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Original article

Sensitivity analysis and comparative studies for energy sustainability in sewage treatment

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ABSTRACT

The paper presents the sensitivity analysis for the utilization of renewable energy sources in wastewater treatment field and the related comparative studies versus conventional power sources. A former work introduced a case-study wastewater treatment plant. It discussed the feasibility of using entirely renewable hybrid system to power the plant under off-grid conditions with minimum life cycle cost and minimum possible emissions. The hybrid power system optimum configuration consisted of fuel cell, micro-turbine, wind turbine and photovoltaic systems. The sensitivity analysis in this paper aims at identifying the system effective variables in the case-study. This is to derive general rule-of-thumbs which express the system behavior. Through using HOMER software, the sensitivity analysis studies the effect of renewable energy potentials and the capital cost of the power subsystems. Besides, the paper measures the feasibility strength of the base hybrid system by holding Comparisons with conventional power systems. The comparative studies determine the breakpoints and feasibility zones which grant the preference of the hybrid system.

Introduction

Renewable energy sources (RES), called sustainable or alternative energy, are energies generated from natural resources such as wind, sunlight, tide, hydro, biomass and geothermal which are naturally replenished [1]. One of the important utilization of the renewable energies is to electrify many remote villages and rural areas or rugged terrains located so far from power stations and distribution networks or utility lines which are uneconomical to install [1,2]. Combining renewable energy sources via building standalone hybrid systems is an interesting solution for the electricity supply in these regions [3]. Moreover, renewable energy sources and their energy conversion devices offer a solution for greenhouse gas emissions and atmosphere temperature [4,5]. A primary advantage of RES is closing the gap between electricity consumption & generation from grid. The continuous fast growth of electrical demands is hardly met by the conventional power sources. This is because fossil fuels used by these power sources are rapidly depleting which doubles the problem in the near future and boundlessly increases fuel prices [6–8]. However, the vulnerability to unpredictable climatic changes is considered a major drawback in the installation of renewable energy-based systems [9]. For this reason, renewable energy systems, despite being efficient solution for providing a sustainable power supply, are commonly used as subsystems beside a conventional power source in the hybrid system [10–12]. Using entirely renewable standalone power system remains unfeasible in many applications because dependency of RES with their intermittent nature results in significant capital cost [13]. However, a facility like wastewater treatment plant is distinguished with the capability to extract anaerobic digester gas as an energy source. With the right utilization of the gas and other available RES, the renewable hybrid system may prove as a competitive solution. Several researches were made to highlight the importance of energy-from-waste. However, the current paper offers a new direction of research through analyzing sensitivity factors in wastewater treatment energy sustainability. The study uses actual plant data, considers both environmental and economic factors alike, analyzes the effect of each factor and finally justifies the system strength through comparing the base system to conventional solutions. A former work, introduced in [14] used the data of the wastewater treatment plant (WWTP) of the town of Toukh (Egypt) as a case-study for a typical rural small-scale plant. The plant has an influent rate of 8000 $m^3\ d^{-1}$ and uses the conventional activated sludge method for water treatment. In Ref. [14], the treatment method and anaerobic digestion process were reviewed. The scope was to study the feasibility of supplying the plant with entirely renewable energy-based standalone hybrid system which offers minimum

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Nomenclature

AC	alternating current
ADG	anaerobic digester gas
CHP	combined-heat-power
CO_2E	equivalent CO_2 emissions (ton yr^{-1})
DC	direct current
FOG	food, oil and grease
MT	micro-turbine
NPC	net present cost
O&M	operating and maintenance
PV	photovoltaic
RES	renewable energy sources
SOFC	solid oxide fuel cell
TAC	total annualized costs
WTS	wind turbine system
WWTP	wastewater treatment plant

amount of emissions released. The study also discussed the energy recovery from the plant and the selection of the suitable combined-heat-power technology for digester gas utilization. The study used solid oxide fuel cell-microturbine hybrid (SOFC-MT), photovoltaic (PV) system and wind turbine system (WTS) combined to supply the plant independently without the need for any conventional power source. HOMER software was used to model RES potential, energy conversion devices, electrical load and energy storage system (Battery bank). It determined the optimum size of each subsystem which grants lowest lifecycle cost or net present cost (NPC). This current paper continues the work through studying the sensitivity analysis to measure the effect of system variables on NPC which is considered the primary indicator for system feasibility. It also studies their effect on the optimal system configuration. In addition, the paper studies the strength of the base system feasibility by evaluating the NPC of electrifying the plant from both extended grid network and diesel generator. For the grid case, the comparison results show the breakeven distance between the plant and nearest grid point. Above this distance, the hybrid system gets economically more feasible. For the diesel generator case, the results give the critical diesel fuel price at which the hybrid system becomes initially feasible. Beside the feasibility, the research evaluates the emissions produced by each system to measure how far the hybrid system is environmentally advantageous.

System modeling

According to the plant data, the evaluated electrical load has a peak of 240 kW and the daily energy consumption is 4815 kW h d^{-1}. The thermal load was evaluated in [14] and completely covered by the useful heat from micro-turbine exhaust. The energy resources modeled in the software included the digester gas volume, solar radiation and wind speed. The operating point of anaerobic digester gas (ADG) volume, evaluated from energy recovery calculations of the plant, is 44.6 m^3 d^{-1}. The daily average radiation of the site per unit area of horizontal surface and wind speed, given the plant coordinates, are 5.52 kW h m^2 d^{-1} and 4.75 m s^{-1} respectively [14]. As for modeling the combined-heat-power (CHP) system, it was modeled in HOMER as a "generator general model". That block gives the flexibility to model any fuel-fed power source by entering its fuel curve. The fuel curve expresses the relation between the fuel consumption and output power. Based on that, HOMER evaluates the efficiency curve which expresses the relation between the generator output and efficiency. Fig. 1 shows the part-load efficiency curve of the CHP micro-turbine, modeled by HOMER, after entering the fuel curve data. Ref [14] justified the possibility of modeling SOFC-MT hybrid model through modeling SOFC and MT individually at ADG production operating point. Modeling the rest of component was introduced earlier in [14].

Also, the study of the lifetime, capital, operating & maintenance (O&M) costs of the hybrid system major components has been carried out in [14]. It was concluded in that the total installed costs and O&M costs for SOFC & MT used in the model were 4000 $ kW^{-1}, 2500$ kW^{-1}, 0.025$ kW h^{-1}, 0.015$ kW h^{-1} respectively. Installed costs and O&M costs were 4000$ kW^{-1} and 12$ kW^{-1} for PV system whereas they were 3000$ kW^{-1}, 30$ kW^{-1} for wind turbines. Capital Cost for converters and batteries is 650$ kW^{-1}, 445$ kW^{-1} respectively. In order to maintain the accuracy of the results, prices are updated in this current paper to the present years. As for PV prices in 2015, medium size industrial PV system total installed cost was significantly reduced to reach 2020 $ kW^{-1} [15]. This cost includes modules, racking, and all balance-of-system (BOS) hardware required for a complete system but not the inverter. The total installed cost of the fuel cell is reported to be 2300 $ kW^{-1}, giving another technology's price sharp-cut [16]. The installed cost used here is 3000 $ kW^{-1} taking into accounts the interconnection with other subsystems and to maintain a safety factor for the overall system cost. The capital cost of inverter is approximately 130$ kW^{-1} as per Ref. [15] and as checked by the prices available commercially.

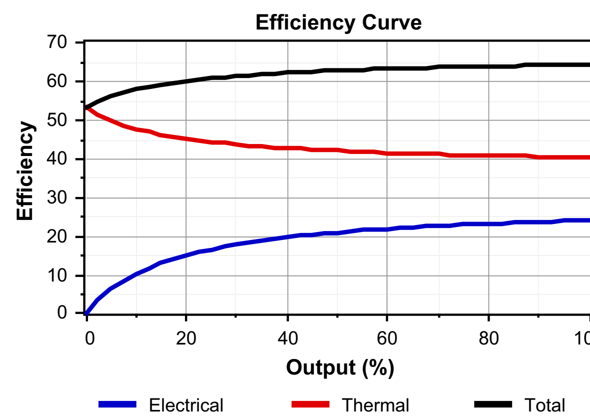

Fig. 1. Efficiency curve of CHP MT modeled by HOMER.

In contrast, the market hasn't shown same noticeable change for micro gas and wind turbines technologies. The capital cost adopted in calculations for micro gas turbine in the year 2015 is 3400 $ kW^{-1} [17]. Prices used for the wind turbine and batteries are kept the same as mentioned in the earlier paragraph. The updated information of prices is used to as input for HOMER to evaluate the total annualized costs. The total annualized costs (TAC) are the sum of the annualized costs of each system component. The latter equals the sum of annualized capital cost, annualized replacement cost, annual O&M cost and annual fuel cost (if applicable) over the project lifetime. The total system NPC is calculated through Eq. (1) as follow[1]:

[1] From HOMER Software, Help Document.