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Modelling an off-grid integrated renewable energy system for rural electrification in India using photovoltaics and anaerobic digestion

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ABSTRACT

This work describes the design optimisation and techno-economic analysis of an off-grid Integrated Renewable Energy System (IRES) designed to meet the electrical demand of a rural village location in West Bengal – India with an overall electrical requirement equivalent to 22 MWh year^{-1}. The investigation involved the modelling of seven scenarios, each containing a different combination of electricity generation (anaerobic digestion with biogas combined heat and power (CHP) and photovoltaics) and storage elements (Vanadium redox batteries, water electrolyser and hydrogen storage with fuel cell). Micro-grid modelling software HOMER, was combined with additional modelling of anaerobic digestion, to scale each component in each scenario considering the systems' ability to give a good quality electricity supply to a rural community. The integrated system which contained all of the possible elements – except hydrogen production and storage presented the lowest capital ($US 71 k) and energy cost ($US 0.289 kWh^{-1}) compared to the scenarios with a single energy source. The biogas CHP was able to meet the electrical load peaks and variations and produced 61% of the total electricity in the optimised system, while the photovoltaics met the daytime load and allowed the charging of the battery which was subsequently used to meet base load at night.

1. Introduction

India has shown an accelerated economic growth, however like other developing countries most of its population (~70%) live in remote rural areas which are not connected to the national electrical grid. These villages and communities either have an insufficient electricity supply or do not have it at all [1]. Whereas the affluent sector are benefiting from the economic expansion of India, remote, rural communities are being excluded. A recent investigation claimed that an extension of the Indian national grid in order to electrify rural communities is not feasible [2]. With 119,560 sites that are not electrified, due to their remote location, it is economically unfeasible to connect 18,000 villages to the national electric grid. On average, these villages require small power units with a capacity between 10 and 250 kW [2]. Taele et al. claimed that due to the lack of public electricity in rural Africa, people are forced to improvise domestic energy systems commonly based on kerosene or small diesel engines [3] which suffer from frequent breakdowns, unsafe electrical and fuel storage conditions, ad-hoc unreliable connections and high power losses.

For these reasons there is an increased interest in installing small scale renewable generation systems to electrify these communities. However, due to the intermittence in energy generation of many renewable systems depending on one single source, this option may be unreliable. To increase the reliability of the renewable energy system, the most suitable method is to develop Integrated Renewable Energy Systems (IRES) which rely on multiple generation technologies.

Kanase-Patil et al. indicated that in some IRES configurations the conversion and reconversion of energy by the battery units decrease the system's efficiency and increases the energy cost [4]. Alzola et al. claimed that the high cost of photovoltaic (PV) panels is the main barrier for the extensive use of stand-alone systems [5]. An investigation performed in Cameroon (average solar radiation 5.55 kWh m^2 day^{-1}) where a PV system (18 kW) was coupled with a Liquid Petroleum Gas (LPG) generator (15 kW), found that the electricity cost for remote sites would be quite high ($[1] 0.720 kWh^{-1}). Nandi et al. showed that PV and battery ($ 0.621 kWh^{-1}) power systems are not as efficient as wind, PV and battery systems ($ 0.439 kWh^{-1}); it was also illustrated that energy

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[1] $ throughout this work refers to $US.

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Nomenclature

a	Specific biogas production [$m^3\ kg^{-1}$ VS]
A	Total surface area of the anaerobic digester area [m^2]
B	Annual biogas usage [$m^3\ year^{-1}$]
C	Specific heat of the feedstock [$kJ\ kg^{-1}\ {}^\circ C^{-1}$]
C_i	Influent Volatile Solids (VS) content [kg VS kg^{-1} Wet weight]
H_L	Heat loss of the anaerobic digester [kW]
H_F	Influent feedstock heating to the operating temperature [kW]
H_T	Total thermal load of the anaerobic digester [kW]
OLR	Organic loading rate of the anaerobic digester [kg VS $m^{-3}\ day^{-1}$]
Q	Volumetric flow rate of feedstock [$m^3\ day^{-1}$]
q	Volumetric flow rate of feedstock [$m^3\ s^{-1}$]
T_a	Ambient temperature [°C]
T_{op}	operating temperature of the anaerobic digester [°C]
U	Total heat transfer coefficient [$kW\ m^{-2}\ {}^\circ C^{-1}$]
V_r	Anaerobic digester working volume [m^3]
ρ	Feedstock density [$kg\ m^{-3}$]

Abbreviations

AD	Anaerobic Digestion
BURD	Bridging the Urban-Rural Divide
CHP	Combined Heat and Power
COE	Cost of Electricity
DC–AC	Direct current to Alternating Current Converter
IRES	Integrated Renewable Energy System
LOLP	Loss of Load Probability
LPG	Liquid Petroleum Gas
NPC	Net Present Cost
O&M	Operation and Maintenance
PV	Photovoltaic
VRB	Vanadium Redox Battery

systems with a big PV generator required large battery storage systems and thus greater investment and eventually higher energy cost [6]. This finding suggests that well managed integrated renewable energy systems, which combine a higher number of technologies, potentially produce cheaper energy than simple energy systems [7].

The objective of this project was to assess the design and optimisation of a hybrid renewable system for providing electricity to a rural location in West Bengal, India. The techno-economic performance of seven scenarios, based on combinations of different technologies, was explored.

2. Materials and methods

Given the abundance of sunlight and biomass available in the research area (India), the chosen energy conversion technologies were PV and anaerobic digestion (AD), with a Combine Heat and Power (CHP) generator fuelled by biogas. CHP systems based on both reciprocating engines and microturbines were considered and scenarios were based on combinations of these along with two storage technologies: vanadium redox batteries (VRB), and the combination of a water electrolyser and hydrogen storage with fuel cell for electricity production. A third storage option, zinc bromide batteries, was also briefly assessed. In order to determine a final optimal IRES configuration, the various technologies mentioned above were combined with each other. Fig. 1 portrays the general concept of the IRES proposal for a typical rural village.

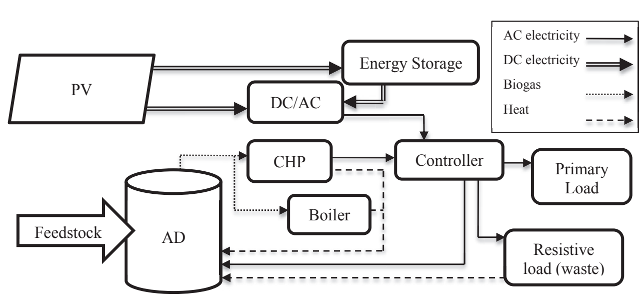

Fig. 1. Integrated renewable energy system general configuration (PV – photovoltaic, DC/AC – direct to alternating current converter, CHP – combined heat and power, AD – Anaerobic digester). Energy storage contains batteries or an electrolyser, hydrogen tank and fuel cell depending on the scenario.

2.1. Load profile

This research forms part of the Bridging the Urban-Rural Divide (BURD) joint India/UK project and as part of this work a load profile was created that represents the electrical demand of a village in West Bengal containing around 1000 residents who currently have no direct access to electricity [8]. This is shown in Fig. 2. The demand is split into various categories and includes economic activity i.e. grinding spices, water pumping, the operation of a medical centre, adult and child education facilities, lighting and entertainment. The overall electrical load is equivalent to 22 MWh/year. The error bars denote a 60% possible variation which is the expected maximum daily variation during each hourly period.

2.2. Micro-grid system modelling – HOMER

Micro-grid modelling was performed using HOMER. This software allows simulation of the performance of an energy system with uncertain operational conditions, allowing robust design with reduced project capital risk. A large number of permutations of the overall system were created with varying capacity (storage, power output) of each component. Each of these permutations was tested to assess whether it could meet the load requirement. The HOMER package was then used to list the permutations of the systems that can meet the demand and reports various economic indicators upon which the optimal scenario could be chosen.

2.2.1. Scenarios considered

The scenarios that were explored are shown in Table 1. Scenarios A and B use PV as the primary energy generator with differing

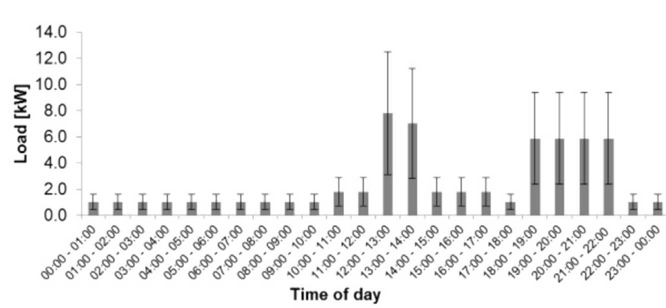

Fig. 2. Load profile in rural Indian village location.

Table 1
Investigated scenarios.

Scenario	Technologies involved
A	PV + VRB + DC–AC
B	PV + Fuel Cell + Electrolyser + H_2 tank + DC–AC
C	AD + 2 CHP (Microturbine); high and low capacity
D	AD + 2 CHP (Microturbine); similar capacity
E	AD + 2 CHP (Reciprocating Engine); high and low capacity
F	AD + 2 CHP (Reciprocating Engine); similar capacity
G	PV + VRB + DC–AC + AD + 1 CHP (Microturbine)

storage technologies. Scenarios C–F use AD and a biogas CHP as the primary energy generation, with differing generation technologies and capacities of the CHP used. For each CHP technology two scenarios were explored; one with a high and low capacity engine and one with two similarly sized engines. Note that this approach was chosen since initial results with only a single CHP showed large amounts of wasted energy since the CHP needed to be scaled according to the peak demand which is much higher than the base load. Finally, scenario G, the fully integrated energy system, was designed based on the better ranked technologies from the previous modelling.

2.2.2. Photovoltaic

The solar radiation is calculated by HOMER based on the hypothetical location of the project site within West Bengal, India (latitude 23° 16′ north and longitude 87° 15′ east) which has a scaled daily average radiation of 4.826 kWh m^{-2} day^{-1} which includes both direct and diffuse sources and measured on a horizontal surface. Table 2 shows the detail of the solar resource considered in this study. A derating factor equivalent to 80% and ground reflectance of 20% were assumed. The 20 years lifetime PV panels were considered not to have a tracking device, thus the angle at which the panels are mounted relative to the horizontal was set at 23°. 16 sizes were considered, distributed between 7 and 50 kW output capacity.

2.2.3. Vanadium redox battery

VRB was selected as the storage element in the PV system, as small sizes appropriate to this system are commercially available. A cell stack with a lifetime equivalent to 15 years was analysed, 8 different sizes of cell stack were considered between 5 and 15 kW. The electrolyte lifetime is much longer (125 years). 9 sizes were considered in the analysis, between 80 and 250 kWh. An overall round-trip efficiency of 80% was used. This data was provided in HOMER by Prudent Energy VRB® Systems (MD, USA) and further supported by personal communication with Golden Energy Fuel Cell Co., Ltd. (China, Beijing).

Table 2
Monthly average solar radiation and temperatures.

Month	Clearness index	Daily radiation [kWh m^{-2} day^{-1}]	Ambiant temperature[a] [°C] max, min, average
January	0.6	4.195	31, 9, 19
February	0.59	4.757	34, 12, 22
March	0.593	5.568	40, 13, 27
April	0.588	6.148	40, 17, 30
May	0.542	5.968	40, 18, 30
June	0.466	5.198	40, 21, 30
July	0.382	4.22	36, 22, 29
August	0.419	4.445	38, 18, 28
September	0.449	4.358	36, 18, 28
October	0.579	4.882	35, 16, 27
November	0.592	4.268	31, 16, 24
December	0.596	3.956	30, 9, 20
Average	0.533	4.829	36, 16, 26

Scaled annual average 4.829 kWh m^{-2} day^{-1}.
[a] Temperature data source: India Meteorological Department [13] and Time and Date Aksjeselskap (Stavanger, Norway).

2.2.4. Hydrogen storage system

The fuel cell system consisted of three elements: fuel cell, electrolyser and hydrogen tank. The fuel cell operating lifetime was considered to be 40,000 h. The hydrogen consumption was fixed at 0.06 kg h^{-1} kW^{-1}. Four output capacities were analysed between 8 and 15 kW. In the case of the electrolyser with a lifetime of 15 years and an efficiency of 85%, four different sizes were considered between 10 and 15 kW. Regarding the hydrogen tank the following hydride storage conditions were assumed: pressure 10 bar, density 0.02 kg l^{-1} and storage efficiency equivalent to 90%. This data was provided in HOMER by Hydrogen Bank Technology Inc. (New Taipei City, Taiwan) and supplemented with additional data from Refs. [9,10]. Various hydrogen tank capacities with a lifetime of 25 years were included in the optimisation analysis with 9 capacities between 15 and 60 kg.

2.2.5. Generators

The expected operating lifetime of the CHP generators was 60,000 h and their operation schedule was assumed to be fixed and manually programmed. To cover the load peaks, the high capacity generators operated between 12pm–2pm and 6pm–10pm; seven sizes were considered between 8 and 15 kW. To cover base load, the low capacity generators operated between 12am–12pm, 2pm–6pm, and 10pm–12am; four sizes were considered between 2 and 5 kW. In the similar capacity generator scenarios, one generator would operate continuously, while the other one would only operate during peak times (i.e. 12pm–2pm and 6pm–10pm). 6 sizes were considered for similar capacity generators between 3 and 8 kW. Microturbines were evaluated considering a minimum part-load of 60%, heat recovery efficiency of 45%, biogas consumption of 0.25 m^3 $hour^{-1}$ kW^{-1} output and an intercept coefficient of 0.2 m^3 $hour^{-1}$ kW^{-1} rated. Reciprocating engines were evaluated considering a minimum part-load of 30%, heat recovery efficiency of 60%, biogas consumption of 0.4 m^3 $hour^{-1}$ kW^{-1} output and an intercept coefficient of 0.267 m^3 $hour^{-1}$ kW^{-1} rated. All CHP data was obtained from Refs. [9–12]. This combined data gave overall efficiency vs. load curves as shown in Fig. 3.

2.2.6. Economic and financial variables

Capital and O&M costs of the main components of the IRES are shown in Table 3 including the sources of data.

Operation and maintenance (O&M) for PV and AD was assumed to be cost free due to the highly robust nature of both of these systems, and in addition that the routine activities have very low time requirements and do not require a skilled workforce. These activities would consist of the cleaning of the PV modules surface, vegetation management, wildlife prevention, the collection of the AD feedstock, the feeding/discharging operations of the digester and in addition none-routine operations such as degritting, removing blockages and minor repairs etc. It has been assumed that the rural community would freely cooperate with these O&M activities in order to minimize the cost of energy. Also the AD feedstock was considered to be cost free as will be discussed in Section 2.3. Note that the O&M cost of the generators was considered separately from the AD system as shown in Table 3.

Regarding the O&M cost of the hydrogen tank and electrolyser, due to the complexity of certain hydrogen equipment, this O&M cost of hydrogen equipment is generally included in the initial capital cost, this means that private companies generally offer leasing purchase contracts where the supplier is committed with the periodical maintenance of the equipment.

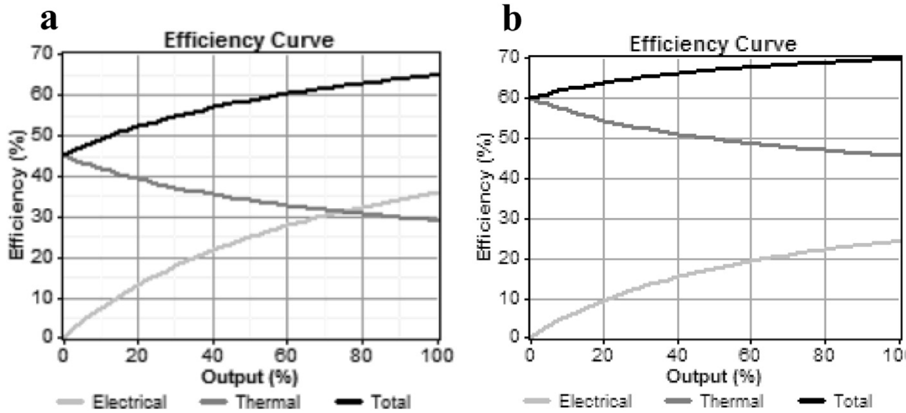

Fig. 3. Efficiency vs. load profiles for microturbines (a) and reciprocating engines (b).

An annual real interest of 6% over a period of 20 years (i.e. life time of this energy project) was used in the calculation of economic indicators.

2.3. Additional modelling – anaerobic digestion

The anaerobic digester was modelled outside of HOMER. Based on the feedstock biomass properties this tool was applied to determine the volume of the digester, feedstock requirement for its operation and the implications of the AD unit within the economic variables of each scenario. The feedstock requirement (Q) was calculated based on the composition and biogas potential of water hyacinth. This biomass source was chosen since it, and other similar aquatic weeds, are prevalent in West Bengal and in other tropical parts of the world and in many cases represents an invasive species which is a nuisance since it rapidly spreads in watercourses [13]. Therefore not only can aquatic weeds be considered a free biomass resource (a waste stream) but also that in some cases it's clearing from local watercourses would be performed periodically anyway. Water hyacinth can easily be cultivated in these areas to provide a reliable feedstock source to the anaerobic digester. The characteristics the input biomass were as reported by Chanakya et al. [13]: 10% of total solids, 85% of volatile solids (VS) (therefore $C_i = 0.085$ kg VS kg^{-1} wet weight), with a specific biogas production equivalent to 0.35 m^3 kg^{-1} VS. The specific heat was assumed to be equivalent to that of water 4.18 kJ kg^{-1} °C^{-1} and the feedstock density was set at 1040 kg m^{-3}.

The output for each scenario from HOMER was the annual biogas requirement to supply the CHP generator. Since anaerobic digesters work best when operated in a steady state the biogas production was assumed to be constant throughout the year, with the daily difference between biogas supply and demand met using a low pressure storage gasometer. The necessary daily feedstock requirement was then calculated by applying Equation (1).

$$Q = B/(365\rho a C_i) \rightarrow \left[\mathrm{m^3 day^{-1}}\right] \quad (1)$$

The working volume of the anaerobic digester was calculated using Equation (2).

$$V_r = (QC_i)/\rho \mathrm{OLR}) \rightarrow \left[\mathrm{m^3}\right] \quad (2)$$

A headspace of 10% of the working volume was added to obtain the total volume of the digester which was assumed to be a cylindrical tank of aspect ratio 1 (height = diameter) to minimise the surface area and therefore heat loss. Thus the surface area could be calculated.

To calculate the thermal demand of the digester a daily temperature profile was created for each month using seasonal data

Table 3
Economic data.

Equipment		Capital cost	Operation and maintenance cost	Source
Photovoltaic panels (Polycrystalline silicon)		\$ 2520 kW^{-1}	–	Energy Saving Trust (London, UK)[a], [21]
Converter		\$ 636 kW^{-1}	–	Sun Electronics (FL, USA)[a], Schneider Electric (Rueil-Malmaison, France)[a]
Vanadium redox battery	Cell stack	\$ 1000 kW^{-1}	\$ 20 kW^{-1} year^{-1}	Prudent Energy VRB® Systems (MD, USA)[b], Golden Energy Fuel Cell Co., Ltd (China Beijing)[b], [16,22]
	Electrolyser	\$ 50 kWh^{-1}	–	
Zinc bromide battery		\$ 20,000 (for 50 kWh)	\$ 0.20 per 50 kWh year^{-1}	[16,17,23]
Electrolyser		\$ 5000 kW^{-1}	–	[24]
Fuel cell		\$4200 kW^{-1}	\$ 0.008 kWh^{-1}	The California Energy Commission (CA, USA)[a]
Hydrogen tank		\$ 250 kg^{-1}	–	Hydrogen Bank Technology Inc. (New Taipei City, Taiwan)[b]
AD[c]		\$ 628.52 m^{-3}	–	[25,26]
CHP Micro-turbine generator		\$1450 kW^{-1}	\$ 0.005 kWh^{-1}	National Institute of Building Sciences (DC, USA)[a], The California Energy Commission (CA, USA)[a]
CHP Reciprocating engine generator		\$1300 kW^{-1}	\$ 0.01 kWh^{-1}	National Institute of Building Sciences (DC, USA)[a], The California Energy Commission (CA, USA)[a], US Environmental Protection Agency[a], 2G - CENERGY Power Systems Technologies Inc[b], [11].

[a] Publicity or marketing material.
[b] Personal communications with company representatives.
[c] AD costs include the necessary civil works, tank construction, associated equipment and commissioning.

Table 4
Digester tank structure physical properties.

Material	Thermal conductivity [W m^{-2} °C^{-1}]	Thickness [m]
Plastic	0.03	0.001
Steel	16.00	0.00025
Mineral wool	0.04	0.1
Epoxy	0.35	0.00018
Steel	16.00	0.00025
Total	0.39	0.10

Source: [27].

from the India Meteorological Department [14] supplemented with daily variation obtained from Time and Date Aksjeselskap (Stavanger, Norway). Digester hourly heat losses were calculated based on a continuously stirred tank reactor (CSTR) with structural properties as shown in Table 4. The thermal load of the digester was calculated using Equation (3), and consisted of the heat loss/gain through the insulated tank, and the heat required heat the incoming feedstock to the operating temperature. These were calculated on an hourly basis using Equations (4) and (5).

$$H_T = H_L + H_F \quad [\text{kW}] \tag{3}$$

$$H_L = UA(T_a - T_{\text{op}}) \quad [\text{kW}] \tag{4}$$

$$H_F = Cq\rho(T_a - T_{\text{op}}) \quad [\text{kW}] \tag{5}$$

The operating temperature of the digester was a design variable. It was found in initial simulations that operation at mesophilic (37 °C) or thermophilic (55–65 °C) temperature led to a large heat load which could not be met using only the waste heat from the CHP. This resulted in additional biogas demand to feed a boiler (as shown in Fig. 1) to produce the required heat. It was found that given the temperature profile in West Bengal, an operating temperature equivalent to 30 °C would reduce the AD heat losses, whilst still allowing a stable anaerobic process. However, such an operating temperature would place a lower limit on the organic loading rate of the digester which was set at 2 kg VS m^{-3} day^{-1}, as suggested by Kiely [15]. Given all of the design constraints above, and the feedstock properties as per [13], the digester was effectively modelled as a conventional mixed tank digester with hydraulic retention time of 42.5 days, a daily volumetric biogas production of $0.7(\text{m}^3_{\text{biogas}}\text{m}^{-3}_{\text{working volume}})$.

3. Results and discussion

3.1. Energy systems depending on a single source

3.1.1. Photovoltaic scenarios

Table 5 shows the outputs from HOMER, representing the most suitable scaling of each of the system components, firstly, based on their ability to meet the load demand with a Loss of Load Probability (LOLP) of 1% and secondly, based on the lowest Net Present Cost (NPC) and Cost of Electricity (COE), which is calculated based on the economic variables of each scenario. It can be seen that the capacity of the system components for scenarios A and B are relatively large with respect to the maximum load on the system (12.5 kW). This is a consequence of the use of PV technology as the energy generating unit. The system not only needs to satisfy the energy demand during the day but also to secure enough energy generation and its storage so there is sufficient stored energy to allow a quality supply during the night and during periods of cloudy conditions. The low LOLP requirement also led to an over dimensioning of the system in these scenarios which could be reduced by increasing the LOLP. However, this would lead to a reduction in the quality of the supply which may be unacceptable to the users who expect energy on demand. The large generation capacities led to high proportions of wasted electrical energy for both scenarios: this occurs when the storage element of the system (VRB or Hydrogen tank) is full and there is no use for the electrical energy produced by the PV during the daytime on days with high solar radiation levels. Such a big amount of wasted energy can be harnessed by including an intelligent battery inverter control unit (e.g. SMA Sunny Island System) so that, whenever there is no energy demand and the batteries are fully charged, the system automatically delivers the energy to secondary energy needs e.g. water pumping for irrigation purposes.

Initially, a third PV based scenario was considered in combination with zinc bromide batteries. However, after researching the availability of these types of battery, this scenario was disregarded because the minimum manufactured capacity is 25 kW [16,17]: as a consequence the system would have been over-dimensioned and uneconomical.

Scenario B, which used hydrogen storage, resulted in bigger capacity of the installed PV and higher cost of energy than Scenario A, which used batteries for energy storage. It is important to take into account that in contrast to a battery backup which consists of a single unit with an overall efficiency of 75–80%, a hydrogen backup system consists of three elements: fuel cell, electrolyser and H_2 tank. Where the overall efficiency of a fuel cell coupled with an electrolyser unit is 25–60%, an H_2 tank efficiency is between 80 and 90% [18]. Although these efficiencies may be seen as high for individual energy equipment, these three elements together represent an overall round-trip efficiency of the hydrogen storage system of approximately 50%. Therefore the PV capacity must substantially exceed the expected electric load. According to the results illustrated up to this point, although Scenario B represents an innovative and promising storage solution, it is still in early development, thus, appears that the most feasible PV energy system is Scenario A where a PV is coupled with a VRB unit.

3.1.2. Anaerobic digestion scenarios

The results from the AD scenarios are summarised in Table 6. The decision to use a combination of two separate CHP units for each scenario was made after initial simulations with a single CHP showed large proportion of excess electricity generated (results not shown). This was caused by a combination of the restraints imposed on the CHP in terms of minimum operating load (60% for microturbine and 30% for reciprocating engine) and the challenging

Table 5
Optimum size and details solar photovoltaic scenarios.

Scenario		PV [kW]	Battery rated power [kW]	Battery storage capacity [kWh]	Converter [kW]	Excess electricity generated per year [%]
A	PV module + VRB + DC–AC	28	12	150	11	35.9

Scenario		PV [kW]	Fuel cell [kW]	Electrolyser [kW]	H_2 tank [kg]	Converter [kW]	Excess electricity generated per year [%]
B	PV module + Fuel Cell + Electrolyser + H_2 tank + DC–AC	40	10	14	40	18	17.3

Table 6
Optimum size and details Scenario D.

Scenario		Feedstock use [tonnes $year^{-1}$]	AD volume [m^3]	Generator# 1 [kW]	Generator# 2 [kW]	Excess electricity generated per year [%]
C	AD + 2 CHP microturbines; high and low capacity	1492	118	3	10	19.2
D	AD + 2 CHP microturbines; similar capacity	1694	134	4	6	28.7
E	AD + 2 CHP reciprocating. engines; high and low capacity	1962	155	3	10	1.29
F	AD + 2 CHP R. engines; similar capacity	2152	170	4	6	4.79

demand profile, having a large difference between base and peak load. Since these scenarios contained no energy storage elements, the CHP was dimensioned such that it could satisfy the peak load (12.5 kW) and therefore the minimum power output was 7.5 and 4.5 kW for microturbine and reciprocating engines respectively which is much higher than the base load (1 kW). Operation with two CHP units resulted in a smaller proportion of electricity wastage. The excess electricity production of these scenarios could have been improved by the addition of a battery since this would have acted as a buffer between the supply and demand when the CHP would have otherwise been operating with excess electrical output. However, in preliminary investigations this type of system was found to be financially intensive (results not shown) due to the requirement of AC–DC and DC–AC converters, the inefficiency of the repeated electrical conversion, and in addition could have a negative impact on the CHP due to a large number of daily stop–start cycles.

From results presented in Table 6, it can be seen that the microturbine based scenarios (C & D) resulted in a larger proportion of wasted electricity but a smaller feedstock usage and anaerobic digester volume, when compared with reciprocating engine scenarios (E & F). The increased wastage results from the inferior part load performance of microturbine, which have a minimum working load at 60% of the rated capacity; despite this disadvantage, the greater fuel efficiency in microturbines resulted in lower overall feedstock use. Clearly, operating with one low and one high capacity generator can reduce the excess energy generated since the lower capacity unit can better supply the base load whereas, the higher capacity unit can be used only during the peak load.

3.1.3. Economic comparison of photovoltaic and anaerobic digestion scenarios

Fig. 4 illustrates the initial investment required for each scenario. Amongst the two PV scenarios, Scenario A is the least capital intensive pathway at $ 97 k while Scenario B is the most expensive alternative at $ 234 k. An additional analysis of the disregarded scenario, PV coupled with ZBB, also was shown to be capital intensive $ 143 k. Indeed, VRB is a cheaper alternative than ZBB due to the fact that in the case of the ZBB, its minimum energy storage capacity is 25 kWh.

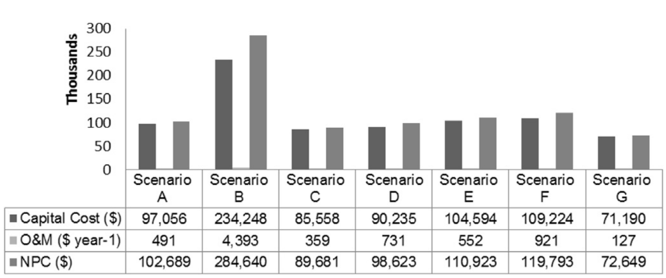

Fig. 4. Financial requirements of the different scenarios.

These results suggest that coupling PV with a VRB provides flexibility to the system where the energy system is not restricted to a minimum manufactured size of the battery. Hence, the battery size can be easily adapted to the electrical load of a particular application. Indeed, manufacturers such as Prudent Energy and Golden Energy Fuel Cell Co., Ltd., some of the world leaders on research and manufacturing of this particular flow battery storage, are targeting the market for off-grid rural electrification and other similar applications such as off-grid telephone masts, and therefore a 12 kW peak electrical load is suitable for using VRB. The capital and O&M costs associated with scenario B are the highest of all of the options considered. This is mostly due to the high costs of fuel cell technology.

The prediction that the NPC of scenarios C and D is lower than those using reciprocating engines (E and F) is due to a combination of advantages offered by microturbine technology at the investigated scale. The largest impact is the higher overall efficiency of these engines and therefore the conclusion is highly sensitive to the input data supplied from the literature and industry as per Table 3. Microturbines were found to have lower O&M costs which are because of their basic mechanical layout and fewer moving parts than reciprocating engines [19,20]. A typical maintenance of a reciprocating engine involves inspection and replacement of valves, pistons, gas and air filters, spark plugs, gaskets, rings and electronic components. However, in India the O&M of reciprocating engines would be performed locally using cheap labour and low-tech expertise, whereas the microturbine would need to be returned to the manufacturer where it would be serviced in a high-tech environment. This means that the two quoted O&M figures may be skewed in favour of microturbines. Despite this, the greater mechanical efficiency of the microturbine results in a smaller dimension of the CHP itself as well as the anaerobic digester since less biogas is required to meet the electrical demand which would still give lower capital and NPC even discounting the difference in O&M cost.

Findings portrayed in this section were used to select the components used to simulate the IRES in Scenario G. It was decided that this should be made from a combination of Scenario A and C. Therefore, in order to increase the flexibility, efficiency of the energy system, its reliability, offer a good and affordable quality of electrical service and maximise the environmental value of the IRES, this fully integrated system should involve PV, VRB, AD and a microturbine based CHP. For maximum system efficiency the generation technologies need to be coordinated such that the CHP is used only during peak load hours.

3.2. Performance of the integrated renewable energy system

The performance of the various elements which interact within the IRES are shown in Fig. 5 and Table 7 gives the details of the scale of the component systems. The share of electricity generation is divided between the PV (39%, 4394 h $year^{-1}$) and the CHP microturbine (61%, 2190 h $year^{-1}$). While the PV operates during appropriate solar conditions to satisfy the base load during the day, the microturbine is schedulable and is only used, during peak load

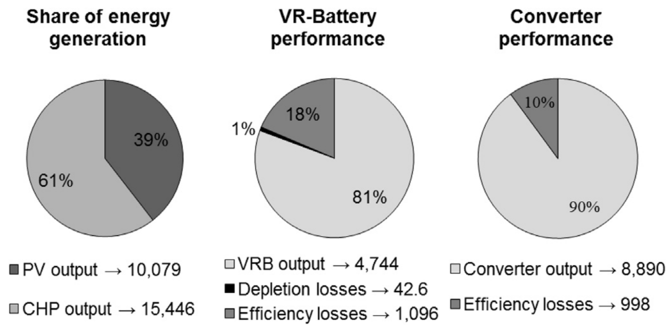

Fig. 5. IRES performance information (kWh year^{-1}).

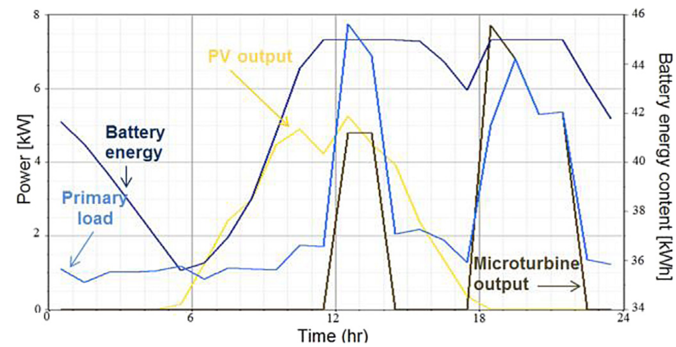

Fig. 6. IRES daily operation.

times, i.e. between 12pm–2pm and 6pm–10pm. At these times, the CHP can operate at full load and thus part load efficiency losses are avoided and furthermore, during these times, the battery can be recharged using the excess electricity. The microturbine operates at an average electrical efficiency of 33.8%, which increases to 63.6%, if the thermal energy recovery which is used to heat the digester is included. An important observation is that, in this case, since the solar cells are not required to meet the peak electrical demand, and are instead combined with a schedulable CHP, the relative sizing of the PV and converter are a factor of four smaller than in scenario A despite them still producing 39% of the total electricity supplied. Further to this, the AD plant is only 52% of the size of that in scenario B while the CHP produces 61% of the electricity supply, the difference mainly being due to the fact that the CHP can be scheduled to only be active during peak load periods leading to a lower excess electricity production.

A typical day's profile of load and electrical production of the IRES is shown in Fig. 6. In this system only the excess electricity generated from the PV is stored in the battery system and any excess biogas is not used. Hypothetically, any excess biogas would be better used as a cooking fuel and/or stored in gasometers until it is required. After 10pm when the energy load decreases, the electrical demand is satisfied by the energy stored in the batteries. By operating the system in this semi-automatic way it was found that the overall efficiency of the IRES may increase along with the life time and therefore the associated costs of the battery. Furthermore, and similarly to what was stated previously, the IRES scenario results in only 4.5% excess energy, lower than in either scenario A or C. However, it may still be worth considering the use of an intelligent high-tech battery inverter control unit which delivers the excess energy to secondary needs which could improve the quality of life of the village inhabitants (Fig. 7).

3.2.1. Economic analysis of the integrated renewable energy system

Although HOMER ranks the different systems according to its NPC, taking into account that this research targeted, low income, rural location within developing countries, the COE was determined as the most important economic feasibility indicator of the project. Fig. 8 illustrates the COE involved in each scenario. Note that the capital cost of each of the scenarios has the largest impact on the effective COE, where the COE is strongly influenced by the overall annualised cost and total electrical supply presented by each scenario.

According to the above statement and results shown in Fig. 8, Scenario G appears as the most suitable pathway. Additionally, due to the fact that it does not simply depend on one technology but on two energy generation technologies such as PV and AD, the IRES could also have increased reliability. The capital cost of the IRES (Fig. 7) is relatively lower than any other scenario which is due to the previously mentioned synergy between the schedulable, non-schedulable and storage elements in this integrated system. It is worth stressing that the scaling of the components in each scenario is highly sensitive to the selected LOLP. The 1% LOLP which has been used in this work represents a relatively high quality of supply in rural India and before embarking on such a project it would be worth considering the required or acceptable quality of supply since economic savings could be made in the case of a higher LOLP. To attempt to quantify this, scenario G was simulated at additional LOLP values of 2, 5, 10 and 20%, the results of which are shown in Table 8. Whilst it is true that reducing the desired quality of supply to a LOLP of 20% results in a reduction in the capital cost and the installed generation capacity by 15% and 27%, respectively, this

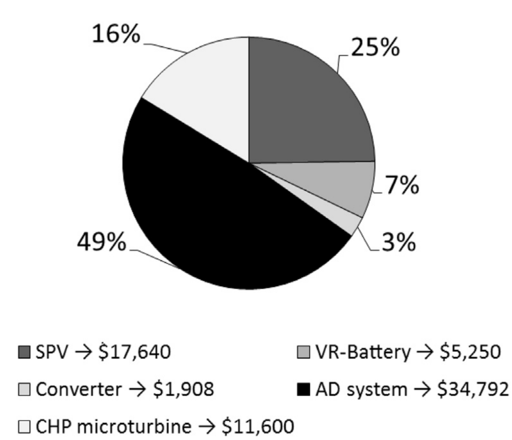

Fig. 7. IRES initial investment distribution.

Table 7
IRES capacity details.

Scenario G	PV + VRB + DC–AC + AD + CHP Microturbine						
PV [kW]	Battery rated power [kW]	Battery storage capacity [kWh]	Converter [kW]	Feedstock use [tonnes year^{-1}]	AD volume [m^3]	CHP Microturbine [kW]	Excess electricity generated per year [%]
7	3	45	3	778	62	8	4.50

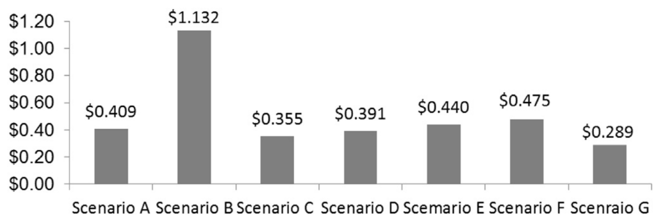

Fig. 8. COE of all the energy system scenarios.

benefit is not carried forward to the cost of the electricity over the life of the project. The COE is only reduced by 2.1% due to less electricity being supplied by the system despite a huge decrease in the supply quality. It is worth mentioning that a benefit of increasing the allowed LOLP is that less excess electricity is generated and therefore wasted, mainly because the PV system is not over-dimensioned to meet unusual peaks in demand. Based on these results depending on the required quality of supply the system may be designed with an expected LOLP of 5% to give some reduction in capital cost, COE and excess generation.

The electricity cost of the system proposed in this work of $ 0.289 kWh^{-1} is comparable with other works in rural India e.g. 0.258 for a PV and battery system [28], 0.24–0.47 for different configurations of PV, wind and batteries [29] and 0.216 for a PV, diesel and battery system [30](all in $ kWh^{-1}). Furthermore a Greenpeace study [21] found that the cost of electricity of micro-grid systems based on biomass (thermal) and PV in India was 0.304–0.384 $ kWh^{-1}, and that this can be reduced to 0.176–0.208 $ kWh^{-1} if a local hydro power source is available. The report goes on to explore the comparison between the cost of electricity from these isolated systems to the extension of the electricity grid. While the cost of electricity for grid connected customers is reported to be as low as 0.08 $ kWh^{-1}, obviously much cheaper than the cost from the IRES reported, once the costs of extending the grid are taken into account the total cost can become greater for a distance as little as 5–13 km.

A broader discussion of the benefits of the IRES would include the fact that AD offers liquid and fibrous by-products which act as soil fertilisers and can improve crop yields and soil conditions. This is a particular benefit to rural communities that otherwise may not have the financial resources to add nutrients to their cultivated fields. Therefore, they would improve the productivity within agriculture and livestock sectors, or could even commercialise the fertilisers to neighbouring villages, thus, increase their economic revenues. Nonetheless, any scenario involving AD represents a commitment to a work load demand from the community and there may be local resistance to this aspect of the technology. AD not only provides biogas to the microturbine, but this purpose is achieved by treating waste, hence, AD is a sanitary remediation alternative. Therefore, in addition to the IRES low COE, this scenario may represent a better option due to the fact that the IRES provides the other benefits from AD.

Table 8
Sensitivity of scenario G to LOLP.

LOLP [%]	Total generation capacity [kW]	Capital cost [$]	NPC [$]	COE [$ kWh^{-1}]	Excess electricity generated per year [%]
1	15	71,190	72,649	0.289	4.50
2	14	69,433	70,855	0.284	1.64
5	13	67,371	68,814	0.282	0.42
10	12	65,332	66,690	0.285	0.10
20	11	60,341	61,103	0.283	0.20

4. Conclusions

The objective of this research was to investigate the electrification of a remote community in West Bengal, India using an IRES. This research has involved the selection of two PV, four AD and a combined AD & PV scenario using micro-grid modelling software – HOMER. Each scenario was designed with the capability to meet a specified electricity demand with daily variations for a full year. The design of the various energy system scenarios was studied in terms of their techno-economic performance to determine the most efficient path to follow while meeting the electricity load of the rural community.

It was determined that the IRES containing PV, VRB, DC–AC converter, AD and a microturbine CHP had many benefits compared with the other scenarios where only one energy source was available. The IRES had a lower capital and electricity cost over the life of the project was lower at $ 0.289 kWh^{-1} (c.f. $ 0.335–1.332 kWh^{-1} for other scenarios) mainly due to the synergy between the various production and storage elements at meeting the demanding load profile with a very high quality of supply.

Rural electrification projects on developing countries such as this one based on the electrical requirement of a typical community in West Bengal – India, not only improve the quality of life of remote villages inhabitants but they also provide business and research prospects for foreign and local engineering institutions. Such institutions could offer the governments of developing countries technical assessment, renewable energy technology supplies and installation services. Indeed, this research has the potential to offer opportunities within several areas such as the environment, technology, economic and social fields.

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