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

J.G. Castellanos, M. Walker, D. Poggio, M. Pourkashanian, W. Nimmo*

Energy Technology Innovation Initiative (ETII), Faculty of Engineering, University of Leeds, Leeds LS2 9JT, UK

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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

* Corresponding author. Tel.: +44 113 3432513.
E-mail address: w.nimmo@leeds.ac.uk (W. Nimmo).

[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} °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} °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.

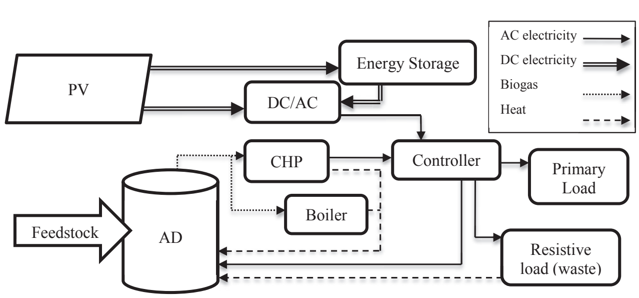

Fig. 1. Integrated renewable energy system general configuration (PV – photovoltaic, DC/AC – direct to alternating current converter, CHP – combined heat and power, AD – Anaerobic digester). Energy storage contains batteries or an electrolyser, hydrogen tank and fuel cell depending on the scenario.

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

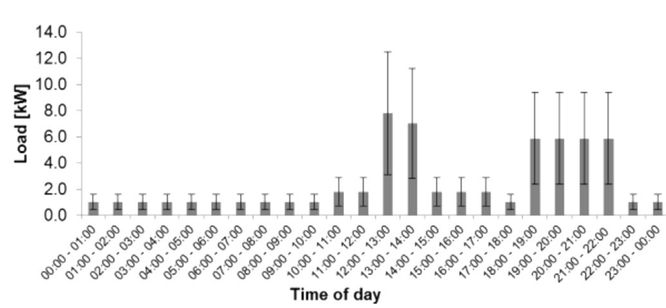

Fig. 2. Load profile in rural Indian village location.