Energy Informatics

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# Solar PV-hydropower enhanced Picogrid as sustainable energy model for hilly remote areas: analytics and prospects thereof

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**Abstract**

This paper presents a techno-economic analysis of 'Picogrid' in hilly remote areas of North-East India, where availability of conventional grid power is either none or limited. A Picogrid is a small microgrid (typically a few tens of kW) containing renewable energy sources like solar, wind, small hydro *etc.* with battery based energy storage of limited capacity. A hybrid solar PV-Hydro based Picogrid of 7.2 kW capacity in a remote hilly area is analyzed, where the solar irradiance varies between 3.5 and 6.2 kWh/Day/m$^2$, a water fall head lies between 1 and 30 m and water flow rate varies from 100 to 50,000 L/h. The study reveals that, the annual total energy generation varies between 1200 and 5000 kWh/kW/Year. Whereas the annual average daily yield and Capacity Utilization Factors for such system are 9 kWh/kWp/Day and 40%, respectively at highest possible water head and flow rate as mentioned above. The optimized Picogrid system is shown to have a levelised cost of electricity of 1.4 INR (0.017 USD) and 1.8 INR (0.022 USD) per kWh for 100% and 30% equity investment, respectively. The energy produced by these methods can be provided in rural areas thereby making electricity and revenue producing probabilities concurrently.

**Keywords:** Distributed generations, Picogrid, Poverty, Renewable energy, Sustainable, Smart grid, Socio-economic-environmental

## Introduction

Energy generation and its efficient utilization must very soon be accessible, decentralized and affordable to greater segment of our society. Whereas a great urban and semi-urban population enjoys the grid power, several remote pockets of the globe such as, remote villages, deserts, hilly areas *etc.* demands decentralized generation and use of energy. In India, region like hilly North-East, energy services for basic livelihood is still under development. Regional 'Picogrid' can give access to clean, green, reliable and affordable energy services.A Picogrid is a small microgrid (typically a few tens of kW) containing renewable energy sources like solar, wind, small hydro *etc.* with battery based energy storage of limited capacity. This Picogrid can function in isolation or ought to join to adjoining homes and different structures, *e.g.* a school or hospital as covered in literature (Desai *et al.* 2014, 2019, 2021, 2022; Sharma and Goel 2017; Cvetkovic *et al.* 2012;

Verizon 2013; GE Home Management System 2013; Hitachi and Management Systems 2013; Nordman *et al.* 2012). The system has additional flexibility of convenient sharing of any surplus power. For example, when a workplace has days off, its excess power will be straightaway sold to its alternative users. Picogrids also tackle a lot of shriveled set of issues, even if with abundant larger utility potential, therefore, they permit the development of in style technological ability which will quickly prove to be vitals mentioned in paper (Verizon 2013; GE, Home Management System 2013; Hitachi and Management Systems 2013; Nordman *et al.* 2012).

Picogrids are the advanced and isolated version of smart grid with some key exceptions: (i) they furnish solely a single voltage and stage of quality/reliability; (ii) they do no longer tackle structures with complicated optimization. Picogrids are mainly design for those areas where larger energy generation (hundreds of kW or more) with the help of renewable sources is not possible. They have complete dual way control of power generation and distribution in their area of implementation as mentioned in literature (Desai et al. 2021, 2022; Sharma and Goel 2017; Cvetkovic et al. 2012; Verizon 2013; GE, Home Management System 2013; Hitachi and Management Systems 2013; Nordman et al. 2012; Nordman 2014).

They also have several other advantages like:

- Exceptional profit margin due to reduced transmission and distribution cost.
- Energy security throughout the year.
- The Picogrid approves one to reduce ordinary expenses and emissions except requiring any alternate in each day lifestyles.
- Picogrid is plausible for areas such as far flung villages, islands and so on with no development or underdeveloped infrastructures.

Globally researchers are making large efforts to learn about Picogrids and its implementation. Additionally, its demonstration sites and allied engineering need to be thoroughly addressed (Nordman et al. 2012; Nordman 2014; Teleke et al. 2014; Hossain et al. 2014). To the best of our knowledge, a systematic model investigation of developing, ambient operation and economic aspects of the Picogrid system have not been reported so far. This paper presents the techno-economic analysis of Picogrid with the ambient, irradiation and weather condition of North-East India.

## Hybrid solar PV-hydro Picogrid concept

Concept of Picogrid is mainly to evolve the electricity network in areas where the access of electricity is restricted. By creating regional Picogrid based on the renewable energy sources mitigate basic energy needs for local community. Picogrid contains renewable energy sources like solar, wind, small hydro etc. with battery based energy storage which are smartly controlled by a controller with the help of communication. This Picogrid can be created either for individual household or for community. As shown in Fig. 1 it individually operates only houses or adjacent houses as well as community hall, school, primary health centre which could be connected. When the school has holidays or week off, its extra generated energy should be bought to its neighbors based on demands and vice-versa. A health centre ought to have units that want excessive energy continuously

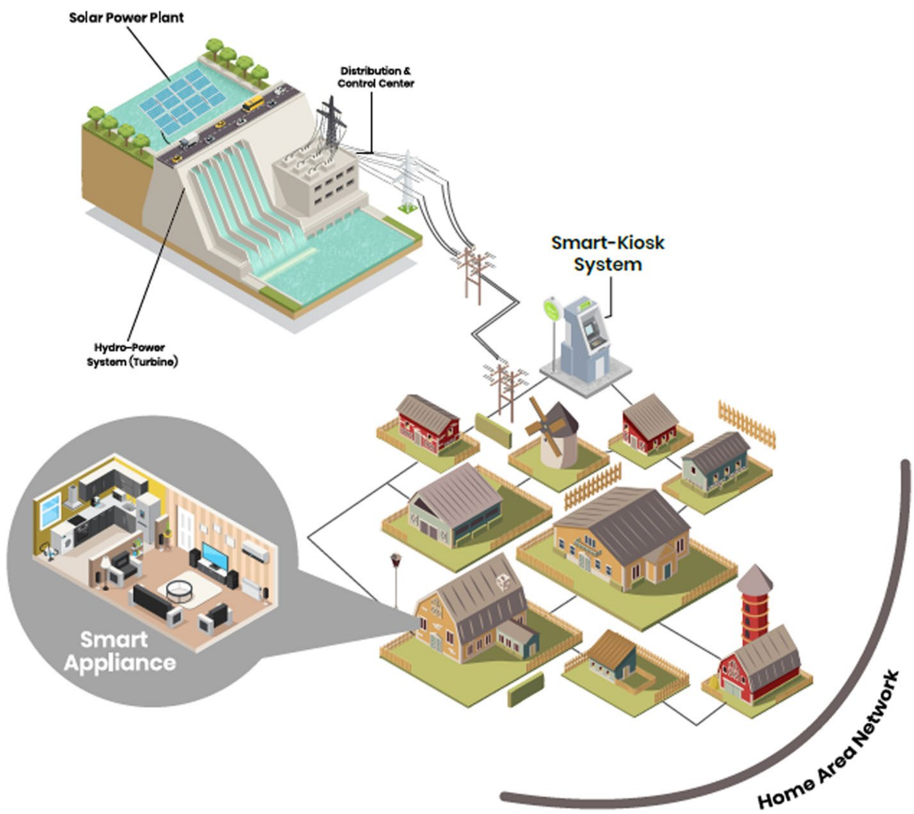


**Fig. 1** An example of renewable energy based Picogrid

to furnish essential life-saving drugs and services or to store vaccines. The power supply to such critical loads will be given utmost priority against non-critical loads as mentioned in references (Nordman et al. 2012; Nordman 2014; Teleke et al. 2014; Hossain et al. 2014; Owens 2014; Murthy Balijepalli et al. 2010; Singh et al. 2014).

As shown in Fig. 2 a community of Picogrids is required to manipulate area's electricity distribution. Power sources might accommodates the utility grid, neighborhood renewable power, and energy storage. At any given time, there would be an internet drift throughout many "links" in the electricity distribution network, with many Picogrids for buying and selling power on special ports. The strength of distribution communication topology can alternate at any time. This raises the trouble of how to decide the quantity of electricity exchanged amongst the related Picogrids. A central controller answer would impose costs, verbal exchange needs, and administrative burdens, and create a plausible single factor of failure for the whole system. A higher strategy makes use of a thoroughly dispensed system, with every Picogrid periodically reconsidering its energy trading for choices primarily based on its personal needs, portions on hand or desired, and prices. This makes the grid scalable from a single remote Picogrid to massive networks of grids of extraordinary sizes (Nordman et al. 2012; Nordman 2014; Teleke et al. 2014; Hossain et al. 2014; Owens 2014; Murthy Balijepalli et al. 2010; Singh et al. 2014).

In growing states like North East India, most humans in far-off areas are no longer in a position to derive advantages from the ongoing electrification process. Since there is no strong network reachable to join the remote villages to the central or

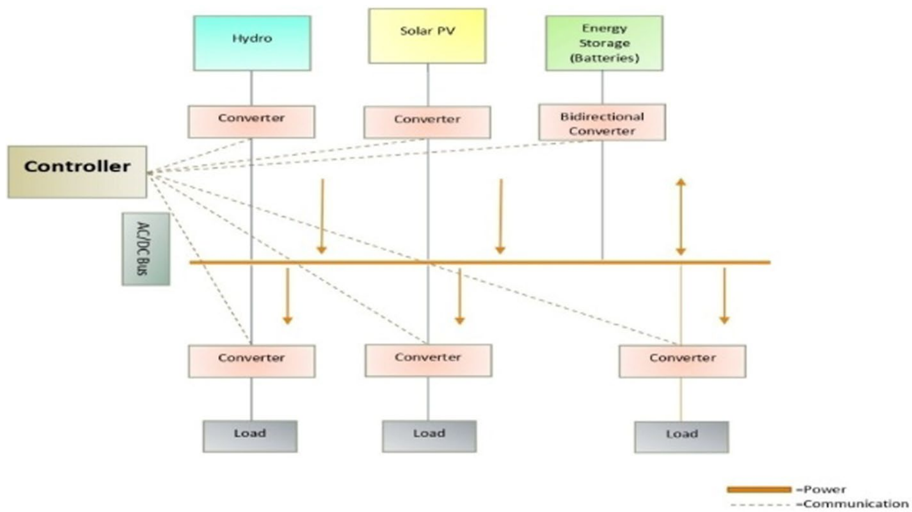


**Fig. 2** Picogrid Architecture

local grids, greater investments are needed. In this connection, the Government had initiated the manner of rural electrification thru regional renewable-based energy sources. Owing to these demarcations, the theme of Picogrids in growing international locations has a special viewpoint and broader scope for discussion. In India, even though there is an initiative for the encouragement of smart grids there is nonetheless a lengthy way to go for imposing the Picogrid as per the mentioned literature (SheerazKirmani and Akhtar 2018; Akikur et al. 2013; Bhutto et al. 2013; Buyer 2014; Lasseter and Piagi 2014; GE 2020). Renewable strength-based dispensed power technology is a nice and top-of-the-line solution. It can grant dependable furnish of electrical energy to enhance shipping of fundamental social needs: health, meals, and education. Picogrid will supply nearby energy to isolated/rural neighborhoods can permit to access health centers and additionally can enable kids to go to school as presented in reference (Jeeva and Aditya 2018; Masrur et al. 2020).

## Mathematcal model of solar hydro based picogrid

### Theory and assumption of solar PV power

#### *Solar radiation on tilted surface of solar module*

Total solar irradiance (radiation) on Tilted surface of the solar module reflected, direct and diffuse radiation (Okello et al. 2015; Padmavathi and Daniel 2013; Peerapong and Limmeechokchai 2014; Pundir et al. 2016; Shukla et al. 2016; Sidrach-de-Cardona and Lopez 1999; Skoplaki and Palyvos 2009; Sundaram and Babu 2015; Tarigan and Kartikasari 2015).

$$I_{TR} = I_b r_d + I_b r_b + (I_b + I_d) I_r \tag{1}$$

where $r_r$, $r_b$ and $r_d$ are reflected, beam and diffuse and $I_r$, $I_b$ and $I_d$ are beam, direct radiation and diffuse instantaneous values, respectively.

#### *Average annual solar radiation on tilted solar panels (without shading)*

Using empirical equation we can measure the beam, direct and diffuse radiation or estimate the total solar radiation falling on solar module. Month wise, daily average monthly global radiation on a horizontal surface $H_{ga}$ is given by Padmavathi and Daniel (Pundir et al. 2016; Shukla et al. 2016; Sidrach-de-Cardona and Lopez 1999; Skoplaki and Palyvos 2009; Sundaram and Babu 2015; Tarigan and Kartikasari 2015; Vasisht et al. 2016; Wittkopf et al. 2012; Odou et al. 2020).

$$H_{ga} = (H_{oa} + H_{ob}) * \{a + b[S_a/S_{ma}]\} \tag{2}$$

where $H_{oa}$ = Average monthly solar radiation at horizontal surface. $H_{ob}$ = Average monthly solar radiation at horizontal surface at rear surface. $S_a$ = month wise average daily sunshine hour. $S_{ma}$ = possible daily maximum sunshine hours at a given location. a and b are constants.

#### *Plant performance ratio*

Solar Plant performance can be identified on the basis of available solar radiation at plant location against the generated energy. This Performance Ratio (PR) is based on the all type of losses right from the solar module to grid losses with respect to radiation and local climate condition. PR value generally varies between 60 and 80% however it is depend on the Solar PV module temperature, DC cable loss, Soiling losses, AC cable loss, transmission losses etc. PR is defined as the ratio of the final yield ($Y_f$= total energy fed to the grid) to reference yield of the total energy ($Y_r$) that the system could have produced without any losses in ideal condition (Pundir et al. 2016; Shukla et al. 2016; Sidrach-de-Cardona and Lopez 1999; Skoplaki and Palyvos 2009; Sundaram and Babu 2015; Tarigan and Kartikasari 2015; Vasisht et al. 2016; Wittkopf et al. 2012; Odou et al. 2020).

$$PR = Y_f/Y_r \tag{3}$$

The Performance ratio (PR) is mainly influenced by module mismatch loss, module temperature loss, DC cable loss, AC cable loss, incidence angle modifier (IAM) loss, soiling loss etc.

#### *Solar PV module efficiency*

Solar PV module efficiency instantaneous is given by

$$\eta = P_{dc}/(G * A_m * 100) \tag{4}$$

As a function of temperature, it can be represented

$$\eta_T = \eta_{Tref} * (1 - \beta_{ref} T - T_{ref}) \tag{5}$$

where, $\eta_{Tref}$ = PV module efficiency at reference temperature. $\beta_{ref}$ = power temperature coefficient. $T_{ref}$ = Reference temperature. T = Cell temperature.

$$T = T_{amb} + \{1.25 * 10 - 3Gt * (NOCT - 20)\} \tag{6}$$

where, NOCT = Nominal operating Cell temperature. $T_{amb}$ = Ambient temperature. Gt = Total solar irradiance in plane.

Photovoltaic system energy

$$Es = \mathrm{At} * \eta * \mathrm{Hga} * \mathrm{PR} \tag{7}$$

Es = Energy generated from solar (kWh). At = Total solar panel Area (m2). η = solar panel efficiency (%). Hga = Average annualsolar radiation on tilted panels. PR = Performance ratio, coefficient for losses (default value = 0.7) (Desai et al. 2019, 2021, 2022).

In orders to simplify the analysis, some assumptions are adopted in Table 1 as follows for 5 kW PV system.

#### Theory and assumption of Pico hydro power

Normally, Pico-hydro energy systems found in rural or remote neighborhood which is usually discovered at hilly area. This system will function the usage of higher water reservoir, which is a few meter excessive from ground. Water flows downhill from the reservoir via the piping system. This downhill distance is referred to as "head" and it lets in the water to reap enough kinetic electricity for rotating the excessive transferring system. Thus, the alternator will be rotated by turbine to generate electricity. This produced electrical energy blended with PV system and storage (Desai et al. 2019, 2021, 2022):

$$\mathrm{Ein} = \left(\mathrm{H} * \mathrm{Q} * \mathrm{g} * \mathrm{hn}\right) \tag{8}$$

where, $E_{in}$ = Input energy from hydro. H = Net Head (meter). Q = Water flow rate (liters per second). g = acceleration due to gravity (9.81 m/s$^2$). $h_n$ = numbers of hour.

This $E_{in}$ input energy available at alternator end which is coupled with Generator to generate the electricity which has internal losses which could be define as hydro electrical system efficiency. With this Actual energy of picohydro system could be defined as

$$\mathrm{Eh} = (\mathrm{Ein} * \eta \mathrm{h}) \tag{9}$$

where, $E_{in}$ = Input energy from picohydro. $\eta_h$ = Hydro Electrical system efficiency.

As shown in Eq. (8) head and water flow are critical and utmost important parameters in Pico-hydropower system. Head is the measure of falling water at turbine through penstock and similarly flow is amount of water flowing in trough turbine. Higher head leads to higher pressure and better water flow rates leads to higher generation of the system (Desai et al. 2014).

In order to simplify the analysis, some assumptions are adopted as follows:

a. Head height varies between 1 and 30 m.
b. Water flow rate considered between 0.03 and 15 LPS.

**Table 1** Monthly generation

| Month | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Irradiance (kWh/Day/m$^2$) | 5.1 | 5.8 | 6.2 | 5.7 | 5.7 | 4.4 | 3. 9 | 4.2 | 4.2 | 3.6 | 4.9 | 3.5 |
| Generation (kWh/kW/Day) | 3.6 | 4.9 | 4.4 | 4.1 | 4 | 3.1 | 2.7 | 2.9 | 2.9 | 2.5 | 3.5 | 2. 5 |

c. Hydro Electrical system efficiency ($\eta_h$) is considered 50% (Desai et al. 2014).

Total Hybrid Energy (Ehybrid) generation from solar and picohydro is:

$$\text{Ehybrid} = \text{Es} + \text{Eh} \tag{10}$$

The modeling methodology based on the picogrid function under the different condition as follows as detailed in the Additional file 1.

Operational Condition 1.1: For Day time

Solar power generation is greater than the sum of the power demand of the loads.

$$\sum \text{PPG(t)} = [\text{PS}] \geq \sum \text{PLoad(t)} \tag{11}$$

where PPG = Power of picogrid, PS = Solar PV power, PH = Hydro power, PLoad = Load power or

If solar power is not enough than hydro will also directly fed to load

$$\sum \text{PPG(t)} = [\text{PS} + \text{PH}] \geq \sum \text{PLoad(t)} \tag{12}$$

Operational Condition 1.2: For Night time

For Night time hydro power will directly fed to loads.

$$\sum \text{PPG(t)} = [\text{PH}] \geq \sum \text{PLoad(t)} \tag{13}$$

Operational Condition 2.1: For Day time

The Generation of the picogrid is less during day time than the sum of the power demand of the loads. However, the power provided by the ESS can meet the gap between load demand and picogrid during day time where they will first use solar than hydro and balance supply from ESS. For Day time capacity of energy storage is given by:

$$\text{PESS(t)} \geq \sum \text{PLoad(t)} - \sum \text{PPG(t)}[\text{PS} + \text{PH}] \tag{14}$$

The upper and lower limits of summations in Eqs. (11)–(14) may be taken as realistic time of usage. It means a day and a night time ranges could be different. Figure 3 and Eqs. (11) to (14) shows the modeling of Picogrid in which we can clearly see that Water, Solar Radiation and Temperature are essential and main parameters base on that energy generation can be predicted. In this modeling PV module, Turbine, Generator, Charge controller, Battery and Inverter are the main components of Picogrid.

## Results and discussion

### Technical exploration

The analysis is based on the model as described above and Additional file 1. The parameters used in the calculation of the system performance are mainly solar irradiation, temperature of ambient, and hydro water flow and its head. It can be seen that the output power has a significant effect of solar and pico-hydro power generation. A further metric of this output power may be presented in terms of the capacity utilization factor (CUF) of the pico-hydro system. In subsequent results, the output power is shown to increase as any one of above sources increases it capacity.

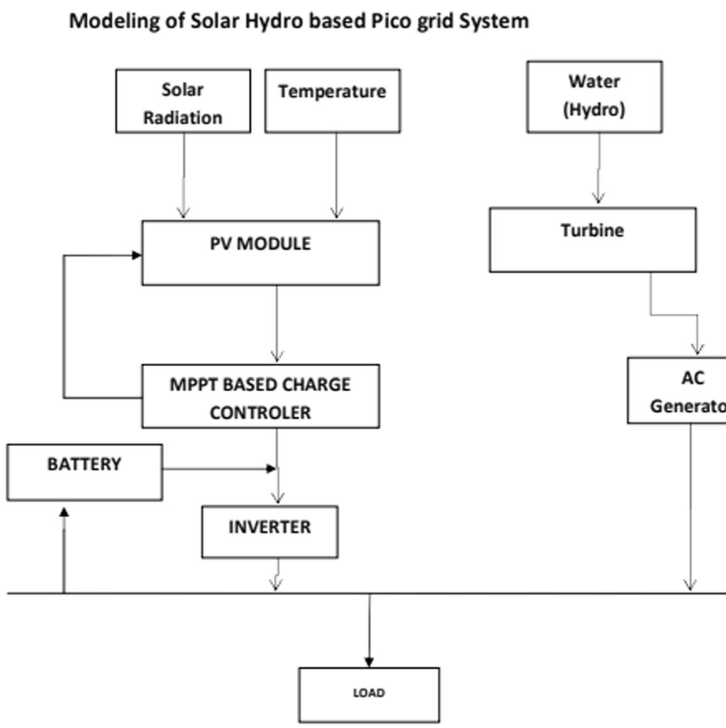


**Fig. 3** Mathematical model flowchart of Picogrid adapted in the study

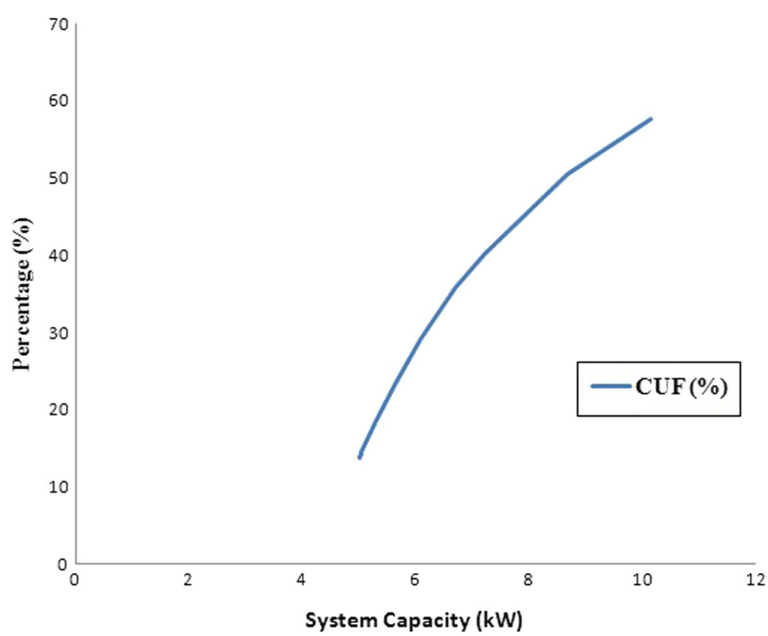


**Fig. 4** CUF at different power capacity from all possible sources

In Fig. 4 we can see the different CUF at different power capacity. Here we have calculated the CUF first at different hydro power capacity. The range of CUF varies from 13.8 to 57% with a hydro power of 16 W- 5 kW along with 5 kW solar PV power plant.

Therefore, with above parametric assumption, one can design a Picogrid of capacity between 5 and 10 kW with an average CUF of 27% which best represents a region like North-East India.

On the other hand, by considering the water head at a given value, the CUF behaves in a fashion the water flow pattern changes with different point of time in a year. As shown in Fig. 5 the effective generation is practically and economically possible by establishing the Picogrid we have considered 30 m head and flow rate of 15 LPS which give 2.2 kw Hydro power.Here we have taken 5 kW solar PV plant totaling to 7.2 kW Picogrid which has an average CUF of 40%. The total Daily average generation, Annual Average Daily Yield, Annual Average Yield and CUF are 70 kWh/Day, 9 kWh/kWp/Day, 2100 kWh/kWp/Year and 40%, respectively at 30 m Head and 15 LPS as explained in mentioned Literature (Al Ali and Emziane 2013; Alonso-Abella et al. 2005; Ayompe et al. 2011; Baltus et al. 1997; Chokmaviroj et al. 2006; Cucumo et al. 2006; Drif et al. 2006; Dubey et al. 2013; Evans and Florschuetz 1977; Hegedus and Luque 2011; Kamalapur and Udaykumar 2011; Kumar and Sudhakar 2015; Kumar and Nagarajan 2016; Kymakis et al. 2009; Marion et al. 2005; Hamdan 2011; Mondol et al. 2006; Mulcué-Nieto and Mora-López 2014; Okello et al. 2015; Padmavathi and Daniel 2013; Peerapong and Limmeechokchai 2014; Pundir et al. 2016; Shukla et al. 2016; Sidrach-de-Cardona and Lopez 1999; Skoplaki and Palyvos 2009; Sundaram and Babu 2015; Tarigan and Kartikasari 2015; Vasisht et al. 2016; Wittkopf et al. 2012) The CUF is certainly higher than the previous case which is about 30%.

## Economy of the Pico-hydro system

In order to find out the economic benefits of the Picogrid we have calculated the payback of the 7.2 kW Picogrid system with two equity models: 100% equity and 30% equity. We have considered following parameters and assumptions in order to estimate their economies:

(i) Picogrid system size is 7.2 kW (5 kW Solar PV + 2.2 kW Pico Hydro)
(ii) An off grid 5 kW Solar PV system cost—300,000/- INR (3650 USD)

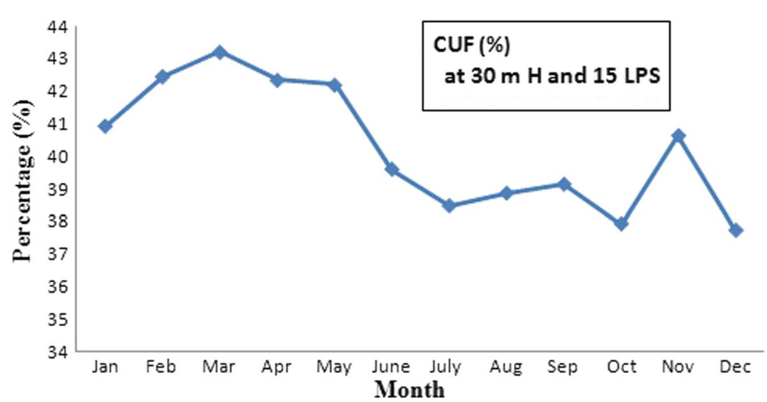


**Fig. 5** CUF of solar PV—hydro hybrid system for 30 m Head and 15 LPS of hydro system for various times in a year in North-East India

(iii) 2.2 kW Pico Hydro system with 500 m Pico grid network cost—300,000/- INR (3650 USD)
(iv) Infrastructure cost—50,000/- INR (610 USD)
(v) O & M cost for 25 years- 150,000/- INR (1830 USD)

For finance of the system we have considered the constant 10% annual finance on 70% debt.

Here, electricity cost is taken to be 5 INR/ unit (0.06 USD/Unit). We have also considered the degradation of the solar system 1%. Assuming economic life of the system of 25 years, the Levelised Cost of Electricity (LCOE) has been estimated. In our present calculation, a conversion rate of 1 USD = 82 INR has been considered.

### *The levelised cost of electricity (LCOE) generation*

The LCOE of renewable energy sources varies with the aid of technology, region and challenge primarily based on the renewable power resource, capital and running costs, and the efficiency/performance of the technology. The method used in the evaluation introduced right here is primarily based on a direct cash flow analysis. This technique of calculating the price of renewable energy is based totally on discounting monetary flows annually over the venture lifetime to a frequent basis, taking into consideration the time price of money as explain in reviewed papers (Odou et al. 2020; Giele 2012). The system used for calculating the LCOE of Picogrid electricity applied sciences is:

$$\mathrm{LCOE} = \sum_{y=1}^{n} \frac{\left(\frac{I_y + O\&M_y + F_y}{(1+C)^y}\right)}{\left(\frac{E_y}{(1+C)^y}\right)} \tag{15}$$

where LCOE = the average lifetime levelised cost of electricity generation; Iy = investment expenditures in the year y; O &My = operations and maintenance expenditures in the year y; Fy = Interest pay in the year y; C = discount rate; and n = economic life of the system.

As shown in Fig. 6 this 7.2 kW Picogrid can meet requirement up to 20 families with 100 W capacity each which consist Lightings, Fan etc. Therefore, this Picogrid earns every year 100,000 INR (~1220 USD) by selling of 20,000 kWh to local communities. A LCOE is found to be 1.4 INR (0.017 USD) per kWh for 100% equity investment and 1.8

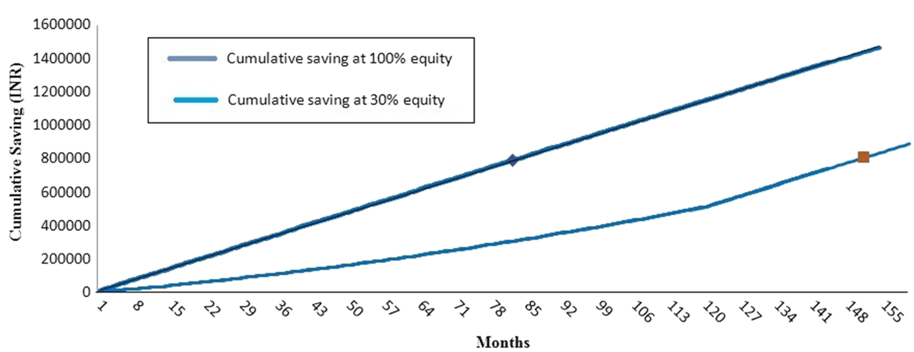


**Fig. 6** Cumulative Saving from the Picogrid in INR. Conversion factor of 1/82 applies for the savings in USD

INR (0.021 USD) per kWh for 30% equity investment. The internal rate of return (IRR) are 15% and 8% for 100% and 30% equity investments, respectively. Eventually the technology can be treated as economically viable besides emerging other technologies such as bifacial PV (Desai et al. 2022).

### Environment impact

Amid solar or hydro power by itself green technologies, their hybrid 'Picogrid' model is found to be even more impactful in reducing the carbon footprints. The saving of annual coal and fuel emissions from the Picogrid in contrast to the traditional coal based complete power generation system is analyzed. In the emission aspect, carbon monoxide (CO), carbon dioxide ($CO_2$) etc. are considered. The traditional coal-based power plant would have produced 11,668 kg/year of $CO_2$ and 2857 kg/year use of Coal where solar-hydro Picogrid reduces 100% air pollution. From this, we determined that complete $CO_2$ emission would be prevented, ensuing around 11,668 kg/year of less carbon footprint.

## Conclusion

Picogrid is an emerging concept in the renewable energy adaptation, especially in remote locations where even microgrids are expensive. Picogrids use primary constructing blocks of smartgrids. Presented work shows notable promise for bringing basic energy offerings to humans dwelling in far flung areas in growing countries. Distributed power based Picogrid consists of a large vary of applied sciences and engineering in a range of ranges of business and technical maturity, including solar photovoltaic, small hydro, wind generator, energy storage system etc. The study presented shows that PV Hydro based Picogrid with capacity up to 10 kW can comply with local government standards. The total annual energy generation may vary between 1200 and 5000 kWh/kW/Year. From profitability standpoint, when taking conventional power plant as base, Picogrid produces a payback period between 6 and 12 years and an IRR between 8 and 15% depending on the mode of finance. The energy produced by these methods can be provided in rural area or remote communities thereby making possible electric powered electricity and revenue producing probabilities concurrently. The concept introduced here is attainable to minimize poverty globally through enhancing the health, education, and financial burden of rural lives and neighborhood with inexpensive electricity.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42162-023-00294-z.

**Additional file 1.** The Supplementary Information file contains details of mathematical model used in this paper.

**Acknowledgements**
Not applicable.

**Author contributions**
AD and IM have conceptualized the article. AD has collected and analysed the data. Also AD involved in writing the first draft followed by corrections and proofreading. IM and AR have corrected and modified paper.

**Funding**
No funding was used for this project.

**Availability of data and materials**
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate
Not applicable.

### Consent for publication
Not applicable.

### Competing interests
The authors declare that they have no competing interests.

Received: 3 July 2023 Accepted: 22 August 2023
Published online: 01 September 2023

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