Modeling and Technical-Economic Optimization of Electricity Supply Network by Three Photovoltaic Systems

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To attain an ongoing electricity economy, developing novel widespread electricity supply systems based on diverse energy resources are critically important. Several photovoltaic (PV) technologies exist, which cause various pathways to produce electricity from solar energy. This paper evaluates the competition between three influential solar technologies based on photovoltaic technique to find the optimal pathways for satisfying the electricity demand: (1) multicrystalline silicon; (2) copper, indium, gallium, and selenium (CIGS); and (3) multijunction. Besides the technical factors, there are other effective parameters such as cost, operability, feasibility, and capacity that should be considered when assessing the different pathways as optimal and viable long-term alternatives. To aid this decision-making process, a generic optimization-based model was developed for the long-range energy planning and design of future electricity supply system from solar energy. By applying dynamic programming techniques, the model is capable of identifying the optimal investment strategies and integrated supply system configurations from the many alternatives. The features and capabilities of the model were shown through application to Iran as a case study.
[DOI: 10.1115/1.4025120]

Keywords: optimization model, multicrystalline silicon PV, CIGS PV, multijunction PV, electricity supply system

1 Introduction

Due to fluctuating oil prices, depletion of fossil fuel resources, global warming, and the escalating demand for energy, renewable energy sources have become much more important than at any time in history. Solar energy is a renewable source of energy whose application avoids most of the negative externalities due to the use of fossil fuels [1]. In addition, prevailing policies consider solar energy as an almost absolutely clean and safe energy source with tremendous environmental benefits [2–5]. PV technology is one of the finest ways to harness solar power. PV conversion is the direct conversion of sunlight into electricity without any heat engine to interfere [6]. Even though commercial PV modules are available and being widely deployed, it is essential that more research is carried out to improve their cost-effectiveness and well known issues are targeted to increase their competitiveness [7].

Nowadays, there are various PV technologies which have been gaining an increasing market share for generating electricity; therefore, the aim of this paper is to evaluate the potential of three effective PV technologies to cover the electricity demand. These PV technologies are (1) multicrystalline silicon, (2) CIGS, and (3) multijunction. The total cost and efficiency of the electricity supply systems are intensely depended on the selected pathways. Consequently, in order to identify the optimal investment strategies and integrated supply system configurations from the existing alternatives, an optimization model seems to be vital.

In this paper, we introduce solar energy model (SEM); a strategic optimization-based model to design an optimal and viable electricity supply system only from solar energy. The model evaluates the existing concentrates, to understand the effects of various factors through different scenarios and sensitivity analyses. We applied SEM to model an electricity supply system for Iran; however, it is a generic model and can be applied to other case studies. On the demand side, we focused on residential sector. Indeed, we considered an equal amount of demand for four cities of Iran with different climate conditions as a case study and the amount of demand was set to increase yearly.

2 An Overview of SEM

SEM is a technoeconomic optimization and also a dynamic programming model of an electricity supply system from solar technologies found on photovoltaic. It was developed based on energy system model (ESM) [8] and MATLAB software and models electricity supply system by considering three effective photovoltaic technologies for Iran in the time span between 2013 and 2022. SEM minimizes the total discounted costs of an energy supply system (which includes capital, operation, maintenance, and obtained income) over a given period and represents the flow of energy from resources to the end users in residential sectors. In SEM, the solar energy could flow through each of three mentioned PVs and then enters conversion units (charge controller, battery, and inverter). Finally, the generated electricity meets the required demand. The energy and electricity balances of the model ensure that the energy demands will be covered. The main objective function of the model is

$$Z = \min(\text{Present value total cost}) = \text{Presentvalue}_{\text{tot,inv}} + \text{Presentvalue}_{\text{O\&M}} - \text{Presentvalue}_{\text{Benefit}} \tag{1}$$

$$\text{Presentvalue}_{\text{tot,inv}} = \sum_{t=1}^{t} \frac{K_t \times Y_t}{(1+i)^t} \tag{2}$$

$$\text{Presentvalue}_{\text{O\&M}} = \sum_{t=1}^{t} \frac{M_t(Y_t + H_t)}{(1+i)^t} + \frac{O_t \times X_t}{(1+i)^t} - \frac{P_t \times E_t}{(1+i)^t} \tag{3}$$

The main equations in the SEM are classified by two groups. The first is the main equations driving the solar systems (Eqs. (6)–(12)). The second group is the base constraints of the model. Constraints of the model are structured according to the flow diagram of SEM. For each technology of the flow diagram two types of constraints should be defined. This approach reflects the basic concept of the model which is said to be a demand oriented analytical tool. This approach stresses the point that balance of demand and supply ought to be ascertained. The first group could be formulated as

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Contributed by the Solar Energy Division of ASME for publication in the JOURNAL OF SOLAR ENERGY ENGINEERING. Manuscript received July 9, 2012; final manuscript received July 15, 2013; published online September 16, 2013. Assoc. Editor: Santiago Silvestre.

Table 1 Efficiency and maximal solar radiation for the case study

	Multicrystalline silicon (%)	CIGS (%)	Multijunction (%)	Maximal solar radiation (kW h/m^2)
Mashhad	12.58	12.21	26.16	1950
Esfahan	12.68	12.30	26.34	2000
Shiraz	12.67	12.29	26.33	2150
Yazd	12.63	12.26	26.25	2200

$$F_{\text{irt}} \times \eta_{\text{it}} \le U_{\text{irt}} \tag{4}$$

where F_{irt} is the consumption of energy (inlet energy flow) in technology i, in region r, and time point t, η_{it} is the efficiency of technology i that converts inlet energy flow into outlet energy flow at time point t, U_{irt} is the outlet energy flow from technology i, in region r, and time point t.

Flow through technology "i" is possible if the capacity of the technology is available. To include capacity limitation in the set of the constraints of the model, the inequality 5 has been formulated

$$\frac{F_{\text{irt}} \times \eta_{\text{it}}}{\Delta L} - \sum_{\substack{\omega=t-\text{PL} \\ \text{or } \omega=1 \text{ if } \omega\le 1}}^{t} Y_{ir\omega} \times \text{PF}_{\text{irt}} \le \sum_{\theta=b-(\text{PL}-t)}^{b} H_{ir\theta} \times \text{PF}_{\text{irt}} \tag{5}$$

where $Y_{ir\omega}$ is the new built capacity of technology i in region r and time point ω, where ω is a point from 1 to t. PF_{irt} is the plant factor of technology i in region r and time point t. $H_{ir\theta}$ is the historical capacity of technology i, in region r and time point θ, where θ is a point from $(b-\theta)$ to b and b is the reference year (i.e., base year) and PL is the plant service life. Δl is the time length of load zone l.

2.1 Resources. Based on SEM, solar radiations are the only considered energy source. The photovoltaic system modules capture portions of the solar radiation reaching the earth's surface: the direct (G_{b}) and diffuse (G_{d}) [9–12]. The total solar radiation (G_{T}) is evaluated by

$$G_{\text{T}} = G_{\text{b}}R_{\text{b}} + G_{\text{d}}R_{\text{d}} + (G_{\text{b}} + G_{\text{d}})R_{\text{r}} \tag{6}$$

These three parameters are given by the following equations [13]:

$$R_{\text{b}} = \frac{\sin\delta \sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta - \cos\phi\cos\delta\cos\omega} \tag{7}$$

$$R_{\text{d}} = \frac{1+\cos\beta}{2}, \quad R_{\text{r}} = \rho\frac{1-\cos\beta}{2} \tag{8}$$

where $\omega = ((12-t)\pi/12)$ is the hour angle in radians as a function of time t (h) and δ the declination angle, is expressed by [14]

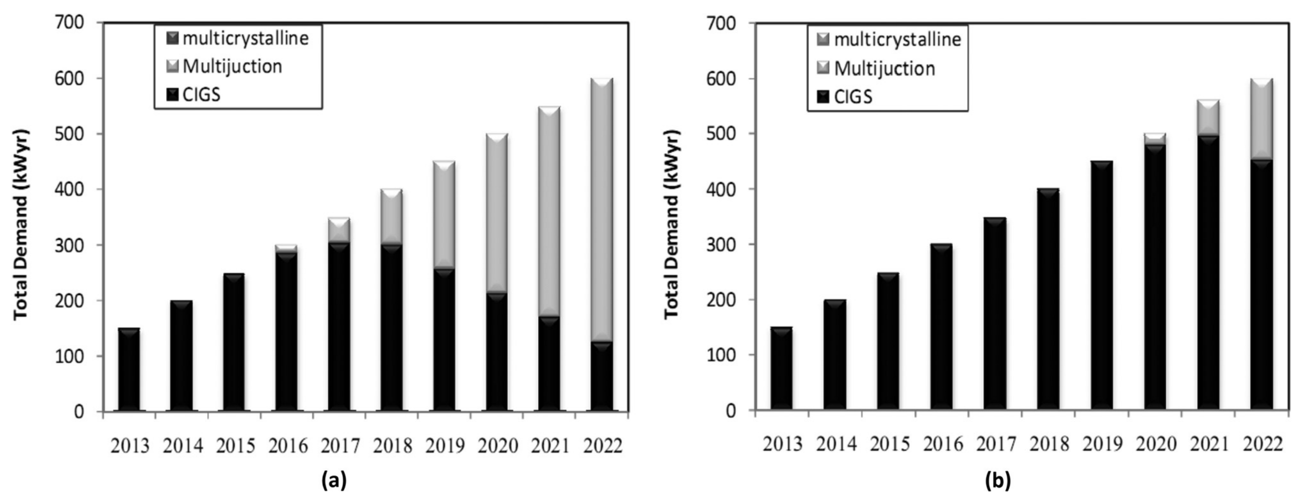

Fig. 1 Optimal planning to satisfy the demand: (*a*) base scenario and (*b*) scenario A

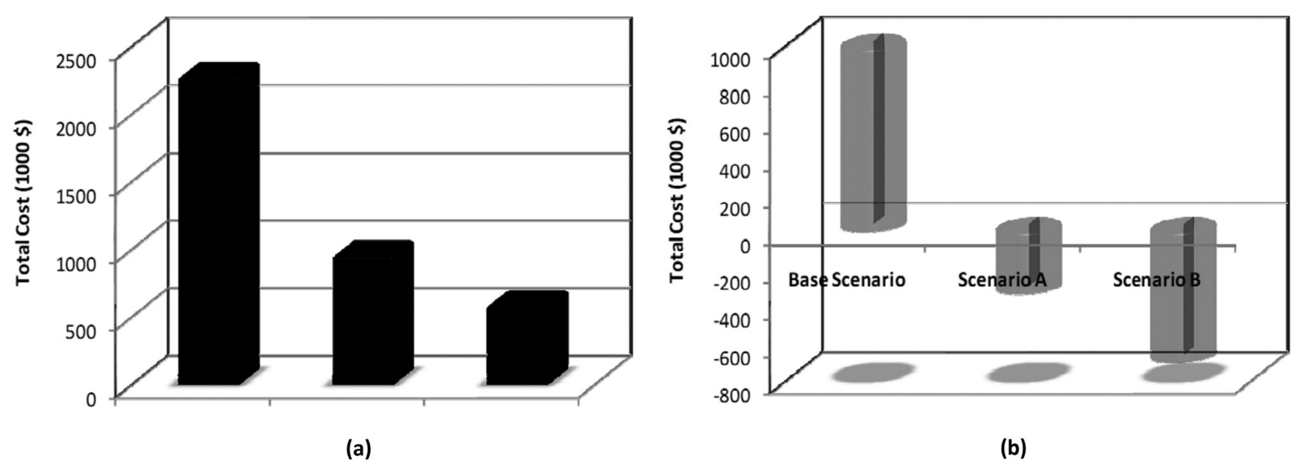

Fig. 2 Total cost of electricity supply system: (*a*) scenario C not executed and (*b*) scenario C

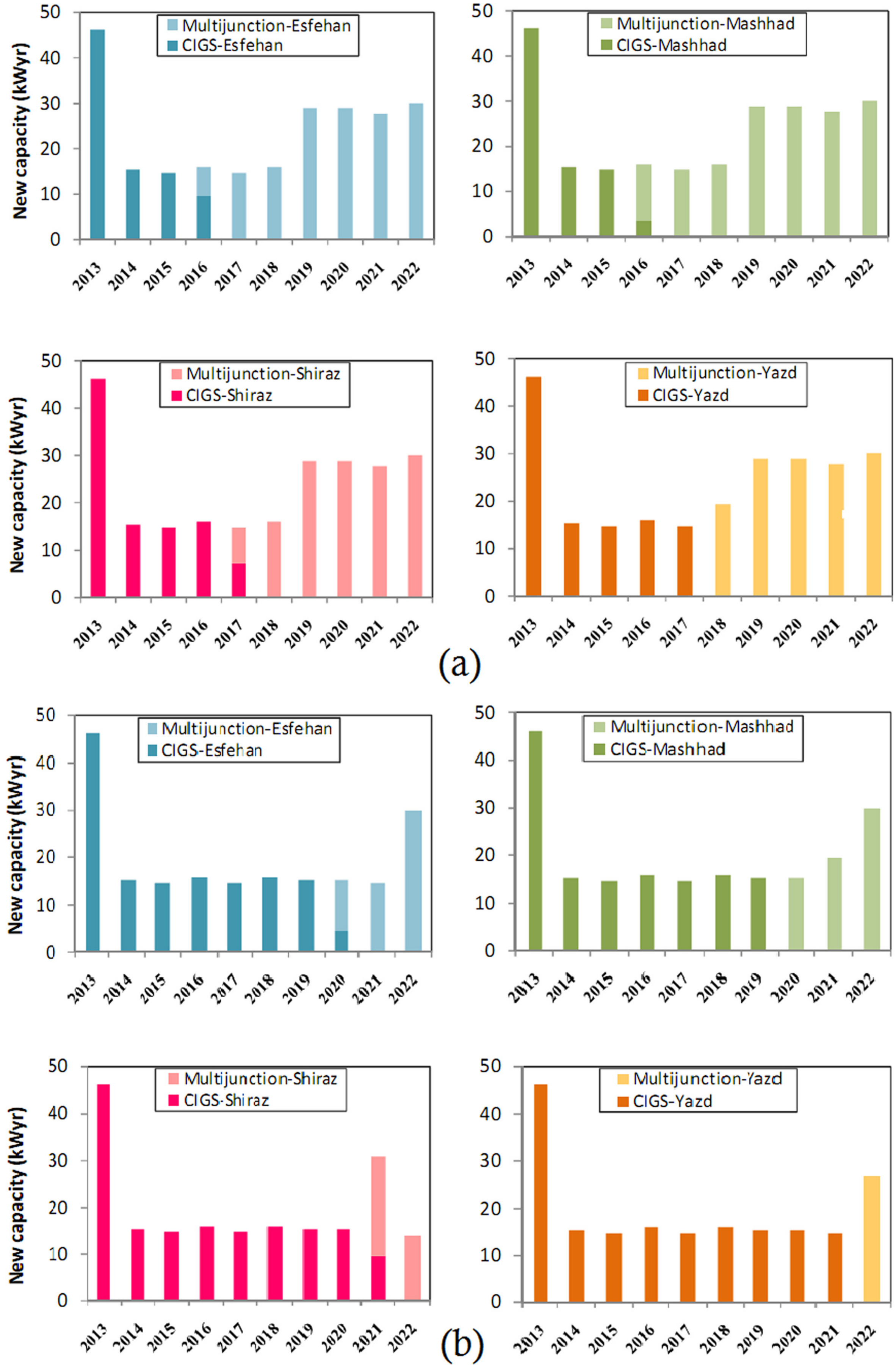

Fig. 3 Capacity construction of PV technologies for case studies: (*a*) base scenario and (*b*) scenario A

$$\delta = 23.45\,\deg \sin\left[\frac{360\,\deg(284+n)}{365}\right] \tag{9}$$

where n is the Julian day of the year, and in this study the tilt angle of the photovoltaic modules is considered equal to the location latitudes ($\beta = \phi$) [15,16]. G_b and G_d represent, respectively, the direct and diffuse solar radiation on a flat surface at an hour angle ω and are expressed as functions of the daily average total direct solar radiation on a horizontal surface (H_{b0}) and the daily average value of the diffuse solar radiation energy (H_{d0}), all expressed in W h/m^2

$$G_b = \frac{180\,\deg}{24} \frac{\sin\delta\sin\phi - \cos\delta\cos\omega\cos\phi}{\omega_s \sin\phi\sin\delta - \cos\phi\cos\delta\cos\omega_s} H_{b0} \tag{10}$$

$$G_d = \frac{180\,\deg}{24} \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} H_{d0} \tag{11}$$

where $\omega_s = \cos^{-1}(-\tan\phi\tan\delta)$ [14]. The site data $(\beta, \phi, \omega, \delta, H_{b0}, H_{d0})$ that are needed to compute G_T are available in certain databases [15].

2.1.1 Resource Constraints. The total solar radiation reaching the earth's surface must be lower than the maximal solar radiation on that surface which is shown below:

$$G_{Ti} \leq G_{Ti,\max} \tag{12}$$

2.2 Conversion. According to SEM, the charge controller, battery and inverter DC/AC were located in the conversion technologies. A charge controller regulates the voltage and current coming from the solar panels going to the battery, and the inverter converts the variable DC output of the solar battery into a utility frequency alternating current that can be fed into the commercial electrical grid or used by a local, off-grid electrical network. In the present study, we account inverter cost 6–7% total cost of photovoltaic systems [17]. The replacement cost of the inverter is not considered because its average lifespan (i.e., 10 years) is equal to the studied period. In this study, the efficiencies of the charge controller, battery and inverter were considered 0.95, 0.95, and 0.9, respectively [15].

2.3 Demand. Demand is the last part in SEM. In this study, electricity demand is obtained by historical data of the daily average electricity demand for each house and the number of considered houses [18].

3 Case Study

The considered case study was conducted on four towns of Iran: Mashhad, Esfahan, Shiraz, and Yazd. Iran, located between 29 deg N and 36 deg N latitudes, is endowed with sufficient solar radiation that can be effectively harnessed as renewable energy resource. The annual average sunshine duration of about 11 h/day and annual average solar radiation of 2000 day has been reported by Sabziparvar [19,20]. The calculated efficiencies of different photovoltaic systems (%) and the maximal solar radiation (kW h/m^2) for each town are shown in Table 1. The study time horizon is 2013–2022 and the discounted rate is assumed 10% for all years of planning. The price of electricity in base scenario is considered 0.05 $/kW h. In addition, the prices of multicrystalline silicon, CIGS and multijunction PVs are considered 3.43, 2.81, and 7.3 ($/W), respectively [17,21].

4 Results and Discussion

In the base scenario, the considered area of solar farm for each town is 2000 m^2. The SEM suggests an optimal option and continues to program for the long-range energy planning and electricity supply system (Fig. 1(*a*)). It can be seen that using multicrystalline silicon PV is not recommended, since its efficiency is a little more than the CIGS efficiency but its cost is considerably higher. Although the efficiency of CIGS PV is the lowest among the mentioned PVs, its use is more than others over the study period. An important reason for the large amount of CIGS implementation is its lower price in comparison to the other PVs. Clearly, using multijunction PV should be increased by growth in demand. In fact, due to limits on considered area, maximal solar radiation and growing demand, implementing a high efficiency technology is vital.

4.1 Solar Farm Area Increase (Scenarios A and B). In scenario A, the considered area for solar farm is elevated to 3000 m^2. Obviously, the multijunction usage is decreased and the higher fraction of electricity demand is satisfied by CIGS PV (Fig. 1(*b*)).

In scenario B, the considered area of solar farm is extended gradually until the total electricity demand is satisfied only with CIGS PV. It can be seen in the base and A scenarios, 60% and 94% of total demand are supplied with CIGS PV, respectively; and the target area in scenario B will be 5226 m^2.

The total costs of three scenarios over the study time horizon are shown in Fig. 2(*a*).The payback periods of all are over 10 years and thus far the scenario B has the lowest total cost.

4.2 Electricity Price Increase (Scenario C). As mentioned above, until the price of electricity is 0.05 $/kWh, payback periods for the scenarios will be over the study time horizon. Therefore in scenario C, the electricity price is extended gradually in order to find the price which the total discounted cost becomes zero over the study period (the obtained benefit is equal to the total cost divided by the payback period, which is 10 years).

The results show at the prices of more than 0.166, 0.099, and 0.08 $/kWh the payback periods for the scenarios (base, A, and B) are lower than 10 years, respectively. Then in scenario C, the electricity price is increased to 0.11 $/kW h, and by using the new price, the total costs of three scenarios (base, A, and B) over the study period are shown in Fig. 2(*b*). It can be seen that for the scenarios A and B, the obtained benefit is more than the required capital and O&M costs over the 10 years. The payback period for scenarios A and B will be 4.5 years after investment. Although their payback periods are equal, the obtained benefit of scenario B is higher, due to multijunction PV implementation in scenario A over the last years.

4.3 Capacity Construction. According to scenarios base and A, acquiring the electricity requires new capacity construction for PV technologies in each town (Fig. 3). Clearly, in the first year the capacity construction is the highest, while in the next years it needs lower change. Through further years, the required capacity is increased by growing demand. The major results of Fig. 3 are shown in Table 2. As seen in Table 2, for demand nodes with greater received solar radiation (according to Table 1), the complete use of multijunction PV occurs. For instance, the city of Yazd has the highest received solar radiation which uses multijunction PV from 2018 and 2022 for scenarios base and A, respectively. Also, the city of Mashhad with the lowest maximal solar radiation and PV technology efficiencies should entirely utilize multijunction PV earlier (from 2017 to 2020).

4.4 Investment Strategies. For different scenarios, the SEM represents a comprehensive planning for investment strategies,

Table 2 Advent and usage percent of multijunction

	Base scenario			Scenario A		
Year	2016	2017	2018	2020	2021	2022
Esfahan	39	100	100	71	100	100
Mashhad	78	100	100	100	100	100
Shiraz	0	51	100	0	69	100
Yazd	0	0	100	0	0	100

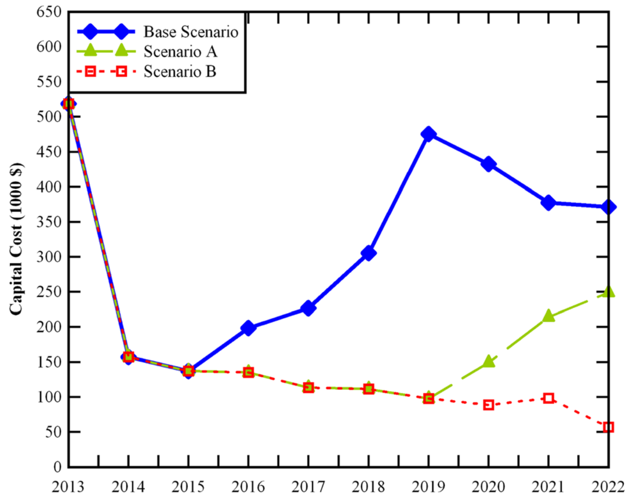

Fig. 4 The total capital cost for different scenarios

i.e., capital cost of new capacity construction which is shown in Fig. 4.

5 Conclusion

In this study, an optimization-based model (SEM) for the long-range energy planning and design of future electricity supply system from solar energy has been introduced. SEM evaluates the potential of three effective PV technologies (Multicrystalline silicon, CIGS, and Multijunction) to cover the electricity demands. Finally, it suggests an optimal planning of electricity supply, investment strategies, and capacity construction over a given period. To achieve this aim, the model minimizes all related operating and investment costs. The model was applied to Iranian electricity network as a case study. However, the SEM is a generic model and it is appropriate for other cases as well. Based on diverse land areas, the model evaluated three scenarios to satisfy the electricity demands. The scenarios consist of 2000 m^2, 3000 m^2, and without limitation of space. Finally, SEM selected scenario B (without limitation of space) as optimal pathway (with the minimum total discounted cost). An important result that should be noted is that the use of multicrystalline silicon PV is not recommended in all scenarios, and the base scenario has the maximum multijunction usage among other scenarios. Furthermore in scenario B, the designated area for solar farm was extended gradually in order to find the area which the total demand is satisfied only by CIGS PV. The results show that this area is 5226 m^2. In sensitivity analysis of electricity price, the price was increased gradually in order to find the price which the total discounted cost becomes zero over the study period (the obtained benefit is equal to the total cost and the payback period will be 10 years). The results show at the prices of more than 0.166, 0.099, and 0.08 $/kW h the payback periods for the scenarios (base, A, and B) are lower than 10 years, respectively.

Nomenclature

E = generated electricity
G_T = total solar radiation
H = new capacity
I = discounted rate
K = Boltzmann constant
K_T = cost of capacity
M = maintenance cost
n = Julian day of the year
N = plant life
O = operating cost
P = electricity price
q = electron charge constant
R_b = tilt factor for direct radiation
R_d = tilt factor for diffuse radiation
R_r = tilt factor for reflected radiation
t = time, in hours
T = temperature
X = flow through the unit
Y = historical capacity
β = tilt angle
δ = declination angle
ρ = ground reflectivity (albedo)
ϕ = location latitude
ω = hour angle, in radians
ω_s = sunrise hour angle

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