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Optimal Dispatching of a Photovoltaic-Biogas Hybrid System

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***Abstract*—**This paper presents an optimal dispatching strategy for a photovoltaic-biogas hybrid system for an autonomous research campus. The aim is to prioritize use of the PV system to meet demand whenever available. If the demand is less than the PV output, the excess generation can either be dumped, or it can be stored via Power-to-X. If the demand is larger than the PV output, the imbalance is met by the biogas system. Since biogas production is continuous, the biogas system can supply power directly to the load and/or store energy during times when PV is meeting demand. During times when PV cannot meet the load the biogas storage system discharges to ensure that all generators run to meet the load. The results show opportunities for implementation of such autonomous systems in most developing countries where electrification rates are low. The outcome of this study is expected to inform micro-grid controller designers of the envisaged operation strategies. In cases where such a system is connected to the grid and feed-in tariffs and net metering are allowed, any excess electricity can be exported to the grid hence generating revenue or credits for the institution.

Keywords*—Net metering, optimal dispatching, controller designers, configurations*

I. Introduction

Distributed generation options such as biogas and solar photovoltaic (PV) are promising options for energy supply in rural off-grid locations and for institutions such as hospitals, clinics, hotels and schools, especially in areas where grid connection is impossible or not economic. Biogas systems feedstock is readily available in most rural areas and also at schools, hospitals, hotels and other isolated institutions while the solar resource is abundant in most developing countries of the world including Africa. Biogas systems have the advantage that they can meet both electrical and thermal energy requirements of the consumer. The biogas system can also include gas storage and hence demand can be met at all times. When the storage is full and demand for biogas is low, the biogas can be flared to avoid the harmful effects of the gas to the environment. Although burning of methane produces carbon dioxide, it reduces the impact of methane on the environment. Typically, a turbine or engine running on biogas is utilized to generate power. In a hybrid system such as the one proposed in this paper, power generated by the biogas engines is used to meet the load during periods of low PV production and at night times.

Various hybrid system configurations have been proposed by various researchers to solve the energy access problem faced by most developing countries [1, 2]. An

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economic optimization model of a micro-combined heat and power (CHP) system for a multi-apartment housing consisting of a natural gas fed prime mover, a thermal energy storage system and an auxiliary boiler is presented in [3]. Two different operational strategies are explored to meet the load with and without heat dumping. In [4], a feasibility study and constraints of biogas usage in Tanzania are examined by randomly selecting two hundred households with and without biogas facilities from four villages. However, the main challenge is to optimally dispatch the various components of a hybrid system [5, 6].

Research and development efforts in renewable energy technologies such as PV/biogas CHP systems for institutional and community energy generation applications are crucial in order to ensure universal access to energy for people living in marginalized and remote areas where it is difficult or uneconomic to extend the grid. In order to ensure supply reliability of such systems, more research effort is required in areas such as performance improvements, optimal sizing, operational and dispatching strategies, among others. This paper presents an autonomous PV and biogas hybrid system and the focus is on optimal dispatching of PV and biogas systems in order to meet the load demand at all times. This work is driven by the need for a feasible opportunity for a waste to energy project by a research campus considering the availability of land, waste in the area, continuously rising landfill gate fees, high electricity consumption of research campus, continuously increasing electricity prices and need for electricity supply autonomy among other factors. The outcomes of this work will inform controller designers on the expected system operational strategies to be considered when designing microgrid systems of this nature. This paper serves to demonstrate the dispatching concept which can be adopted for managing supply mix at supervisory level and to inform campus decision makers on the optimal combination based on the proposed operational strategy. The following sections focus on the description of the PV-biogas system, model formulation, results and conclusion.

II. THE PV-BIOGAS HYBRID SYSTEM

The hybrid system evaluated consists of three subsystems, the PV system, the biogas system and generators. Priority is given to the PV system to meet demand. If the demand is less than the PV's output, the excess power generated will be dumped, or it can be stored via Power-to-X or sent to the grid if the later options are applicable. If the demand is larger than the PV's output, the imbalance will be met by the biogas system. Since biogas production is continuous, the biogas system can supply energy directly to the load or store it during times when demand is being met by PV. During times when PV cannot meet the load the biogas storage system also discharges to meet the load.

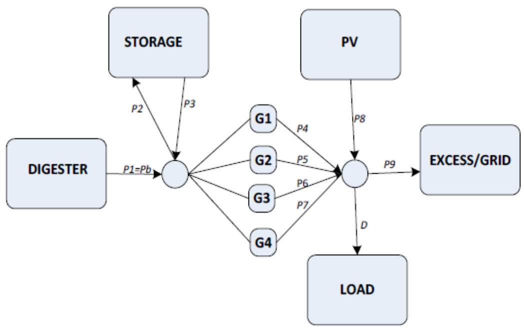

Fig. 1: Schematic of the hybrid system

Fig. 1 shows the schematic of this hybrid system, in which the direction of arrows represent the power flow in the system. $P_b(t)$ is the power produced by the biogas system; $P_2(t)$ power supplied to the storage system; $P_3(t)$ is the power from the storage system; $P_4(t)$ - $P_7(t)$ represent the power from generators G_1 - G_4 respectively; $P_8(t)$ the PV power and $P_9(t)$ is the excess power all at hour t. Controllers and converters have been left out for simplicity purposes.

A. PV System

Each solar array consists of several solar cells to convert sunlight into direct current (DC) power. The hourly power output for a given area is formulated as follows:

$$P_{pv} = \eta_{pv} I_{pv} A_c, \qquad (1)$$

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where P_{pv} is the hourly power output from the PV array; Ac is the size of PV array; η_{pv} is the efficiency of power generation; I_{pv} is the hourly solar irradiation on the PV array (kWh/m^2).

The hourly solar irradiation on the PV array is closely related to time of a day, season of a year, tilt angle, location, global irradiation, diffuse fraction and so on. In this study, the simplified isotropic diffuse formula [7, 8] was used as:

$$I_{pv} = (I_B - I_D)R_B + I_D, \qquad (2)$$

where I_B and I_D are the hourly global and diffuse irradiation respectively. R_B is a geometric ratio of the actual irradiation on a tilted plane to the standard irradiation on a horizontal plane; and for north facing collectors, it is given by:

$$R_B = \frac{\cos\theta}{\cos\theta z} = \frac{\sin\delta\sin(\phi+\beta)+\cos\delta\cos\omega\cos(\phi+\beta)}{\sin\delta\sin\phi+\cos\delta\cos\phi\cos\omega} \qquad (3)$$

where θ is the angle of incidence i.e. angle between the sun's direct rays(beam radiation) on a surface and the normal to that surface. θ_z is the Zenith angle i.e. angle between the vertical and the line joining the sun and the observer or simply angle of incidence of beam radiation on a horizontal surface. δ is the declination angle i.e. angular position of the sun at solar noon with respect to the plane of the equator (positive in the northern hemisphere, NH and negative in the southern hemisphere, SH) expressed as:

$$\delta = 23.45 sin\left[\frac{360(284+n)}{365}\right]; \qquad (4)$$

where n is the day of year number; - is the latitude i.e. angular location N or S of the equator . β is the tilt angle i.e. angle between the plane of the surface in question and the horizontal; ω is the hour angle i.e. the angular displacement of the sun E or W of the local meridian due to the rotation of the earth on its axis at 15^o per hour (morning negative and afternoon positive). The efficiency of power generation has a complicated model. It is expressed as a function of the hourly irradiation I_{pv} and the ambient temperature T_A as follows :

$$\eta_{pv} = \eta_R\left[1 - \frac{0.9\beta I_{pv}(T_{C0} - T_{A0})}{I_{pv0}} - \beta(T_A - T_R)\right] \qquad (5)$$

where η_R is the referenced efficiency that measured under standard test conditions (STC); T_R is the referenced cell temperature at STC (25^oC); β is the temperature coefficient for cell efficiency (typically 0:004-0:005%/^oC). T_{C0} (typically 45^oC) and T_{A0} (typically 20^oC) are the cell and ambient temperatures at Nominal Operating Cell Temperature (NOCT) test conditions. I_{pv0} is the average solar irradiation on the array at NOCT conditions [9].

A PV module will be typically rated at 1kW=m2 and 25^oC under STC . However, when operating in the field, they typically operate at higher temperatures and at somewhat lower insolation conditions. In order to determine the power output of the solar cell, it is important to determine the expected operating temperature of the PV module. The NOCT is defined as the temperature reached by open circuited cells in a module under the following conditions: irradiance = 0.8 kW/m^2, wind speed = 1 m/s, and mounting = open back side. The data used was obtained from a nearby whether station and an installed capacity of 6000 kWp as proposed by the research campus was used.

B. Biogas and generator systems

The biogas process parameters include the amount of substrate added to the digester, loading rate in $kgVS/m^3$ where VS stands for volatile solids and biogas production rate in $Nm^3/tonTS$ as well as carbon and nitrogen content in the substrate (i.e. C:N ratio). Other parameters are the weight of the substrate after drying (Total Solids TS, % of wet weight or weight of the substrate including water); weight of organic matter in the substrate (Volatile Solids % TS) and operating temperature range (e.g. mesophilic or thermophilic). Pre-treatment (i.e. pasteurization, thickening, disintegration); methane concentration (percentage by volume); methane yield ($Nm^3/tonTS$) and the average time that the substrate is inside the digester (i.e. hydraulic retention time) are also important parameters. In addition to these, it crucial to consider how much of the substrate that is degraded in the digester (i.e. degradation of VS as %VS); digestion of substrate with around 2-15 %TS (i.e. wet digestion) and digestion of substrate with around 15-35 %TS (i.e. dry digestion) [10].

The schematic of the biogas process chain considered is as shown in Fig. 2. Storage tanks have been conveniently omitted (these can be piped to a separate biogas holder or integral with the digester) and any excess gas that cannot be stored is flared. An entity may decide not to flare (i.e. waste) any gas by running a generator to add to the excess production if this makes a business sense.

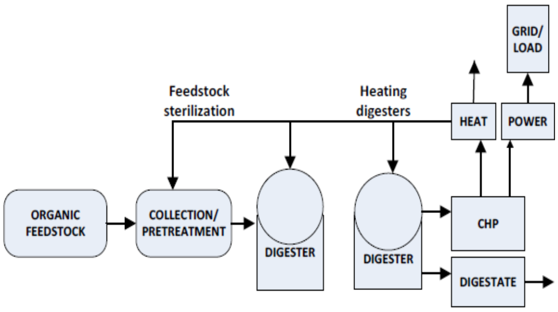

Fig. 2: Schematic of the biogas system

Constrained in the capacity of the storage, the state of charge (SOC) is dynamically changing due to possible charge by the biogas system and possible discharge for the customer usage. Let S(t) denote the SOC of the storage at the t^{th} hour. Based on the SOC at the previous hour, the dynamic change of SOC formulated as follows:

$$S(t) = S(t-1) + \alpha P_2(t) - \alpha P_3(t), \qquad (6)$$

where $\alpha = \frac{\Delta t}{Cb}$ with Δt as the time-step and Cb the storage capacity); $P_2(t)$ is the charging power for the storage; $P_3(t)$ is the discharging power from the storage system; S(t) is the SOC at the t^{th} hour; S(t -1) is the SOC at the previous hour. The SOC of storage system must be less than or equal to the storage capacity S^{max} and larger than the minimum allowable value S^{min}

$$S^{min} \leq S(t) \leq S^{max} \qquad (7)$$

In this paper, four biogas generators are incorporated in the system. These generators are dispatchable and can therefore be dispatched at any time when the PV system output is not enough to meet the load. The generators have minimum and maximum limits within which they operate as per manufacturer's specifications. The following generator capacities used were 1500 kVA (G1), 800 kVA (G2), 1000 kVA (G3) and 1200 kVA (G4). A constant supply of 2500 kW from the biogas system was assumed and a storage capacity of 30000 kWh equivalent of gas. Considering the fact that a typical normal cubic metre of methane has a calorific value of 10 kWh, while carbon dioxide has none, the energy content of biogas can be directly related to the methane content. It follows therefore that biogas with 60 % methane content will have an energy content of 6 kWh/m^3 and the higher the methane content the higher the energy content of the gas.

III. MODEL FORMULATION

Optimal control of the target hybrid system aims to minimize use of energy from the biogas system and excess energy, while maximizing use energy from PV. Detailed calculations related to the biogas and generator systems have been omitted but will be subjects of future works of this ongoing research. The production is assumed to be constant based on a preliminary study carried out by the research entity and is out of the scope of this paper. The maximum PV capacity is also based on the same preliminary study and proposed implementation plans. The energy consumption data of the research campus and the planned PV project projections therefore informed this work. Outcomes of a feasibility study undertaken for the design of an optimal anaerobic digestion facility were used, however, the details of the feasibility study are beyond the scope of this work. Based on the feasibility study, the average biogas production would be 1 100 Nm^3/h, amount used for anaerobic digester (AD) consumption of 240 Nm^3/h and an average available biogas of 860 Nm^3/h. This would translate to an average AD power of about 2500 kW, which is assumed to be constant in this work and a total stored volume of about 50 000 Nm^3 which translates to 30 000 kWh

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assuming biogas methane composition of 60%. A substrate flow rate of the mixed waste of about 285 ton/day was used based on the available feedstock with approximately 60% of organic content. For the proposed plant, the ADs will operate under mesophilic conditions at an optimal temperature of 37°C within the typical range of 30-40°C and hydraulic retention time of 30 days within the typical retention time of 20-45 days [11].

The mesophilic operating range is preferred as it is more robust and cheaper compared to thermophilic conditions and is suitable for slurries and food wastes, which are the proposed feedstock for this plant. This operating range can withstand day and night temperature changes as well as extended periods of inactivity. Because the linear objective function has linear constraints, the linear programming optimization tool in MATLAB was used to solve the problem. The function "linprog" is used which generally solves problems in the form:

$$\min f^T x, s.t. \begin{cases} Ax \leq b \\ A_{eq}x = b_{eq} \\ lb \leq x \leq ub \end{cases}, \quad (8)$$

where $f^T x$ represents the objective function, and f, x, b, beq, lb, and ub are vectors, while A and A_{eq} are matrices. The objective function can be formulated as:

$$\min \sum_{t=1}^{24} (w_1(P_4(t) + P_5(t) + P_6(t) + P_7(t)) \quad (9)$$
$$-w_2 P_8(t) + w_3 P_9(t)),$$

where ω_1-ω_3 are weight factors. For this problem, the control variables are: $P_2(t)$, $P_3(t)$, $P_4(t)$, $P_5(t)$, $P_6(t)$, $P_7(t)$, $P_8(t)$, $P_9(t)$ ($0 < t \leq 24$). The objective function is solved subject to the satisfaction of several constraints:

(1) Biogas system output constraint: The biogas system is responsible for charging the storage and for immediate customer usage.

$$P_2(t) - P_3(t) + P_4(t) + P_5(t) + P_6(t) + P_7(t) = P_B(t). \quad (10)$$

(2) Power balance constraint: The load demand of customers must be satisfied by the combined power of the PV array and the biogas system with storage.

$$P_4(t) + P_5(t) + P_6(t) + P_7(t) + P_7(t) - P_9(t) = D(t), \quad (11)$$

where D(t) is the load demand at hour t.

(3) SOC boundary constraint: According to dynamic Eq. (6), the SOC of the storage system, S(t), can be expressed in terms of the initial SOC, S(0), at the beginning of each day:

$$S(t) = S(0) + \alpha \sum_{\tau=1}^{t} P_2(\tau) - \alpha \sum_{\tau=1}^{t} P_3(\tau). \quad (12)$$

(4) Power flow constraint: For safety and other physical or operational reasons, power flow from each source must be non-negative, and less than or equal to the minimum and maximum allowable values.

$$P_i^{min} \leq P_i(t) \leq P_i^{max}, \quad (13)$$

Where P_i^{max} is the defined maximum power delivered per hour. Optimal control was utilized to dispatch P_i (i = 2,…, 9) over a day.

IV. RESULTS

The results show that demand is met at all times and there is maximum utilization of PV output. In Fig. 3, the PV output is high resulting in excess energy of 4184 kWh (sum of P_9 over the 24 hour period) and consequently during the same period the generators are switched off. The excess energy can either be sent into the grid, if this is allowed, or it can simply be dumped, or it can be stored via Power-to-X (i.e. conversion technologies that allow for the decoupling of power from the electricity sector for use in other sectors (such as transport or chemicals).

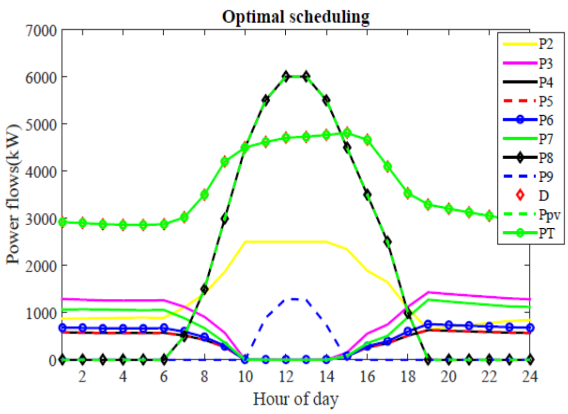

Fig. 3: Optimal dispatching

Fig. 4 shows the charging and discharging of the storage system, which is within the specified limits. The storage system is shown to discharge in the early hours of the morning and at night with the generators supplying the load. The generators are shown to be off during the day when PV output can fully meet the load from about 10:00-15:00.

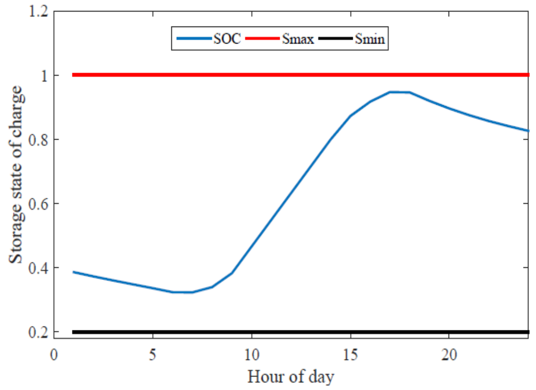

Fig. 4: Charging and discharging states of storage system

In Fig. 5, the PV output is reduced and consequently the generators are operating throughout the day to meet the load. Such a condition may be expected during periods of bad weather. It is important to note that the largest generator is never dispatched. These results therefore reveal that it may not be necessary to have the fourth generator which is not used even under the low radiation scenario.

In Fig.6, the storage dynamics show that there is less charging owing to the fact that the biogas system is utilizing most the produced energy to meet the load.

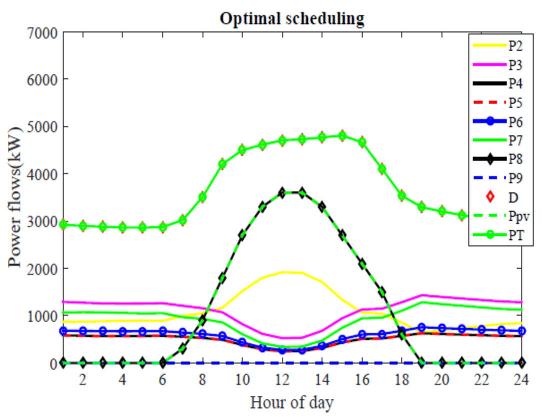

Fig. 5: Optimal dispatching with reduced PV output

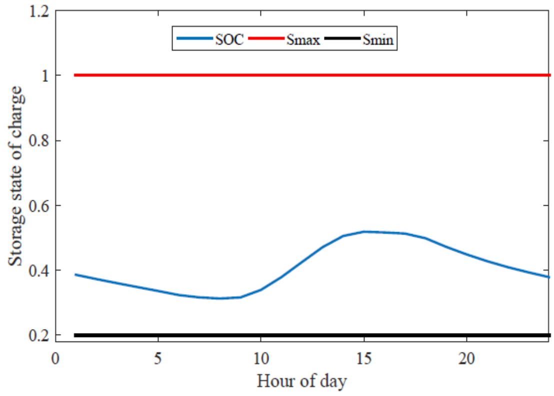

Fig. 6: Charging and discharging states of storage system

V. CONCLUSIONS

An optimal dispatching strategy of a stand-alone PV-biogas system has been presented showing how the load is met completely by such a system. It has been shown that during periods of high production from PV the biogas system generators can be switched off and all gas produced can be stored for later use. The biogas system was mostly deployed during night time. In unfavorable weather it has been shown that he generators can run throughout the day to compliment PV production. It may be necessary in future work to consider reducing the number of generators to one or two large capacity generators by considering the costs involved. Future work will investigate grid connected PV-biogas systems in order to quantify the benefits of such a system in reducing both energy bills and peak demand charges. Detailed analyses of the various components of the system will also be subjects of future works.

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References

[1] D. Zhang, S. Evangelisti, P. Lettieri and L.G. Papageorgiou, "Optimal design of CHP-based microgrids: Multiobjective optimisation and life cycle assessment" Energy, 85, 181-193, 2015.

[2] Z. Zhou, P. Liu, Z. Li and W. Ni, "An engineering approach to the optimal design of distributed energy systems in China." Applied Thermal Engineering, 53(2), 387-39, 2013.

[3] M. Caliano, N. Bianco, G. Graditi and L. Mongibello, "Economic optimization of a residential micro-CHP system considering different operation strategies." Applied Thermal Engineering, 101, 592-600, 2016.

[4] A.G. Mwakaje, "Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints." Renewable and Sustainable Energy Reviews, 12(8), 2240-2252, 2008.

[5] B. Zhu, H. Tazvinga and X. Xia, "Model predictive control for energy dispatch of a photovoltaic-diesel-battery hybrid power system. IFAC Proceedings Volumes," 47(3), 11135-11140, 2014.

[6] T. Hove and H. Tazvinga, "A techono-economic model for optimising component sizing and energy dispatch strategy for PV-diesel-battery hybrid power systems," Journal of Energy in Southern Africa, 23(4), 18-28, 2012.

[7] M. Collares-Pereira and A. Rabl, "The average distribution of solar radiation correlation between diffuse and hemispherical and between daily and hourly insolation values," Solar Energy, 22: 155–164, 1979.

[8] H. Tazvinga, X. Xia, and J. Zhang, "Minimum cost solution to photovoltaic-diesel-battery hybrid power systems for remote consumers," Solar Energy, 96: 292-299, 2013.

[9] H. Tazvinga and T. Hove, Photovoltaic/Diesel/Battery Hybrid Power Supply System. VDM Publishers, 2010

[10] Center, S.G. 2012. Basic data on biogas. Available Online, Accessed 23 June 2018.

[11] M. Poschl, S.Ward and P. Owende, "Evaluation of energy efficiency of various biogas production and utilization pathways," Applied Energy, 87(11), 3305-3321, 2010.