Economic Assessment of Small-scale Grid-connected Roof-top Solar PV System for Domestic Consumers of Himachal Pradesh

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Abstract – *Small-scale rooftop solar PV systems are convenient forms of energy providers for the household worldwide. Himachal Pradesh receives abundant solar energy with average annual Global Horizontal Irradiations (GHI) above 4.5kWh/m2/day which is adequate for installation of solar PV systems. Government of India has launched several schemes to promote the grid-connected roof-top solar PV systems. Objective of this study is to perform the economic analysis of grid-connected roof-top solar PV system for the domestic consumers of Himachal Pradesh (HP). Three different size of solar PV systems are selected (1020Wp, 2040Wp and 3400Wp) for comparative economic assessment for domestic consumers with monthly electrical energy consumption in the range of 60kWh to 600kWh. This study provides the comparative financial analysis with expected returns on investment and payback period for solar PV systems for domestic consumers with different energy demands under government policies and subsidies. Results of this in-depth analysis demonstrates that grid-connected roof-top solar PV systems would be economically viable for the domestic consumers of Himachal Pradesh with monthly average electrical energy consumption of 200kWh and above, can generate an alternate source of income for the consumers and contribute to the environmental friendly solution.*

Key Words: Solar PV System, Grid-connected, Roof-top, Economic assessment

1. INTRODUCTION

India's geographical area receives about 5000 trillion kWh of solar energy each year with most sections receiving 4-7 kWh per m^2 per day [1]. The National Institute of Energy estimated the countries solar potential to be at 748 GW, assuming solar photovoltaic modules cover 3% of the geographical surface. India is a perfect location for solar energy because of its geographical location. India receives around 250 to 300 days of sunshine each year [1], [2].

Under the Paris Agreement of 2015, India is committed to generate 40% of electricity (450GW) from renewable energy sources by 2030. Solar energy plays a vital role in achieving the target with a target of 280GW from solar power by 2030 which is around 60% of the total renewable energy target [3].

Himachal, hill state of India receives annual average Global Horizontal Irradiations (GHI) above 4.5kWh/m^2/day [4]. This is a tiny hill State with a height of between 300 metres in Kangra and Una, and over 7,000 metres in Lahaul and Spiti, central Himalayans. It spans an area of 55,673 km^2, about 1.69% of the total surface area of the nation [5]. GHI in the region are influenced by diverse topography of the state. The lower- and middle-elevation zones (<3500m) with tropical to wet-temperate climate receives higher GHI (>5 kWh/m^2/day) for a major part of the year compared to the higher elevation zone (>3500 m) with dry-temperate to alpine climate (4–4.5 kWh/m^2/day) [4].

Himachal has set a target of achieving 10GW of solar power by 2030 [6]. Himachal Pradesh, among all States and territories of the Union of the nation, is the state with the greatest proportion of rural people to the overall population. 89.97% of population of Himachal Pradesh resides in the rural of state [7]. Small-scale roof-top solar PV system can contribute to the Himachal's ambitious target of achieving 10GW by 2030.

Government of India is promoting the roof-top solar PV systems and have launched PM Surya- Har Ghar Muft Bijli Yojana. Under this scheme, subsidy is provided for consumers to install roof-top solar PV system. This paper analyze economic aspects of the small size of grid connected roof-top solar PV system for the domestic supply consumer for Hamirpur. This study also evaluates the electricity tariffs and net metering applicable for the consumers of Himachal Pradesh. Site selected for study, Hamirpur is one of the districts of Himachal located in the lower west central outer Himalayas at an average elevation of 790m above sea level [15]. Study provides the detailed comparison of three different size of solar PV system according to the consumer's energy demand.

Three grid-connected roof-top solar PV systems A, B and C with capacity 1020Wp, 2040 Wp and 3400Wp respectively are used for the study. Domestic consumer can install solar PV system based on the electrical energy needs or economic feasibility therefore objective of selection of different capacity solar PV systems is to provide a comparative analysis of 3 different size solar PV systems for domestic consumers with electrical energy needs in the range of 60kWh to 600kWh per month

1.1 Definition of Domestic Consumers

This study is applicable to the domestic supply for the electrical energy consumers of Himachal Pradesh and is applicable to the following consumers of energy [8].

- Consumers using electrical energy for lights, fans, heaters, cooking ranges, ovens, refrigerators, air conditioners, stereos, radios, televisions, mixers, grinders, electric iron, sewing/embroidery/knitting machines, domestic pumping sets and other domestic appliances in a single private house/flat or any other residential premises;
- Religious places with connected load up to 5 kW;
- Orphanages, homes for old people and homes for destitute;
- Working Women Hostels, Hostels attached to the educational institutions, if supply is given separately to each hostel and the electricity charges are recovered from the students;
- Leprosy Homes run by charity and un-aided by the Government;
- Panchayat Ghars with connected load up to 5 kW;
- Patwar Khanas and Kanungoo Bhawans (Government Buildings only) with connected load up to 5 kW;
- Community gausadans, goshalas and cow sanctuaries not registered with Gow Sewa Ayog with connected load up to 20kW;
- Monasteries and Nunneries;
- Heritage Hotels approved under HP Government's Heritage Tourism Policy, 2017;
- Residential Paying Guests;
- Incredible India Bed-and-breakfast as per GoI, Ministry of Tourism guidelines;
- "Home Stay Units" in rural areas duly registered with the District Tourism Development Officer;
- Offices of the Himachal Pradesh Senior Citizen Forum;
- Personal Garage for parking of personal light motor vehicle;
- For Industrial Consumer which are under PDCO due to non-payment of dues or sick closed units with maximum connected load of 20 kW for lighting and security purpose only till regular connection is restored (Pre-paid meter provisionally); and HPSEBL-D Business Plan and MYT Order for 5th Control Period (FY25-29) Himachal Pradesh Electricity Regulatory Commission
- MES and other military establishment

1.2 Electricity Tariffs and Subsidies

In Himachal Pradesh, the provision of electricity is overseen by the Himachal Pradesh State Electricity Board Ltd. (HPSEBL). Electricity charges to the domestic consumers of the state with the subsidy provided by the government of Himachal are as per [8].

2. BRIEF ON ROOF-TOP SOLAR SYSTEM POLICIES

To economically analyze the grid-connected roof-top solar PV systems, it is important to understand the government policies and subsidies provided to promote renewable energy. In accordance with the Electricity Act, 2003, every state in India has come up with a net metering policy or a rooftop solar policy which dictates the modalities of installing a grid-connected rooftop solar or a small solar power plant in the given state. In the net metering mechanism, the electricity generated by the solar PV system is consumed by the user and any excess electricity is injected into the grid. In case the consumer requires more power than what is produced by the solar PV system, they can import the balance from the grid. At the end of the settlement period, the consumer is only charged for the 'net' energy utilized – the difference between the energy produced through the solar PV system and the energy consumed over the billing period. A bi-directional meter is used to measure the net electricity consumption of the system [9] .

2.1 Net Metering Regulations

Himachal Pradesh Electricity Regulatory Commission, makes the amendments in 2022 in the Himachal Pradesh Electricity Regulatory Commission (Rooftop Solar PV Grid Interactive System based on Net Metering) Regulations, 2015 [10] as listed below:

(a) The rooftop solar system upto capacity of 50 kWp may be installed under net metering.

(b) Under net metering, the solar energy generated from the rooftop solar system, installed at premises of the eligible prosumer, is used by the prosumer in his premises and the surplus energy, if any, is delivered to the Grid.

(c) The energy imported by the Prosumer from the Grid, on net basis, during a billing period is billed to the Prosumer at applicable retail tariff

(d) A net-meter to measure the net flow of energy is installed by the distribution licensee at Prosumer premises. The cost of net-meter is borne by the prosumer.

(e) The carry forward of unadjusted surplus energy from one billing period to the subsequent billing period(s) within the same settlement period is done in shape of unit's kWh or kVAh, as the case may be.

(f) The unadjusted surplus energy, if any, as per the bill for the last billing period of the settlement period shall be settled as per the provisions of Regulation.

"Prosumer" means a person who consumes electricity from the grid and can also inject electricity into the grid for distribution licensee, using same point of commencement of supply. In this paper Prosumer is identified as consumer.

2.2 Capacity of Roof-top Solar PV Systems

All eligible consumers of electricity in Himachal Pradesh are eligible for the roof-top solar PV system. Maximum size of roof-top solar PV system is decided based on the sanctioned connected load to the consumer as per the slabs decided by the Himachal Pradesh Electricity Regulatory Commission [11] in 2018. Table 1 provides the maximum solar PV system capacity based on sanctioned load for consumers.

Table 1: Capacity of roof-top solar PV system

Sr. No.	For consumers having sanctioned connected load	Maximum peak capacity of Solar PV Project
1	5kW or less	100% of sanctioned connected load
2	Exceeding 5kW but not exceeding 10kW	70% of sanctioned connected load or 5kW; whichever is higher
3	Exceeding 10kW	50% of sanctioned connected load or 7kW; whichever is higher

2.3 Solar PV System Subsidy Policy

To encourage the domestic households to install roof-top solar PV plants, Government of India launched PM Surya Ghar Muft Bijli Yojana on February 15, 2024 [12]. Under this scheme, subsidy is provided on small-scall roof-top solar plants per below:

4 Rs 30,000/- per kW roof-top solar plant is provided by government up to 2kW plant size.
5 Rs 18000/- per kW additional capacity up to 3kW roof-top solar plant size.
6 Total subsidy for systems larger than 3kW capped at Rs 78,000/-.

2.4 Settlement Rate for Solar PV System Consumers

As per Himachal Pradesh Electricity Regulatory Commission regulations, 2015 and subsequent amendments, the rates for settlement of surplus power exported to Grid by PV system consumer is Rs 1.051/kWh for domestic category consumers [13].

3. METHODOLOGY

3.1 Data Collection

The performance of solar PV systems can be different according to their different configurations and locations [14]. In this study, three configurations of capacity 1020Wp, 2040Wp and 3400Wp of grid-connected roof-top PV system are considered for techno-economic analysis and suitability for the domestic consumers of Himachal Pradesh. Three grid-connected roof-top solar PV systems A, B and C with capacity 1020Wp, 2040 Wp and 3400Wp respectively are modelled in the software tool PVsyst. Domestic consumer can install solar PV system based on the electrical energy needs or economic feasibility therefore objective of selection of different capacity solar PV systems is to provide a comparative analysis of 3 different size solar PV systems for domestic consumers with electrical energy needs in the range of 60kWh to 600kWh per month.These solar PV systems are identified by Solar PV System A, System B and System C respectively in this paper. This present paper considers the Hamirpur district of Himachal for the study purpose. The geographical co-ordinates of Hamirpur is 31.68°N 76.52°E [15]. Meteorological weather data provided provided by National Solar Radiation Database managed by The National Renewable Energy Laboratory (NREL) is used for the study purpose [16]. Electricity tariffs and subsidies provided by the Government of India and Government of Himachal Pradesh applicable in Year 2023-24 as defined in section 1 and section 2 are used for the economic analysis of grid-connected roof-top solar PV systems. Cost of small-scale solar PV components is received from local suppliers.

3.2 Economic Assessment Method

Techno-economic analysis is performed for small-scale grid-connected roof-top solar PV system by using following calculation methods. Electrical energy consumed by consumers varies and depend upon the no. of family members in family and type of appliances used at household based on income of the family. Electrical energy consumption in the range of 60kWh per month to 600kWh per month is selected for the economic assessment of grid-connected roof top solar PV systems A, B and C.

Electricity bill is calculated based as total cost of the energy units consumed by consumer minus no. of energy units generated by PV system. In case the no. of units generated by PV system is more than the no. of units consumed by consumer, surplus energy units are exported to the grid at settlement rate defined by the Himachal Pradesh State Electricity Board for the domestic category consumers as per section 2.4.

Monthly Electricity Bill (Rs.) = No of units consumed by consumer (kWh) x energy charges + fixed charges [8]

No. of energy units (kWh) generated by PV system more than, equal to or less than energy consumption by consumer. Total cost saving per month with installation of grid-connected roof-top solar PV system is calculated for two cases as defined below to calculate net annual cash-inflow.

Case I: If No. of energy units generated by PV system ≥ monthly energy consumption of consumer

Cost Saving on Electricity Bill (Rs.) = Monthly electricity bill

Surplus Energy Exported to Grid (kWh) = No. of units generated by PV system - No. of units consumed by consumer

Cost of Surplus Energy Exported to Grid (Rs) = Energy exported to Grid x settlement rate

Total Cost Saving (Cash In-flow) / month (Rs) = Cost saving on electricity bill + cost of surplus energy exported to grid

Case II: If No. of energy units generated by PV system < monthly energy consumption of consumer

Cost Saving on Electricity Bill (Rs.) = Monthly electricity bill – Cost of energy units imported from grid

Total Cost Saving (Cash In-flow) / month (Rs) = Cost saving on electricity bill

Payback Period [PB]: Payback period is defined as the amount of time it takes to recover the cost of an investment and can be calculated as ratio of initial investment to net annual cash in-flow.

$$PB = \frac{Investment\ Required}{Net\ Annual\ Cash\ Inflow}$$

Levelized Cost of Electricity [LCOE]: The levelized cost of electricity (LCOE) is a measure of the average net present cost of electricity generation for a generator over its lifetime. It can be expressed as the ratio of plant cost (capital cost [CC] + present Value of Maintenance Costs [MC]) to the total electricity generated [E].

$$LCOE = \frac{CC + MC}{E}\ Rs/kWh$$

A roof-top solar PV system is defined as unprofitable when Net Present Value (NPV) of the project is less than zero.

3.3 Software Tool for Solar PV System Modeling

The PVsyst tool is commercially available software that is used to simulate solar PV projects. This study used PVsyst tool for the simulation of solar PV system. The PVsyst software library contains detailed data most common photovoltaic modules and inverters offered by different suppliers, and all that is needed for a photovoltaic system project. Furthermore, it records losses due to the partial shadowing effects, mismatches between connected PV modules, wiring losses, inverter losses, and the effect of the ambient temperature variations on its electrical output power calculation. This functionality makes it a precise tool to estimate the amount of electrical energy produced by a designed system [17].

4. PV SYSTEM MODELING

Three grid-connected roof-top solar PV systems A, B and C with capacity 1020Wp, 2040Wp and 3400Wp respectively are modelled in the software tool PVsyst. Models are analyzed for domestic consumers with energy demand in the range of 60kWh to 600kWh per month. Final results depends on the net metering, energy imported or exported by consumer for solar PV systems A, B and C. Identical technical parameters are selected for comparative study purpose.

4.1 Weather Data & Tilt Angle

Hamirpur experiences short warm summers from late April to June when temperature may go up to 40 °C, and cool winters from mid-October to April having as low as 7 °C. Monsoon season starts in late June and lasts till early September with fair amount of rainfall. The optimum tilt angle for solar PV is 30^{o} at which it receives an irradiation of 4.96 kWh/m^2/day. Detailed irradiation data for Hamirpur is provided in Table 2. The present study has considered the meteorological weather data provided by National Solar Radiation Database (South Asia 2000-2014) managed by NREL [16]. Geographical co-ordinates of Hamirpur are 31.68^{o}N 76.52^{o}E.

Table 2: Monthly solar irradiation data for the investigated Hamirpur district of HP.

Month	Global Horizontal Irradiation (kWh/m²/day)	Horizontal Diffuse Irradiation (kWh/m²/day)	Temp (°C)
January	3.43	1.31	11.8
February	3.95	1.73	13.2
March	5.52	2.03	19.6
April	6.39	2.54	24.0
May	6.92	2.74	29.0
June	5.98	3.07	30.6
July	5.14	3.15	27.1
August	4.87	2.76	25.3
September	5.20	2.21	24.7
October	4.91	1.99	22.2
November	3.83	1.47	16.8
December	3.38	1.21	12.8
Year	4.96	2.19	21.4

The tilt angle of solar panels is significant for capturing solar radiation that reaches the panel's surface. The azimuth is defined as the angle between the south direction and the direction the panels face. Fig. 1 shows the plane tilt angle and azimuth angles (30° and Azimuth 0° respectively).

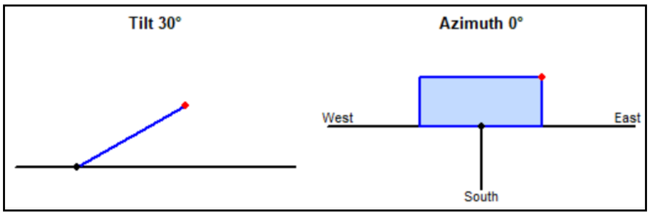

Fig. 1: Orientation parameters of PV modules arrangement system: tilt angle and azimuth angle

4.2 Technical Specifications

Three small-scale PV systems A, B and C of different capacity are modelled in the PV Syst software tool for the assessment. Selection of PV module and inverter in the PV syst database is based on the most suitable capacity and size for the designing of solar PV system and is listed out in Table 3.

Table 3: Technical specifications of solar PV system

Solar PV System	A	B	C
DC PV array capacity	1020 Wp	2040 Wp	3400 Wp
PV module (AEG AS-M1203B-H-360)	340 W / 29 V , η = 23.08%	340 W / 29 V , η = 23.08%	340 W / 29 V , η = 23.08%
Inverter	1000 W, η = 98.10%	2000 W, η = 98.10%	3000 W, η = 98.10%
PV module connection	1 string of 3 modules	1 string of 6 modules	2 strings of 4 modules each
Roof area required	6 Sq.m	11 Sq.m	15 Sq.m
Performance ratio	0.854	0.845	0.844
Irradiance (G)	1811.7 kWh/Sq. m. annum	1811.7 kWh/Sq. m. annum	1811.7 kWh/Sq. m. annum

4.3 Cost Details

Estimated cost of solar PV systems is received from system suppliers in the region as listed in Table 4. Government subsidy on the PV system is applied under PM – Surya Ghar: Muft Bijli Yojana [12].

Table 4: Cost details of grid connected roof-top solar plant.

System	**PV System Cost (Rs.)**		
Solar PV System	**A**	**B**	**C**
DC PV array capacity (Wp)	1020	2040	3400
PV array cost	26700	53400	89000
Mounting structure Cost	3500	7000	10500
Inverter cost	7500	14500	17500
Charge controller & other components cost	4000	8000	10000
Installation and other charges	7800	15780	21840
Total capital cost	49500	98680	148840
Govt. subsidy	30000	60000	78000
Capital cost after subsidy	**19500**	**38680**	**70840**

5. ECONOMIC ASSESSMENT

Solar PV systems are assessed economically based on the tariffs plans and electricity generated by each PV system for the consumers with different electrical energy needs in the range of 60kWh per month to 600kWh per month. In addition, following factors are considered for the economic analysis:

- The life expectancy of PV models is over 25 years [18].
- Inverter life has been considered as 10 years [19].
- The overall maintenance cost of solar PV plant has been considered as 1% of the capital cost [20].

Solar PV system A with capacity of 1020Wp consists of 3 solar modules of 340Wp connected in series. Total electricity generated by 1020Wp PV system model is 1807kWh yearly. Levelized cost of electricity is 1.39 Rs. /kWh.

Solar PV system B with capacity 2040Wp generates 3578kWh electricity yearly with 6 solar modules of 340Wp. 2 strings of 3 modules each are used for solar PV system modeling. Levelized cost of electricity for 2040Wp PV system is 1.38 Rs. / kWh.

Solar PV system C with capacity 3400W generates 5967kWh electricity yearly with 10 solar modules of 340Wp. 2 strings of 5 modules each are used for solar PV system modeling. Levelized cost of electricity for 3040Wp PV system is 1.20 Rs. / kWh.

All three solar PV systems are non-profitable for the consumers with low electricity demand (<200 kWh/month). This is because of the subsidies provided by HPSEBL for low income consumers on electricity bill. However system will be profitable for the consumers with monthly consumption of more than 200kWh with payback period and return on investments as shown in Chart - 1 and Chart - 2. Payback period for system A is minimum among 3 models though it is noted that system B with capacity 2040kWh would be most suitable for domestic consumers with monthly average electrical energy consumption of 400kWh. Reason is the tariff rates applicable in this range of electricity consumption [8].

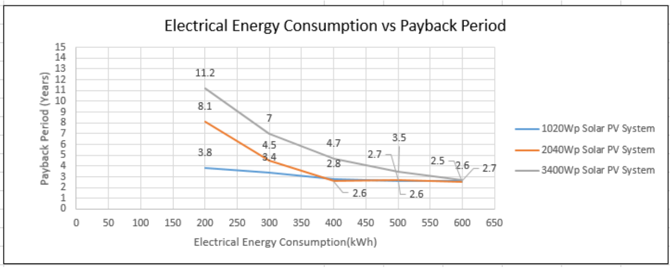

Chart - 1: Electrical Energy Consumption vs Payback Period for three solar PV systems

Similarly, return on investment for the solar PV system A would be highest among all as shown in Chart - 2. However net present value of solar PV system C is highest as shown in Chart - 3.

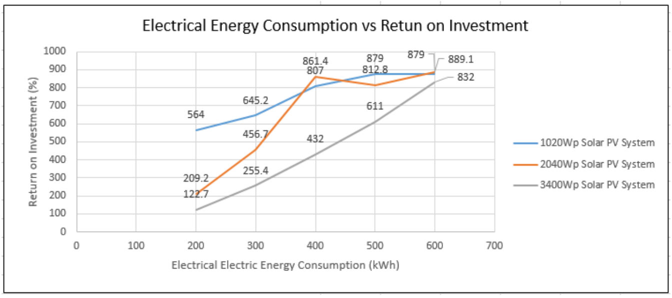

Chart - 2: Electrical Energy Consumption vs Return on Investment (ROI) for three solar PV systems

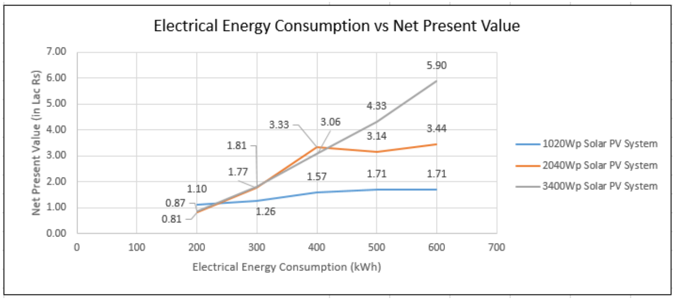

Chart - 3: Electrical Energy Consumption vs Net Present Value (NPV) for three solar PV systems

6. ENVIRONMENTAL IMPACT

To achieve a global target of net-zero carbon emissions by 2050 requires substantial scaling up of solar photovoltaic (PV) and other renewable energy production [21]. The global installed capacity of solar PV power has increased 30-fold from 2009 to 2019, while its cost of generation has declined by 90% [22]. It is important to measure the environmental benefit of grid-connected roof-top solar plant over its life-time cycle. Chart - 4 shows the amount of CO_2 emission saved by the different small-scale grid-connected roof-top solar plants. The calculations depend majorly on the value of the life cycle emissions (LCA), which represent CO_2 emissions associated with a given component or quantity of energy. This includes the total life cycle of a component or the amount of energy, including production, operation, maintenance, disposal, etc. The rationale behind the carbon footprint tool is that the electricity generated by the photovoltaic system will replace the same amount of electricity in the existing grid. If the carbon footprint of the PV installation per kWh is smaller than the one for the grid electricity production, there will be a net saving of Carbon Dioxide emissions. Thus, the total carbon balance for a PV installation is the difference between produced and saved CO2 Emissions. From Chart - 4, CO_2 emission is negative until the last 10 years (or close) of the project; then, it becomes positive.

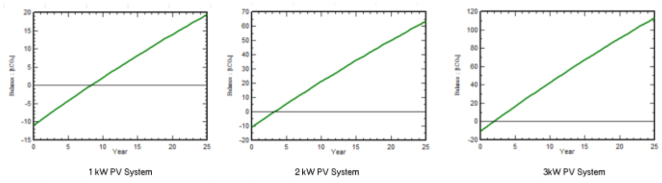

Chart - 4: CO_2 emission reduction vs. time for PV Systems

7. CONCLUSIONS

This paper performed comparative economic assessment of three small scale grid-connected roof-top solar PV systems of capacity 1020Wp, 2040Wp and 3400Wp for domestic consumers of Himachal Pradesh with average electric consumption in the range of 60kWh to 600kWh per month. Under PM – Surya Ghar: Muft Bijli Yojana [12], it is found that grid-connected roof-top solar PV systems would be economically viable for the domestic consumers of Himachal Pradesh having average month electrical energy consumer more than 200kWh. Though solar PV systems would not be economically viable for the consumers with monthly average electrical energy consumption less than 200kWh because of the tariff rates and subsidies provided to the consumers. Study also highlights the environmental benefits of installing grid-connected roof-top solar PV system for different slab consumers of electricity during its life cycle. This study can be used as base for further economic evaluation of grid-connected roof-top solar PV system considering more technical details e.g. adding the impact of shadow area on the performance of solar PV system. From the study, it is evident that promoting the grid-connected roof-top solar PV system in rural as well as urban areas of Himachal Pradesh under PM - Surya Ghar: Muft Bijli Yojana [12] could help domestic consumers to install economic feasible grid-connected roof-top solar plants and contribute to achieve solar energy target of 450GW by 2030 for India.

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