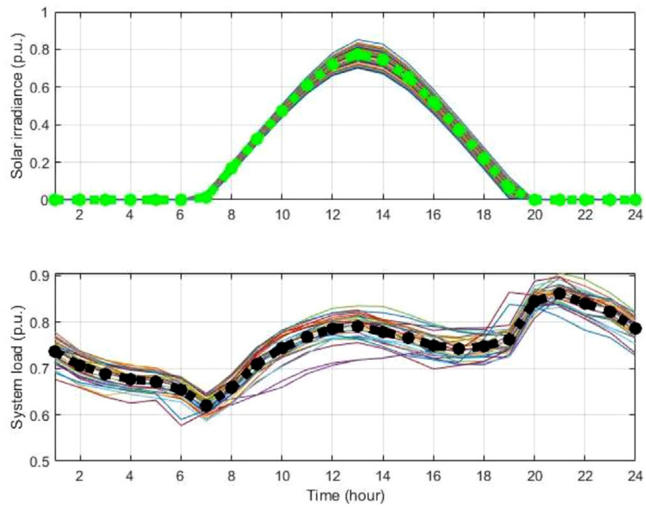

FIGURE 6 Result of solar irradiance and load data clustering for a sample cluster.

5.2 | Data clustering result

As described in Section 4 and denoted previously, FCM is employed to catch the uncertainty of the problem. To reach this goal, firstly the historical data related to the solar irradiance in the area of the test system is gathered from [28]. The variation of the load of the system is also obtained from the smart meter installed in the existing HV/MV substation. In this study, the number of clusters is set to 12 clusters. Therefore, yearly information is grouped into 12 series of data, and then, instead of evaluating the whole year's data, this series of information is utilized. A sample result for cluster number 7 and its relevant data are shown in Figure 6. Furthermore, the result of data clustering procedure and the probability of each cluster is summarized in Table 3.

5.3 | Test system results

Here, two planning options are considered to demonstrate the effectiveness of jointing batteries to PV systems in long-term planning. The first one is the existing plane that includes residential customers who just install PV panels and no battery is employed in the system (RPIWOB). But in the second planning option, a compound system including both PV and battery banks (RPIWB) is suggested and evaluated. The proposed method and the solving strategy are programmed and run in MATLAB version 2018b. The summary and the

TABLE 2 Parameters and system specifications for the real test system (exchange rate: 1\$ = 4200T̄)

parameter		Unit	Value
System planning parameters	Planning horizon	year	20
	Total stages of planning	–	4 (5 year per stage)
	Load power factor	%	90
	Annual load growth	%	0.02
	The upper limit of operation voltage	%	105
	The lower limit of operation voltage	%	95
	Total residential customer	–	21982
	Percentage of residential customers in the system	%	76
	Upside Off-peak energy price	(\$/MWh)	100
	Upside Middle-Peak energy price	(\$/MWh)	140
	Upside peak energy price	(\$/MWh)	180
System economic parameters	Inflation rate	%	16
	Interest rate	%	19
	Base FiT_{PV}	\$/kWh	0.3467
	HV/MV substation installation cost	M\$	21.4
	MV line installation cost	K\$/Km	95.23
RPI parameters	PV investment cost	\$/kW	3574.1
	PV operation & maintenance cost	\$/kW/year	2% investment cost
	PV module degradation	%/year	0.7
	Battery investment cost	\$/kWh	952.4
	Battery operation and maintenance cost	\$/kW/year	2% investment cost
	Battery life span	year	5
	Battery efficiency	%	95
	Battery depth of discharge	%	80
	Battery self-discharge rate	%	0.02
	Inverter rated power	kW	5
	Inverter investment cost	\$/kW	1190.5
	Inverter efficiency	%	95
	Inverter life span	year	10

TABLE 3 Result of FCM and the probability of each cluster

Cluster number	Members in the cluster	Probability of the cluster
1	42	0.12
2	48	0.13
3	22	0.06
4	24	0.07
5	33	0.09
6	14	0.04
7	34	0.09
8	51	0.13
9	19	0.05
10	28	0.08
11	28	0.08
12	22	0.06

comprehensive results of the planning for both planning options are presented in Tables 4 and 5, respectively. As the result of Table 4 demonstrates, both plans have almost the same total planning cost, about 149 M\$ over the planning horizon. This is due to the evaluation of $\mathrm{FiT_{bat}}$ in the upper level of the RPIWB plan concerning the total saved cost that leads to planning with almost the same cost as RPIWOB plan. The PBY of these planes however has a meaningful difference, while the PBY of RPIWOB plan increases from 5.1 years to about 8.1 years in the RPIWB plan. This lessens the possibility of private investor participation to about just 7.4%. Although the $\mathrm{FiT_{bat}}$ of this plan is higher than $\mathrm{FiT_{PV}}$, it is not so that enough to make a project with a lower PBY. This is due to the high investment cost of batteries that impose a higher initial cost on the investors and consequently, the net cash flow is decreased. But it should be noted that the RPIWB plan decreases the maximum load of the system to 0.95% of the RPIWOB plan which can postpone the requirement of installing the new HV/MV substation.

Detailed information of planning results listed in Table 5 reveals that the paid cost to investors to buy produced energy by PV system of RPIWOB plan is significantly reduced in comparison with RPIWOB plan. Charging batteries from PV systems is the reason for this reduction. On the other hand, the total paid costs to investors to buy both injected power by PV and battery has almost similar values. It should be mentioned that employing a battery in the suggested plan just shifts a part of produced energy by PV to evening hours and the battery can be charged just by PV. Thus, the total energy that every customer injects into the system is similar in both plans. But the simulation results show that paid cost to the upside network in the RPIWB plan is lower than RPIWOB plan. The reason is that in the RPIWB plan, a part of the evening load of the system that is more expensive than the load of other hours is supplied by batteries. Moreover, the losses cost of the RPIWB plan is lower than RPIWOB plan since a part of the energy produces close to the load which results in a lower power in MV lines and therefore system losses are decreased. But in stage 2 and stage 3, the losses of RPIWOB plan are less than RPIWB plan. The installing cost of the substation ascertains the reason for these lower losses, whereas in RPIWOB plan the system needs to install a new HV/MV substation at the beginning of the second stage. Installing a new substation makes a system with a lower feeder length and as a consequence, the losses of the system are declined. On the contrary, the necessity of installing a new substation in the RPIWB plan differs up to the last stage, and therefore, in the second stage and the third stage the system contains longer feeders and higher losses costs.

TABLE 4 Summary of planning results considering RPI participation

	Total planning cost M$	PBY years	Total customer in the planning –	FiT_{bat} \$/KWh	Probability of RPI participation %	Load shedding %
With RPIWOB participation	149.14	5.1	1025	–	100	0
With RPIWB participation	148.96	8.1	1025	0.587	7.4	0.95

TABLE 5 Detailed information on the planning costs with respect to upper and lower costs of each stage

Planning costs (M$)			With RPIWOB participation				With RPIWB participation			
			Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
Upper level	Paid to investor	PV	12.97	13.07	10.29	8.24	8.84	8.91	7.01	5.61
		battery	0	0	0	0	6.21	6.46	5.25	4.65
	Paid to upside network		19.91	19.85	19.81	20.01	19.02	18.97	18.93	19.12
	Losses cost		0.24	0.19	0.23	0.29	0.22	0.29	0.37	0.18
Lower level	Installing substations cost		0	19.34	0	0	0	0	0	14.98
	Installing lines cost		1.03	1.97	0.98	0.72	1.03	1.09	0.77	1.05
Total stage cost			34.15	54.42	31.31	29.26	35.32	35.72	35.72	32.33
Total planning cost			149.14				148.96			

TABLE 6 Status of the system new lines, HV/MS substations, and total installed PV and battery by RPIs

	Installed line and substation	Number of customers participated in the stage	Total installed PV in the stage (KW)	Total installed battery capacity in the stage (KWh)	Cumulative installed PV (KW)	Cumulative installed battery capacity (KWh)
Stage 1	3–64, 15–65, 11–66, 50–67, 44–68	714	3570	7140	3570	7140
Stage 2	20–69, 26–70, 61–71, 4–72	78	390	780	3960	792
Stage 3	27–73, 34–74, 67–75, 53–76	110	550	1100	4510	9020
Stage 4	81–44, 81–68, 68–61, 81–59, 40–77, 75–78, 25–79, 61–80	123	615	1230	5125	10250

The status of system components for all stages in the RPIWB plan is listed in Table 6. As mentioned previously, the output of each stage is considered as the input of the next stage. In other words, the result of each stage determines the system structure as well as the total investors who participate in the project. This structure then is utilized as the input data for the next stage. The total number of residential customers who should participate in the project is 714 in the first stage, while this value reaches about 1025 customers at the end of the planning horizon. This means about 4.1% of residential customers should participate in the project to reach such results. The total installed PV system in the last stage of planning is about 5.1 MW and the total installed capacity of batteries in the network would be about 10.2 MWh. As a result, the capacity of the battery bank for each customer is 10 kWh.

The system structure of stage 3 for both RPIWOB plan and RPIWB plan is depicted in Figure 7. This figure demonstrates that in the third stage of planning, the RPIWB plan can supply all load nodes with just one HV/MV substation. Therefore, the planner can save costs due to postponing the installing a new substation. However, since the RPIWB plan has longer MV feeders, the losses of this plan are higher than the RPIWOB plan.

The voltage of system buses in stage 3 of planning for the RPIWB plan is also presented in Figure 8. This figure is depicted for the best (off-peak) and worse (peak) conditions of the last stage of planning. This figure clearly shows that the voltages of buses even in worsen conditions are located within the permitted interval. The RPIWB plan has an improved voltage situation in contrast with the RPIWOB plan because of preparing a portion of energy close to the consumption nodes.

Finally, the total load of the system for three circumstances is represented in Figure 9; planning without RPI participation, with RPIWOB, and RPIWB. As this figure illustrates, in the system without any RPI participation, neither noon peak shaving nor evening peak shaving happened. But in the presence of RPI

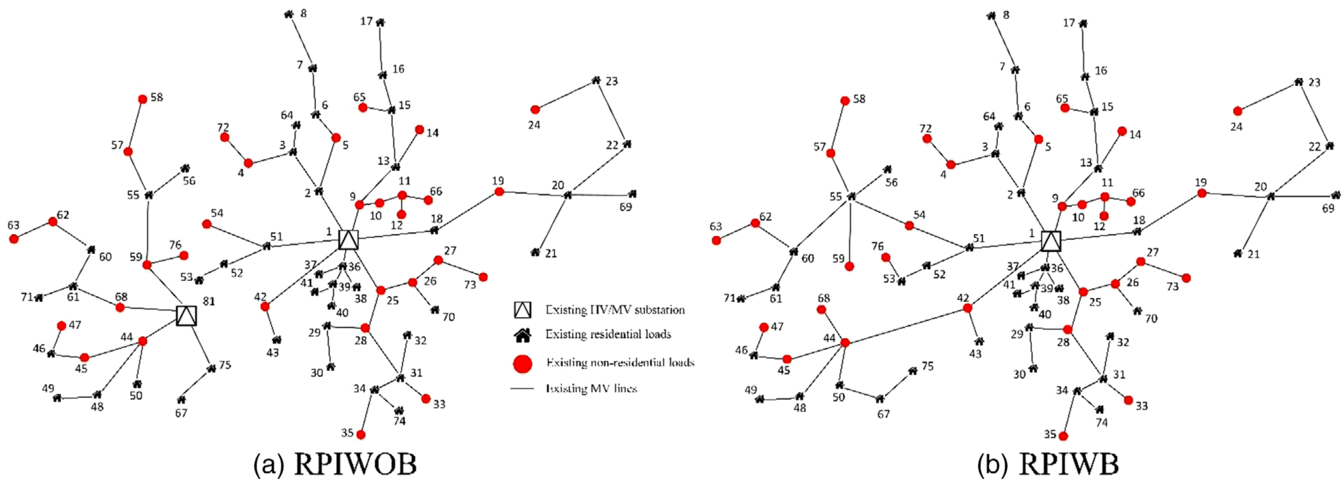

FIGURE 7 Result for stage 3 of two planes: (a) RPIWOB, and (b) RPIWB.

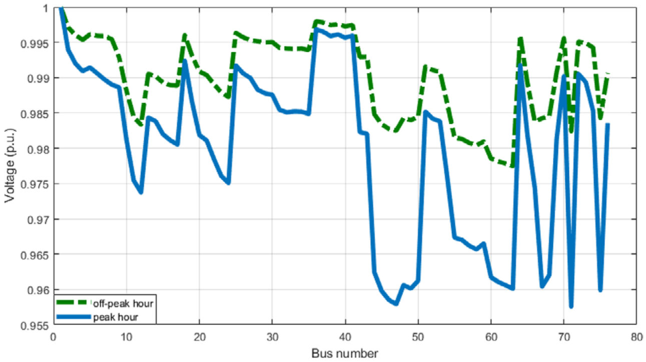

FIGURE 8 Bus voltage at the third stage of planning in the presence of RPI.

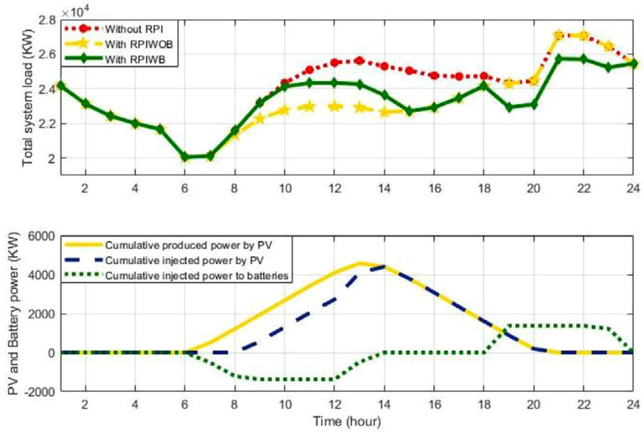

FIGURE 9 Total load of the system with respect to PV generation and battery status.

according to the existing plan (RPIWOB plan), only noon peak shaving is performed and the evening load of the system does not face any change. Accordingly, from a planner's point of view, the maximum load of the system is not reduced in comparison with the system without RPI participation. On the other hand, the both noon and evening peak of the system is properly shaving in the modified plan (RPIWB plan). The cumulative injected power to the system in lower side of this figure reveals how the RPIWB plan realize this valuable targets. This total load shedding is the key of the proposed framework that helps the system planner to save costs and then support the investors.

TABLE 7 Variety of the planning costs and parameters with respect to the possibility of RPI participation

Possibility of RPI participation (%)	PBY (year)	$FiT_{battery}$ ($/kWh)	Total planning cost (M$)	Cost increment (%)
20	7.1	0.732	150.56	1.05
40	6.4	0.901	156.99	5.39
60	6.0	0.987	160.26	7.58
100	5.5	1.006	160.95	8.04

5.4 | Sensitivity analysis

Since in the modified plan the possibility of the investors' participation does not show a considerable value, in this subsection sensitivity analysis on system parameters is performed to reach a more profitable plan from both planner and investors' point of view.

Firstly, the total planning cost regarding the possibility of RPI participation is carried out. This procedure is repeated for the possibilities of 20%, 40%, 60%, and 100%, and the result is summarized in Table 7. As the result shows, increasing the possibility of participation leads to a lower PBY as it was predictable. A lower PBY makes the project more profitable from an investors' standpoint which causes a higher possibility of investors' participation. However, the planner should offer a higher FiT for buying energy from batteries in order to present a

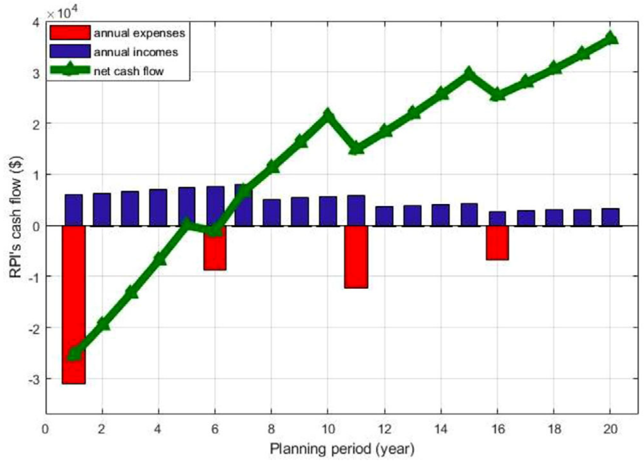

FIGURE 10 Cash flow of a RPI over the planning period (for $FiT_{\text{battery}} = 0.987\$/\text{kWh}$).

more attractive plan. But it should be noted that the result is not presented for the possibility of 80%. This is due to two reasons; firstly, the suggested exponential function for the investors' participation causes an almost similar result for the PBY with values less than 6 years. Secondly and more importantly, the invested battery by customers should be replaced every 5 years, which means a lower cash flow in the sixth, eleventh, and sixteenth years of the project as depicted in Figure 10. As this figure shows, the net cash flow of the project in the fifth and sixth years of the project does not change significantly. Therefore, a slight increase in the FiT causes a reduction of PBY from 6 to 5.5 years. It is worth mentioning that according to the result of Table 7, the planner can reach a network with the same PBY as the existing plan with just PV (PBY of 5.5 year) by increasing the total planning cost by 8.04%. For many governments such as Iran, it is considered as a worthwhile project since they support the new and clean technologies, instead of installing or expanding fossil fuel power plants.

Finally, the size of a typical PV system approved by the ministry of energy of Iran is discussed in this section. As mentioned before, the typical size in Iran is set to 5 kW which mainly causes an overproduced energy by residential customers. Despite the technical issues such as raising voltage and reverse power flow, the produced energy by the PV system is more than what a system operator needs to shave the noon peak of the system. Accordingly, the total planning cost concerning lower PV system sizes, for example, 3 and 4 kW is evaluated and the results are summarized in Table 8. These results are assessed for a system with the same planning cost and with the same PBY. In the first case, the total planning cost is almost the same as the last column of the table verify. In this case, a lower size of PV system causes to a lower paid cost to PV systems, and therefore the planner can offer a higher FiT to buy energy from batteries. Consequently, the PBY of the project can decline from 8.1 year to about 6.7 year for a system with 3 kW PV system. But in the second case, the PBY is supposed to a similar value to the existing plan (8.1 year). In this case, as well as the last case, the planner should present a higher FiT for the lower size of PV

TABLE 8 Sensitivity analysis on the RPI'z PV size

	PV size (KW)	FiT_{battery} (\$/kWh)	PBY (years)	Total planning cost (M\$)
Planning with the same total cost	3	1.053	6.7	149.79
	4	0.818	7.3	149.61
	5	0.588	8.1	148.96
Planning with the same PBY	3	0.848	8.1	142.44
	4	0.714	8.1	145.66
	5	0.588	8.1	148.96

system. The reason is that by decreasing the size of PV system, the sold energy by a customer is also reduced. Thus, the FiT to buy energy from battery should be increased to compensate the reduced paid cost to buy from PV system. This leads to a system with lower total planning cost as in the table is illustrated.

6 | CONCLUSION

According to the supporting scheme presented in many countries, in this paper, a bi-level multi stage distribution network expansion planning framework concentrated on the enacted rule in Iran was proposed. In the upper level of the proposed method, the total number of customers and therefore the total installed PV and battery in the system is determined, while the system structure is specified in the lower level. All technical and economical considerations are taken into account through the bi-level model. Additionally, since the private investor is one of the main participants in the project, economic criteria from the investors' standpoint are assessed as well. Meanwhile, the uncertainty associated with system load and solar irradiance is addressed using the data clustering method.

The proposed planning framework was applied to a real 81 bus distribution test system in Iran. Meanwhile, the revised version of the supporting instruction enacted by the ministry of energy of Iran is employed to reach actual results. Furthermore, two planning options including the existing plan (residential customer with just PV) and the modified plan (joint implementation of PV and battery) were evaluated. A possibilistic concerning the experience of hiring residential customer in last years was also defined and employed. Simulation results demonstrated that the planner can engage the customer equipped with PV plus battery system to shave both noon and evening peak of the system. However, if the planner wants to reach a network with no additional cost, the possibility of RPIs' participation may not be as enough as possible. The alternative solutions were also investigated, where either the size of the PV system is decreased or the total planning cost increase by 8.04%. In conclusion, this study reveals that enacted rules in countries such as Iran can be revised in order to implement battery systems with the aim of peak shaving. This modification however may increase the total system cost, but a considerable part of this increased cost can be compensated by postponing the requirement of installing or upgrading HV/MV substations and MV feeders.

NOMENCLATURE

Γ_b	number of data in cluster b
C_{np}	national production coefficient
$E_{bat}(h)$	state of the charge of battery bank
$E_{bat}(h)$	state of the charge of battery bank
$E_{cu}^{bat.max}$	maximum stored energy in battery
$FiT_{PV}(y)$	feed-in tariff for PV
$FiT_{bat}(y)$	feed-in tariff for PV
G_{ij}	conductance of branch ij
G_{ij}	conductance of branch ij
G_{ij}	conductance of branch ij
IC_{PV}	investment cost of PV panels
IC_{bat}	investment cost of battery units
IC_{inv}	investment cost of inverter
$J_b(U.\Gamma)$	the objective function of FCM
LSH_{max}	Maximum load shedding
$MP_{h.y}$	Market prices at hour h of year y
N_{PV}	number of PV panels
N_{bat}	number of battery units
OM_{PV}	operation and maintenance cost of PV
OM_{PV}	operation and maintenance cost of battery
$P_{h.sci.s}^{sub}$	Active power produced by substation s
$PLoss_f$	active power losses of feeder f
P_{cu}^{PV}	rated capacity of PV system
$P_{ij.t}$	active power flow in the feeder
Pr_{cu}^{bat}	power rated of batteries
$Q_{ij.t}$	reactive power flow in the feeder
V_i	magnitude of bus voltage
ca_{cu}^{bat}	Capacity of battery per customer
$p_{PV}(h)$	generating power by PV panel
x_c	data (in data clustering)
$\alpha_{s.t}$	binary variable related to establishing a new substation
$\gamma_{f.t}$	binary variable related to establishing a new feeder
$\delta_{i.t}$	angel of bus voltage
$\delta_{i.t}$	angel of bus voltage
η_{bat}	efficiency of the battery
η_{inv}	efficiency of the inverter
λ_b	cluster centre
μ_{bc}	the membership degree
ξ_y	binary variable for replacing inverter
$\rho_{sci.h}^{LV}$	probability of load variation at scenario sci and hour h
$\rho_{sci.h}^{SI}$	probability of solar irradiance at scenario sci and hour h
χ_{cha}	binary variable for charging battery
χ_{dis}	binary variable for discharging battery
ψ_{bus}	set of system buses
ψ_{cus}	set of customers participated in the planning
ψ_{fee}	set of feeders
ψ_{sci}	set of scenarios
ψ_{sub}	set of substation
ϑ_y	binary variable for replacing battery
h	index for hour
Γ	cluster center matrix
$AC(y)$	yearly adjustment coefficient
$C(y)$	yearly coefficient
DOD	depth of discharge
EER	Euro exchange rate
$Pos(PBY)$	possibility of private investor participation
$RPIF$	retail price index
T	number of periods of planning
Y	number of years in period
$b.c$	indices for data clustering
cu	index for customer
d	PV nodule degradation factor
$d(x_c.\lambda_b)$	Euclidean distance of data x_c to cluster Γ_b
dr	interest rate
f	index for feeder
i	inflation rate
ij	indices for system buses
m	the fuzzifier parameter
s	index for substations
t	index for time of period
y	index for the year of planning
ω	rate of hourly self-discharge

AUTHOR CONTRIBUTIONS

Ali Ashoornezhad: Conceptualization; Formal analysis; Methodology; Software; Validation; Writing—original draft. Hamid Falaghi: Investigation; Supervision; Writing—review amd editing. Amin Hajizadeh: Data curation; Resources; Supervision; Writing—review and editing. Maryam Ramezani: Formal analysis; Supervision.

CONFLICT OF INTEREST STATEMENT

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DATA AVAILABILITY STATEMENT

Data available in article supplementary material.

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APPENDIX

Real test system parameters with respect to the nodal load and lines' characteristics are summarized in Table 9. Furthermore, candidate lines for the expansion of the system are also presented in Table 10.

TABLE 9 Detailed information on the real test system

stage	From bus	To bus	A load (KW)	R load (KVar)	R (Ω)	X (Ω)	stage	From bus	To bus	A load (KW)	R load (KVar)	R (Ω)	X (Ω)
existed	1	2	120	58	0.2888	0.118552	existed	1	42	165	80	0.55594	0.228213
existed	2	3	180	87	0.2166	0.088914	existed	42	43	100	48	0.15162	0.06224
existed	3	4	180	87	0.2166	0.088914	existed	42	44	350	170	0.71478	0.293417
existed	2	5	230	111	0.2527	0.103733	existed	44	45	145	70	0.2888	0.118552
existed	5	6	150	73	0.12996	0.053349	existed	45	46	180	87	0.18772	0.077059
existed	6	7	115	56	0.20216	0.082987	existed	46	47	125	61	0.15162	0.06224
existed	7	8	170	82	0.28158	0.115589	existed	44	48	200	97	0.31046	0.127444
existed	1	9	2200	1066	0.10108	0.041493	existed	48	49	170	82	0.18772	0.077059
existed	9	10	2400	1695	0.09386	0.03853	existed	44	50	150	73	0.19494	0.080023
existed	10	11	1900	920	0.10108	0.041493	existed	1	51	220	107	0.41876	0.171901
existed	11	12	2300	1671	0.05776	0.02371	existed	51	52	90	44	0.2166	0.088914
existed	9	13	120	58	0.29602	0.121516	existed	52	53	105	51	0.12274	0.050385
existed	13	14	175	85	0.20216	0.082987	existed	51	54	210	102	0.33934	0.139299
existed	13	15	135	65	0.23826	0.097806	existed	54	55	230	111	0.35378	0.145227
existed	15	16	265	128	0.13718	0.056312	existed	55	56	90	44	0.2166	0.088914
existed	16	17	145	70	0.2888	0.118552	existed	55	57	135	65	0.25992	0.106697
existed	1	18	175	85	0.41154	0.168937	existed	57	58	150	73	0.22382	0.091878
existed	18	19	155	75	0.36822	0.151154	existed	55	59	130	63	0.41154	0.168937
existed	19	20	120	58	0.34656	0.142263	existed	55	60	270	131	0.4332	0.177829
existed	20	21	160	77	0.31768	0.130408	existed	60	61	270	131	0.15884	0.065204
existed	20	22	115	56	0.44042	0.180792	existed	60	62	130	63	0.24548	0.10077
existed	22	23	210	102	0.40432	0.165973	existed	62	63	165	80	0.20216	0.082987
existed	23	24	180	87	0.37544	0.154118	1	–	64	100	48	–	–
existed	1	25	190	92	0.2888	0.118552	1	–	65	110	53	–	–
existed	25	26	120	58	0.12996	0.053349	1	–	66	700	339	–	–
existed	26	27	170	82	0.13718	0.056312	1	–	67	110	46	–	–
existed	25	28	120	58	0.20216	0.082987	1	–	68	100	53	–	–
existed	28	29	175	85	0.12274	0.050385	2	–	69	95	73	–	–
existed	29	30	100	48	0.13718	0.056312	2	–	70	140	68	–	–
existed	28	31	100	48	0.2527	0.103733	2	–	71	140	48	–	–
existed	31	32	150	73	0.15884	0.065204	2	–	72	90	213	–	–
existed	31	33	120	58	0.12274	0.050385	3	–	73	150	68	–	–
existed	31	34	150	73	0.06498	0.026674	3	–	74	100	58	–	–
existed	34	35	115	56	0.19494	0.080023	3	–	75	140	53	–	–
existed	1	36	1000	484	0.05054	0.020747	3	–	76	110	48	–	–
existed	36	37	600	291	0.0361	0.014819	4	–	77	440	68	–	–
existed	36	38	970	470	0.06498	0.026674	4	–	78	120	44	–	–
existed	36	39	400	194	0.02888	0.011855	4	–	79	110	53	–	–
existed	39	40	730	354	0.04332	0.017783	4	–	80	90	44	–	–
existed	39	41	500	242	0.02166	0.008891							

TABLE 10 Candidate lines for the real test system

From bus	To bus	R (Ω)	X (Ω)	From bus	To bus	R (Ω)	X (Ω)	From bus	To bus	R (Ω)	X (Ω)
6	64	0.0722	0.029638	33	74	0.08664	0.035566	61	71	0.16606	0.068168
3	64	0.12996	0.053349	34	74	0.0722	0.029638	60	80	0.1444	0.059276
15	65	0.11552	0.047421	41	77	0.05776	0.02371	61	80	0.13718	0.056312
5	65	0.18772	0.077059	40	77	0.07942	0.032602	53	76	0.13718	0.056312
11	66	0.09386	0.03853	42	77	0.18772	0.077059	54	76	0.16606	0.068168
12	66	0.11552	0.047421	42	41	0.2166	0.088914	59	76	0.17328	0.071131
20	69	0.38266	0.157082	81	75	0.23826	0.097806	4	72	0.1805	0.074095
22	69	0.361	0.148191	75	78	0.20938	0.08595	56	75	0.2527	0.103733
25	79	0.1805	0.074095	75	67	0.22382	0.091878	81	44	0.25992	0.106697
26	79	1.0108	0.414933	50	67	0.2166	0.088914	81	42	0.36822	0.151154
27	73	0.27436	0.112625	81	68	0.30324	0.12448	81	68	0.28158	0.115589
26	70	0.18772	0.077059	44	68	0.23104	0.094842	81	59	0.29602	0.121516
32	70	0.15884	0.065204	61	68	0.2166	0.088914	81	53	0.12996	0.053349
31	74	0.07942	0.032602	47	71	0.17328	0.071131				