Technological and economic feasibility of de-centralised (off grid) hybrid system located in rural India

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Abstract

This paper seeks to explore the viability of both PV and hybrid of de-centralised (off grid) systems in rural third world locations. The viability of the system will be based upon the sustainable development goals [1] developed by the United Nations, specifically in line with providing affordable clean energy to everyone worldwide. It was found that neither system was sustainable based on the currently available equipment and pricing, however if the project were to be overtake by a community rather than a single entity, there wouldn't need to be a large shift in project size to achieve this, possibly making it a viable option.

Keywords: India, Hybrid, PV, Load profile, HOMER

1.   Introduction

Microgrids are localised grids that are disconnected from the main electrical grid. They operate separately and autonomously from the main grid, allowing for the generation and storage of electricity. This separation from the main grid means that microgrids can be developed without any need for prior infrastructure. Because of this, it is a very attractive option to implement within developing countries with hard to reach, and under developed rural areas, making it a feasible method for providing access to electrical resources.

Providing access to clean and affordable energy is important for the development of rural areas, and it is one of the main sustainable development goals (SDG's) [1]. These goals which were set by the United Nations aim to move the world towards a place where poverty is eliminated, access to education and healthcare is universal, and generally a world where the necessities of live are freely available to everyone. To achieve this, as series of sustainability goals were developed and reviewed each year for progress. This paper looks specifically at goal 7, which is to substantially increase the total percentage of renewable energy within the global consumption, double the rate of improvement in energy efficiency, and provide affordable and clean energy to everyone worldwide, all by the year 2030.

1.1. Objectives

This report will assess the technological and economic feasibility of de-centralised photo-voltaic micro-grids in the rural locations of Cameroon, Haiti, India, Kenya, Nigeria, South Sudan, and Zambia. These countries are current members of the 'IEEE smart village' program, a program which helps to implement and maintain these types of off grid systems, giving affordable access to renewable electricity in locations where before there

was none. This report will be assessing the feasibility of these systems as an option in the progression of the sustainable development goal 7. This access to clean energy will be essential in achieving many of the other sustainable development goals. Giving rural locations reliable access to energy will allow for them to develop and expand their state of living. Access to electricity will allow for an increase in agriculturally viable land, the pumping of clean water, and allow for access to necessities such as lighting, heating, and safe cooking methods.

Because of the importance of the availability of clean affordable energy, this report will be looking at the ways it can be provided, and if off-grid photo-voltaic systems are a feasible solution to this issue. This report will be looking into the countries in which these systems are currently being implemented, looking at their climates and how they will affect the need for electricity throughout the week / year, as well as current governmental programs that may either help of hinder. This will then be used to create a model of a photovoltaic grid in the given environment, which will be used to evaluate the feasibility of the system in achieving the goals of the sustainability development goals.

2.   Literature analysis

The purpose of this review is to gain an understanding of the differences of load profiles between seasonal changes within the countries looked at by the IEEE smart village program. It will identify the differences of electrical usage between differing countries due to differences in climate, geographical location, and governmental interventions. This review will focus on the different load profiles of households within these countries.

2.1.   Literature analysis method

To find all the literature that is relevant to the topic we are undertaking, different variations of key words and their synonyms were used to retrieve the greatest array of useful articles. Searches were undertaken using the table of search terms from table 1, each of these key words and their synonyms were used in conjunction with the others to complete a search (i.e. "India" AND "IEEE" OR "rural" AND "Photovoltaic" OR "Seasonal" AND "Appliance usage"). The resulting articles will be analysed for their validity and their reliability, before the information pertaining to our posed question is utilised to create a general load profile that can be applied to any IEEE county. This load profile will then be used to assess if de-centralised photovoltaic grids, or hybrid grids are feasible within the given circumstances.

Table 1. Key words used to search

Key Word	Synonym 1	Synonym 2	Synonym 3
'Country'	-	-	-
IEEE	-	-	-
Renewable	Solar Panel (PV)	Wind turbine	Hybrid
Seasonal	Summer	Winter	Monsoon
Load profile	Daily load	Weekly load	Yearly load
Appliance usage	Power usages	Rural appliances	-

2.2. Other sub-sections

Across all IEEE countries, it remains constant that within rural areas the must common occupation is agricultural. This leads to all countries the countries we are researching having a relatively similar distribution of load throughout the period of the day, and quite similar access to electrically draining appliances [2], [3]. From this we can assume that our given entity will have a waking time of 5:00am in the morning, at which time there may be minimal light usage depending on season. Then throughout the majority of the day, the load will be static, either drawing nothing, or drawing a load for either heating or cooling for the occupants that remain home during the day. The load will then spike again as work is usually concluded as sun sets, at which lights within the entity will be used along with the possible usage of a small radio, or possibly a TV. It is assumed that the entity will have access to only very basic appliances including lightbulbs (most likely incandescent), some form of heating or cooling such as a fan or a space heater, and only very limited entertainment [4]. Because of these similarities between all of the IEEE countries, it is assumed that the major reasoning for differences in load profiles will be due to seasonal and weather affects within their respective countries.

Africa as many highly varying climate zones, all of the countries within Africa that we are researching (Cameroon, Nigeria, Zambia, South Sudan, Kenya) are within the same climate zone of tropical savanna (Very close to the equator). Because of this the climate across these countries can be assumed to be very similar. Within Africa at this location there are only two distinct seasons, the 'season of long rains', which lasts from April to June. And the 'season of short showers' lasting between October and December [5]. During the season of long rains, humidity is very high (nearing 100%) across all countries, this combined with the average indoor temperature of 24º will result in the usage of fans all throughout this season to combat the humidity. During the season of short showers, the humidity decreases, however the annual average temperature raises to the 30's and therefor will still incur the usage of a fan as a source of cooling. With these countries being so close to the equator, the seasonal variation in sun rise and sun set is very minimal, overall this leads to very similar load usages in both major seasons of the African climate.

India has many climate zones, each with drastically different conditions ranging from arid desert, to tropical rain forest. For simplicity we will be focusing on the tropical locations of India. The tropical zone is subject to 3 main seasons, summer (April – June), winter (December – March), and monsoon (July – November). During the summer months, the temperature averages 26º, because of this it can be assumed that there will be constant load placed onto cooling of the entity while it is occupied, also during the summer season the sunrise is early enough to no longer need lighting in the early hours of the morning. During the monsoon season the average temperature drops close to 20º but with 100% humidity. During this season it can again be assumed that some electricity be spent towards the cooling of the entity, however this will most likely be less than that of the summer seasons. During the monsoon season there is also greatly decreased lighting due to the constant cloud cover, which would lead to an increase in light usage. Finally, in the winter season temperatures can get at low as 10º, with little to no electricity being used to cool the house. However, with the now much later sunrise, and earlier sunset, there will be a large increase in the usage of lighting, with a possible 3 hours in the morning and 6 hours in the evening.

2.3. Conclusion

From this research it is clear to see that the main difference between the load profiles of these countries will be their cooling usages, however it remains constant that all studied countries will be fully utilising the cooling during the summer months, and most during the rainy/wet season. From this we have a very clear idea for what the summer/dry seasonal

load profile across these countries will be. With the winter/rainy season there is an overall decrease in the usage in the cooling system, however the daylight hours will also decrease therefor there will be an increase in the usage of lighting within the entity. Overall a very basic and simplistic load profile that would suit all of the IEEE countries would be a profile with light usage beginning at 5:00 am along with fan usage. The lighting would then be switched off after an hour, but the fan will remain running for the rest of the day. From 5:00 pm onwards as people return back from work the entertainment system will be switched on and there will be light usage again till the late hours of 11:00 pm.

3.   Designing an appropriate solar PV system

This report will be looking to develop a PV and wind system for a rural household within the country of India. India has many climate zones, each with drastically different conditions. This report will only be looking at a household located within the tropical zone. The tropical zone is subject to 3 main seasons, summer (April – June), winter (December – March), and monsoon (July – November). The household will only have very basic electrical needs, limited to some basic lighting, a water pump, a ceiling fan, and a radio for entertainment. This report assumes an average household size of 5 people (2 adults, 3 children) [6], with both parents working throughout the day, and children going to school. It is also assumed that the lights in use are LED lights rather than incandescent lights. This is assumed because of the 'Domestic Efficient Lighting Program' [7] implemented in India, May 2015, which applies a subsidy to LED lighting, and urges people to purchase LED bulbs.

Table 2 lists the components of the daily power usage that are not subject to variation due to seasonal climate changes. These power usages will remain constant throughout the year. Pump usage will always be in the early morning after waking, to maintain the clean water needed for the day's tasks (cooking, cleaning, drinking). Radio usage will be in the early evening to listen to news, or other forms of entertainment.

**Table 2. Daily loads of entity with no seasonal variation**

Electrical appliances	Number used	Wattage	Total Wattage	Daily Duty Cycle	Daily Energy Consumed kWh/day
Water Pump	1	250	250	1	0.250
Radio	1	30	30	2	0.060
Constant Load Total			**280**		**0.310**

Table 3 list the components of the daily power usage that are subject to seasonal variations. These components are the ceiling fan, and the house lights. The ceiling fan is only ever in use in the summer months as this is the only season where temperatures regularly exceed 25º [5]. Lighting usage varies across all season with the lowest usage in the summer when no lighting is needed in the morning due to the sunrise occurring between 5:00 – 5:30, with only 5 hours required at night with sunset between 6:30 – 7:00. In monsoon no fan is needed, however there is an increase in the need for lighting as the sunrise shifts to 6:00 – 6:30 and sunset to 6:00 – 6:30, meaning that there are fewer daylight hours a day. During the winter season the fan is once again not needed, and there is an increase in light usage as the daylight hours shorten again, sunrise 6:00 – 6:30 and sunset 5:00 – 5:30. [8]

Table 3. Daily loads of entity subject to seasonal variation

| Season	Electrical appliances	Number used	Wattage	Total Wattage	Daily Duty Cycle	Daily Energy Consumed kWh/day
Summer	Ceiling fan	2	30	60	15	0.900
	Lights (LED Bulbs)	4	20	80	5	0.400
Load Total				**60**		**1.300**
Winter	Ceiling fan	2	30	60	0	0
	Lights (LED Bulbs)	4	20	80	9	0.720
Load Total				**60**		**0.720**
Monsoon	Ceiling fan	2	30	60	0	0
	Lights (LED Bulbs)	4	20	80	7	0.560
Load Total				**60**		**0.560**

3.1. Solar and Wind resource
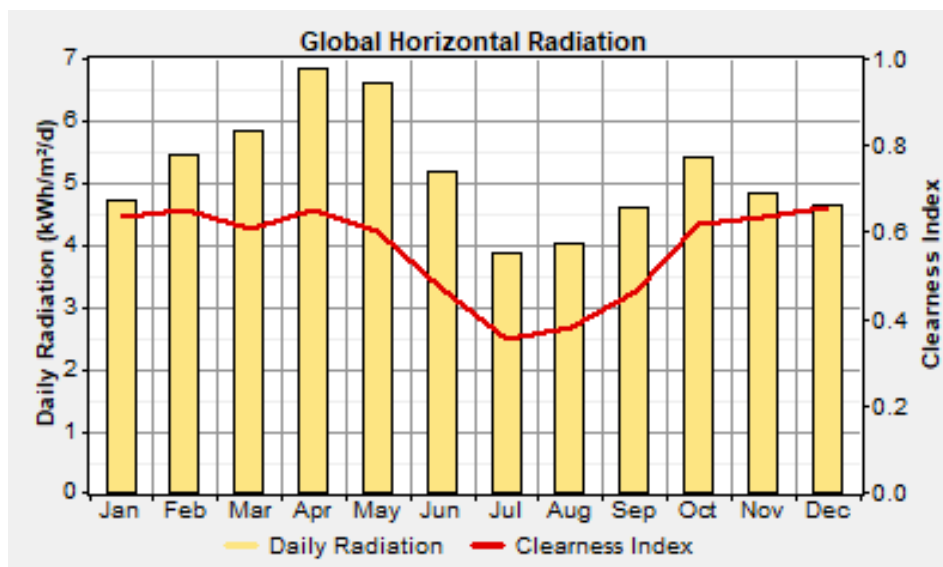
Figure 1. Monthly average solar radiation & clearness
(source: [15])

Figure 1 displays the monthly solar irradiance at the location of our given household. From this we can see that in the season of summer (April – June) has the highest average solar irradiance of 6.21 kWh/m^2/d, winter with the next highest at 5.17 kWh/m^2/d, and the monsoon season with the lowest average of 4.55 kWh/m^2/d. This matches what we would expect due to seasonal change, in summer there would be a large amount of solar radiation due to both the clearness of the sky during this time, and the angle of incidence of the sun's rays being more direct. Then in winter we see the next larges solar irradiance, during this period the angle if incidence of the sun's rays will be larger leading to a decrease in irradiance. During the winter the sky's will also be clear therefore there will be little solar energy lost. In the monsoon season the angle of incidence of the sun's rays will be in between that of summer and winter, however during this period there are large

amounts of rain, greatly decreasing the clearness index of the area, and decreasing the total solar irradiance.
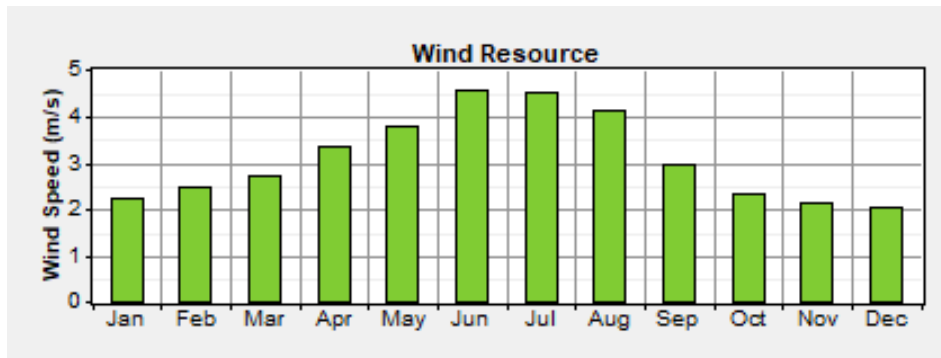
Figure 2. Monthly average available wind resource
(Source: [15])

Table 4. Average monthly wind speed's [9]

Month	Average wind speed ms^{-1}
January	2.2
February	2.5
March	2.7
April	3.4
May	3.8
June	4.6
July	4.5
August	4.1
September	3.0
October	2.3
November	2.1
December	2.1

The available wind resource in the location of the household is not particularly large, reaching a peak wind speed of 4.6 ms^{-1} in June, and only reaching speeds above 3 ms^{-1} for less than half of the year. The average wind 'cut-in' speed is between 3 – 4 ms^{-1} [10], this means that assuming that a turbine with a low wind 'cut-in' speed was used, it would still only be utilised for half of the year.
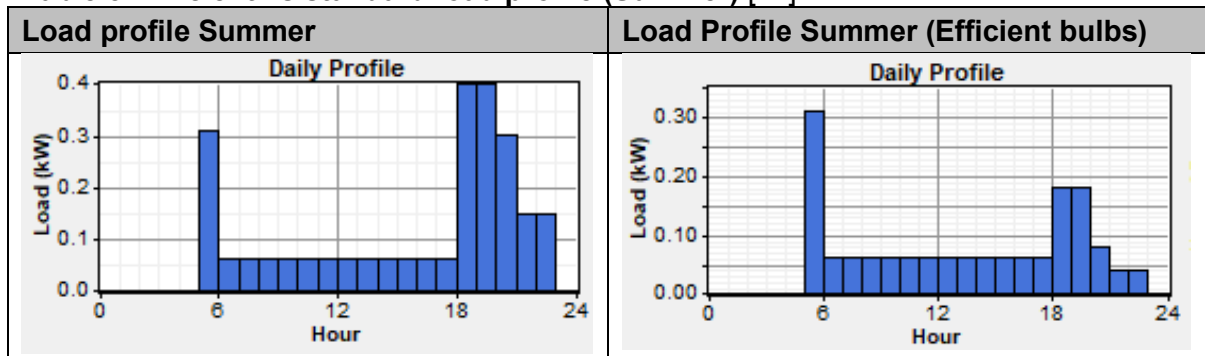
3.2. Load profile

To increase the efficiency of each profile there was a switch between incandescent light bulbs with a wattage of 75W, and LED bulbs with a wattage of 20W. This was done because of the 'Domestic Efficient Lighting Program' [7] implemented in India May 2015. No other changes were made as the household is very simplistic, only consisting of lights, fans, water pump and radio. These are not feasible for a low-income company to buy specific low wattage versions.

The daily procedure of the household in question begin with either one, or both adults waking up at the hour of 5:00. At this time water is always pumped for later usage during the day in cooking, cleaning and drinking. Then one adult leaves the household to begin

working, while the other organises the children (either for work, or school) and then remains at the home to clean and prepare for everyone to return. Everyone is assumed to be back within the household by 6:00, at this time the radio is turned on for two hours. After this the children are placed into bed and the parents remain awake for to more hours before going to sleep themselves.

Table 5. Efficient vs standard load profile (Summer) [11]

| Load profile Summer	Load Profile Summer (Efficient bulbs)

(Source: [15])

Table 4 contains the summer load profile. With the sun rising at 5:00am, there is no need for lighting currently, with the only loads being the ceiling fan, and the water pump. Throughout the day the only load present on the system is the ceiling, until 6:00pm, when all four house lights are turned on and the radio. Then at 8:00pm the children are placed into bed and the radio is turned off, leaving two lights on, and both ceiling fans until 11:00pm.

Table 6. Efficient vs standard load profile (Winter) [11]

Load profile Winter	Load Profile Winter (Efficient bulbs)
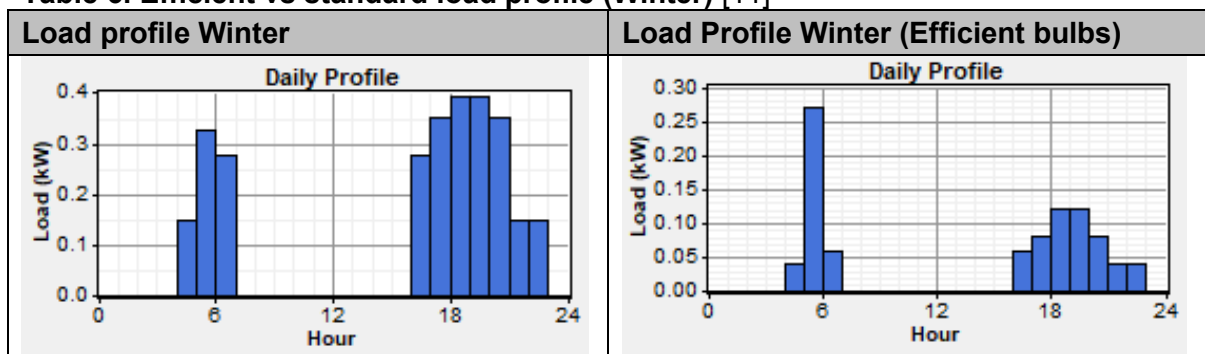
(Source: [15])

Table 5 contains the winter load profile. With the sun rising at 6:00am, two of the house lights are turned on in the morning, along with the Water pump. Then as the children wake at 6:00, a third light is turned on. No power is used throughout the day, as the temperature is not high enough to require it, so there is no load draw till 4:00, when 3 of the house lights are turned on again. At 6:00 the radio is again switched on for two hours before the children are placed into bed and only two lights are left on till 11:00.

Table 7. Efficient vs standard load profile (Monsoon) [11]

Load profile Monsoon	Load Profile Monsoon (Efficient bulbs)
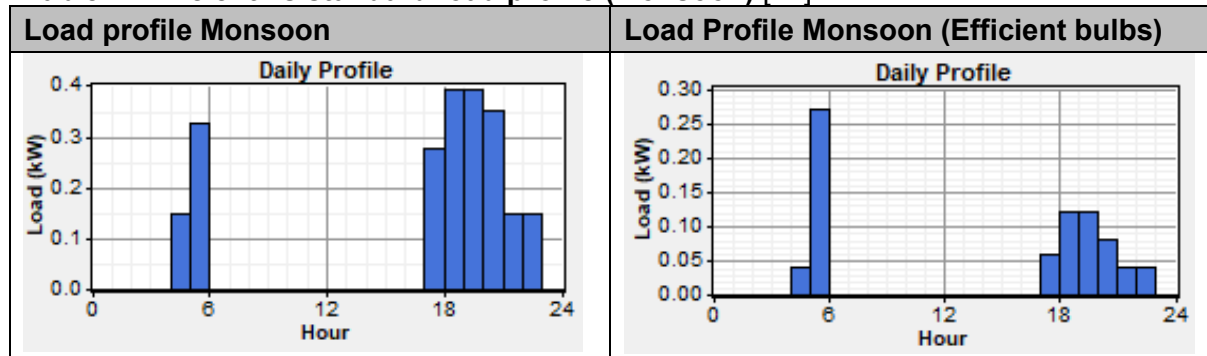
(Source: [15])

Table 6 contains the monsoon load profile. With the sun rising at 6:00am, two of the house lights are turned on in the morning, along with the Water pump. Then as the children wake at 6:00, and all lights are turned off. No power is used throughout the day, so there is no load draw till 5:00, when 3 of the house lights are turned on again. At 6:00 the radio is switched on for two hours before the children are placed into bed and only two lights are left on till 11:00.

3.3. Sizing the solar PV system

Table 8. HOMER country specific data

Geographical Location	20.35, 82.47
Time zone	India (GMT + 05:50)
Life time of system	25 years
Panel Slope	20.58º
Turbine height	5m
Annual real interest rate	5.86% [13]

Table 9. PV System

Equipment/Capital	Number required	Cost USD
LUMINOUS Solar cells [12]	3 x 160W, 12V 1 x 100W, 12V	$494
Trojan T-105 Battery [13]	4 x 225Ah, 6V	$696
MASCOT DC/AC Inverter [14]	1 x 600W, 12V	$335
Total Cost		**$1525**

Table 10. PV System & Wind

Equipment/Capital	Number required	Cost USD
LUMINOUS Solar cells [12]	3 x 160W, 12V 1 x 40W, 12V	$445
SW AIR X Turbine [15]	1 x 400W, 12V	$650
Trojan T-105 Battery [13]	3 x 225Ah, 6V	$522
MASCOT DC/AC Inverter [14]	1 x 600W, 12V	$335
Total Cost		**$2113**

4.   Analysis of the solar PV & hybrid system's

The two system configurations from table 7 (PV), and table 8 (Hybrid PV & wind) were modelled to compare their cost and overall sustainability. These systems were modelled using HOMER [11] to find the most efficient configuration of each system, and RETScreen [16] to evaluate the overall cost. The sustainability of a system will be dependent on the overall environmental cost of producing the components of the system, this will also factor in the replacement of parts over the lifespan of the system. It will also be reliant on the entities ability to purchase and maintain the system. This will be dependant of the entity's available disposable income.

4.1.   Analysis with HOMER

				PV (kW)	AIR	T-105	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
				0.58		4	0.6	$ 1,525	50	$ 2,177	0.460	1.00
				0.52	1	3	0.6	$ 1,953	71	$ 2,876	0.608	1.00

Figure 3. HOMER system configuration (Top: PV, Bottom: Hybrid)
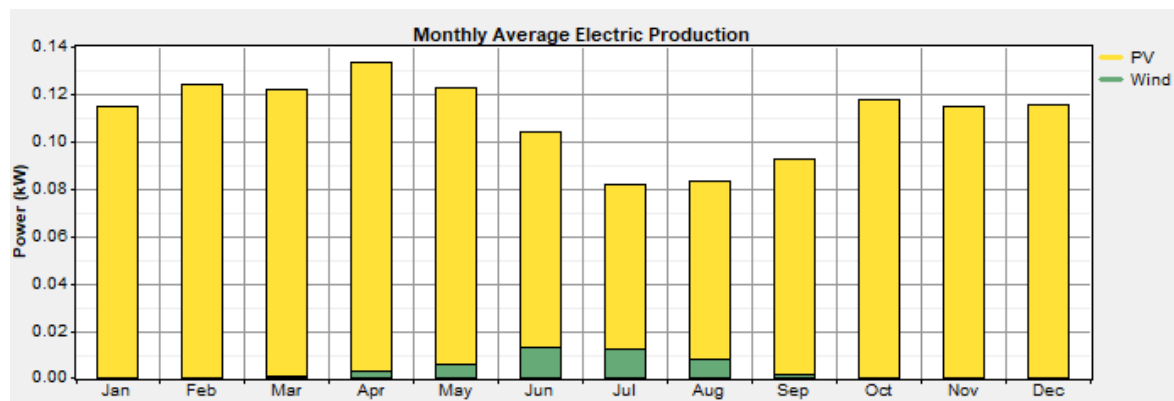

Figure 4. Monthly average electricity production across PV and wind

When comparing the PV system with the hybrid system we see that the total NPC (Net Present Cost) found in figure 3 for the PV system is $700 less than that of the hybrid system. This means that if the entity were to set aside the total amount of money required for the system over the 25-year period, they would need $700 less than if they went with the hybrid system. The initial capital requirement of the PV system is also $428 less than that of the hybrid system, meaning that less disposable income is required for an entity to be able to purchase the PV system.

When comparing the capital required for each system, PV requires a greater number of solar panels, requiring an array of panels totalling 580W, compared to 520W for the hybrid. However, those savings made on solar panels total to $49, which is immediately lost to the cost of the wind powered turbine required in the hybrid system, totalling to $650. The hybrid system however does relieve stress from the battery banks, meaning that over the period of 25 years, three batteries will be required to maintain the system rather than the four that are required for the PV system.

4.2. Analysis with RETScreen
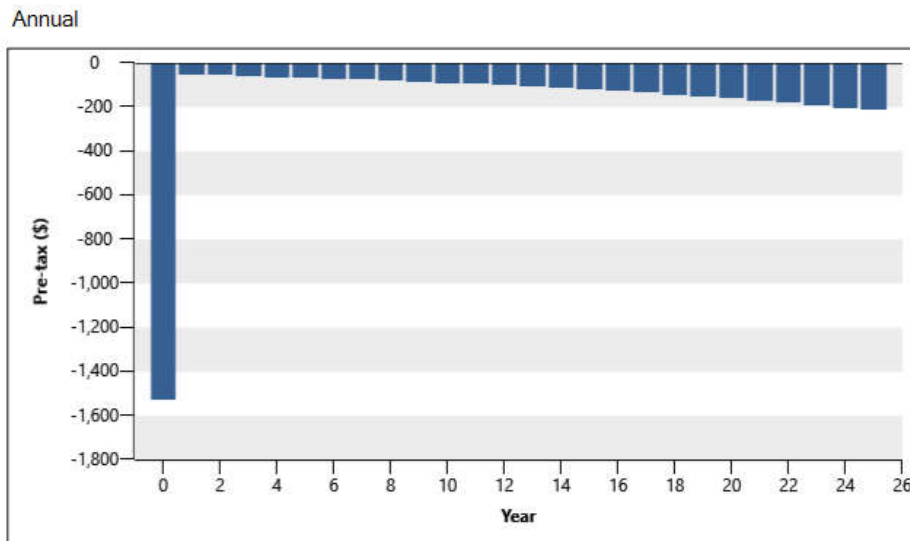
Annual

Figure 5. RETScreen annual cash flow [16]

Figure 5 from RETScreen displays the total annual cash flow when purchasing a PV system. With the first initial purchase of capital being the greatest immediate cost totalling to $1,525. After this initial purchase of the system, each year there will be operating costs in relation to servicing the panels and replacing parts of the system that may be to old such as the batteries.
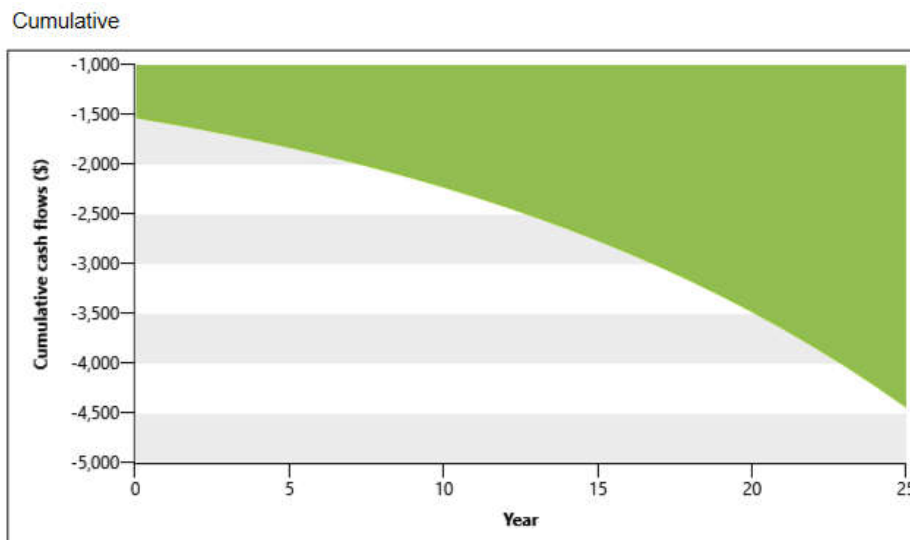
Cumulative

Figure 6. RETScreen Cumulative cash flow [16]

Figure 6 from RETScreen displays the total cumulative cashflow over the 25-year period. From this figure we can see the total cost of the system if it were to be payed upfront at each year, considering the real interest rate of the location, degradation and replacements. We can see here that after the 25-year period a total of $4,460 will have been spent of the system.

4.3. Discussion

When comparing the PV system to the hybrid system, the disparity in their pricing is clear. The PV system being the much cheaper option, both in terms of the initial cost, and the overall cost of the system over the 25-years, would appear to be the more sustainable option of the two. However, it does have its drawbacks, the nature of a solely PV system is that during the hours of lower solar irradiation such as during the night, there is very little to no electricity being generated. To compensate for this lack of electrical generation, there is a greater load placed on the battery systems. When looking at figure 3 above we can see this increased dependence on batteries, the PV systems requires four batteries over the 25-year period, and the hybrid system requires 3. This means that means that the hybrid system spends $174 less on batteries, and with batteries being one of the more environmentally costly components of an off-grid system [17], the hybrid system would seem to be less impactful environmentally. The hybrid system does still require the inclusion of a wind turbine however, costing $650 extra, and negating the money saved on the system by reducing the battery usage. When looking at the specifications of the turbine considered in our models [15], we can see that the 'cut-in' speed of this model is 3ms^{-1}, and the rated speed of this model if 12ms^{-1}. When looking at figure 2 of the average monthly wind speeds at our geographical location, and figure 4 showing the percentage of total power output technology is outputting per month, the wind turbine is only outputting power between the months of April and August. The turbine is also never fully reaching its potential output due to the low wind speeds found within the area. Because of this, very few solar panels can be replaced by the turbine within the systems, meaning that the overall cost of the system is much greater. Because of this, the system that is most viable within this location is the purely PV system.

When using a purely PV system, to meet the electrical requirements of the system year-round there must be some buffering in terms of the electricity generation. Because of this there is a large portion of the electricity generated by the grid that is not utilised. According to our system model in HOMER [11], the total yearly production of electricity totals 1,000 kWh/year, while the systems consumption is only 365kWh/year. Considering the discharge cycles of the battery system so as not to ever drain past the recommended 60% [18], there will be an excess of 538kWh/year. This excess power could be put to many uses, for instance this grid could be connected in series with a neighbouring entity to also provide them with electricity. This however would require a greater amount of battery storage within the system, but it would be able to provide electricity to more than one household, reducing the initial capital cost of the system across two households. This excess electricity could also be utilised to power more industrial based systems, such as water pumping for farming, or for the powering od sowing machines. This would mean that the excess power output by the system is used to improve the economic state of the given entity. Alternatively, this electrical excess could be used as a buffer for the given entity to purchase more electrically intensive products such as stoves, or space heating for during the winter. This would require the purchasing of additional battery storage for they system, but not require the purchase of any more panels or converters, decreasing the cost of expansions greatly.

According to statistica [19], over 75% of rural Indian households have a monthly income under 7,500 Indian rupees, which with the current 2018 conversion rate will translate to $101 US a month. If we assume that our household is within the top earning bracket of this 75%, and earns the full $101 a month, this would total to yearly earnings of $1,212. If we are to assume that each year the household was able to set aside 10% of these earnings into a fund to purchase this PV system and that the yearly interest rate remains stable at 0.58%, it would take 13 years of saving before the household was able to meet the total NPC (net present cost) of the system. Because of the cost of the system, this household would not currently be feasible to purchase and maintain such as system, the

amount of upfront money required to purchase the equipment required for the system is too large for an average rural household within India to be able to save towards and purchase.

5. Conclusions and recommendations

Due to the large disparity in the initial capital cost of the PV system, and the percentage of average annual income that can be feasibly be used towards purchasing said system, it is not recommended that at this current time a purely PV systems be considered as a stand-alone method of rural electrification. Although this method of electrification would allow for a large amount of future proofing in terms of increasing the load on the grid, either by including other households in the system, or just by increasing the number of appliances on the system. However, it is not feasible for the occupants of an Indian rural household to purchase the suggested system.

5.1. Recommendations to modelling practitioners

While both HOMER and RETScreen are software designed to help model hypothetical electricals systems, either connected or disconnected from the electrical grid, they both have very different usages, and will be effective at modelling very different types of systems. RETScreen **[16]** is designed to provide for a much more commercially based clientele, it looks much deeper into the finances of the project. RETScreen allows for connection to the main grid, calculation of green house emissions, risk analysis and provides a far greater selection of financial options which to consider. Because of this, RETScreen would be preferable for modelling the feasibility of a large company with known electrical requirements, which wants to reduce their reliance of the grid by a given percentage. RETScreen would allow to evaluate the risks of purchasing said system, the time till payoff of the system, the annual costs of maintenance, and initial funds required.

HOMER **[11]** is far less focused on the financial and risk assessment side of modelling, instead looking to optimise the configuration of the system. Allowing for the user to input their own entity specific load profiles, along with wind and global irradiance data, HOMER will provide a much more accurate representation of the total number of panels, batteries, and converters required within the system. The ability to have multiple configurations of parts such as panels is also paramount to identifying the most efficient configuration that is available to the entity.

To achieve the most practical and realistic modelling of a system, if should be recommended that the modelling begin with HOMER. With the edition of entity specific load profiles, and the ability to test multiple different configurations, this will provide the most cost effective and sustainable overall system. Once this has been achieved, enter the details of the suggested system into the RETScreen software along with the monetary and risk data that is available to you to be able to provide the most realistic cost analysis of the given system.

6. References

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