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Optimal Synthesis of a Community-Based Off-Grid Polygeneration Plant using Fuzzy Mixed Integer Linear Programming Model

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Polygeneration provides an alternative approach for producing clean energy with enhanced overall thermodynamic efficiency, thus reducing environmental emissions and wastes. The growth of energy demand can be attributed to population growth together with the economic progress of developing countries. Such countries need to map out carbon-constrained growth trajectories that make intensive use of clean energy. In developing countries, there are still sites found in remote rural areas or islands which are still off-grid. Provision of electricity to such isolated communities is often problematic due to lack of economies of scale. Most of the livelihood of citizens in these areas is mainly based on agriculture and fisheries, which requires basic utilities such as electricity, clean drinking water, and cooling or refrigeration to preserve the agricultural produce and fishery catch. Polygeneration systems offer an efficient means of satisfying the utility needs of such remote communities. Hence, this study is focused on the development of a model for the optimal synthesis of community-based off-grid polygeneration plants needed to supply the basic needs of electricity, potable water, and cooling. The proposed approach uses a fuzzy mixed integer linear programming (FMILP) formulation. A hypothetical but realistic case study of a community-based off-grid is used to demonstrate the model.

1. Introduction

Sustainability concerns such as climate change have risen due to the growth of economies mainly attributable to industrial emissions and the production of energy (IEA, 2017). The drive for industrialization pushes the boundaries of the planet's safe tolerable limits on environmental footprints (Rockström et al., 2009). The polygeneration concept is a viable approach to sustainably produce energy with high-valued co-products while minimizing environmental emissions (Serra et al., 2009). It produces multiple product streams from integrated processes, providing opportunities for the reuse of material and energy streams. Even with the growth of economies and global electrification programs of various countries, there are inherent off-grid locations constricted by geography and economic limitations. One approach in providing power to the off-grid sites is to design a polygeneration plant based on the locally available natural resources. Most of the off-grid locations are rural areas where there is an access to abundant biomass resources. Some rural areas have access to running water with potential for microhydro plants. Source of income for communities in such areas include farming and fishery products. To increase the income of farmers and fishermen it is necessary for them to refrigerate their produce or catch. In addition, access to clean potable water is another concern in these areas. Thus, the basic common needs of an off-grid community are access to electricity, cooling, and purified water.

The design of polygeneration systems can be facilitated by computer models (Liu and Pistikopoulos, 2009). Process systems engineering (PSE) is a branch of chemical engineering that focuses on the development and use of computer-aided techniques for system design and operation (Grossmann, 2017). The use of mathematical programming models for generic process synthesis problems is well-established (Grossman and Santibanez, 1980). Mathematical programming models in PSE can be classified based on formulation, such

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as linear programming (LP) (Lozano et al., 2009), mixed-integer linear programming (MILP) (Liu et al., 2007), and fractional programming (Ubando et al., 2013). An off-grid polygeneration system has been designed by Ray et al. (2017) using an LP model by maximizing the annual profit of the plant considering power, fuel, and cooling as main products. However, multiple objectives should be considered in the design of a polygeneration plant to anticipate simultaneous long-term factors such as economics and environmental impact. Fuzzy set theory was adapted by Zimmermann (1978) in LP models to accommodate multiple objective functions. A fuzzy P-graph approach based on a MILP model was proposed by Aviso and Tan (2017) for the optimal synthesis of a polygeneration plant. Previous work on the design of an off-grid polygeneration system was reported by Ubando et al. (2017) using fuzzy linear programming (FLP) model to select a backup power technology while maximizing the profit and production level, and minimizing the capital costs. The study excludes the accounting of carbon dioxide (CO_2) emissions of the system.

This study proposes a fuzzy mixed-integer linear programming (FMILP) model to design a community-based off-grid polygeneration plant considering electricity, cooling, and purified water as products, which seeks to maximize the economic potential and production level and minimize the CO_2 emission of the plant. The paper is organized as follows. Section 2 states the problem formally. Section 3 discusses the proposed FMILP model. Section 4 describes the case study of an off-grid community together with the results. Lastly, section 5 summarizes the findings of the study with a brief discussion of the future works.

2. Problem Statement

The problem is formally stated as follows. The technology matrix is defined by the number of technologies and the number of product streams for the off-grid community. The raw materials in the technology matrix are represented by negative values while the product outputs are represented by positive values. The production output of the polygeneration plant is directly influenced by the product demand limits defined exogenously by a fuzzy membership function. The economic potential of the polygeneration plant is defined by the sales of the product streams, purchase of inputs, and the capital cost. It is influenced by the economic target of the polygeneration plant owners which is represented by a membership function for maximization. The carbon emission of the polygeneration plant is regulated by the local government and is represented by a membership function for minimization. The selection of the appropriate technology is indicated by a binary selection function. The problem is to determine the optimal configuration of the polygeneration plant which satisfies the requirements of the off-grid community.

3. Fuzzy Mixed-Integer Linear Programming Model (FMILP)

The developed FMILP model consists of the objective function shown in Eq(1) satisfying all the constraints shown in Eqs. (2-12).

$$\text{Maximize } \lambda \tag{1}$$

$$\Sigma_j A_{ij} x_j = \Sigma y_i \qquad \forall\, i \tag{2}$$

$$\Sigma_j D_{kj} x_j = \Sigma z_k \qquad \forall\, k \tag{3}$$

$$P = CF(\Sigma_i C_i y_i) + AF(\Sigma_j FC_j b_j + \Sigma_j VC_j x_j) \qquad \forall\, j \tag{4}$$

$$\Sigma_j G_{pj} b_j \le Q_p \qquad \forall\, p \tag{5}$$

$$x_j \le M\, b_j \qquad \forall\, j \tag{6}$$

$$b_j \in \{0, 1\} \qquad \forall\, j \tag{7}$$

$$y_i \ge y_i^a + \lambda(y_i^b - y_i^a) \qquad \forall\, i \tag{8}$$

$$y_i \le y_i^d + \lambda(y_i^c - y_i^d) \qquad \forall\, i \tag{9}$$

$$z_k \le z_k^u + \lambda(z_k^l - z_k^u) \qquad \forall\, k \tag{10}$$

$$P \geq P^l + \lambda(P^u - P^l) \tag{11}$$

$$0 \leq \lambda \leq 1 \tag{12}$$

where λ is the degree of satisfaction, A_{ij} refers to the technological matrix associated with product stream i and technology j, x_j is the capacity scaling factor for technology j, y_i is the net material or energy flow, D_{kj} is the associated environmental intervention k for technology j, z_k is the environmental footprint, P is the economic potential of the polygeneration plant, CF is the conversion factor to annualize the profit/cost of the product streams, C_i is the price for the product stream i of the polygeneration plant, AF is the annualizing factor to annualize the cost function, FC_j is the fixed cost of technology j considered in the polygeneration plant, VC_j is the variable cost of technology j considered in the polygeneration plant, b_j is a binary variable which indicates the selection (b_j = 1) or non-selection (b_j = 0) of technology j, G_{pj} is the topological matrix, Q_p is the technology limiting factor, M is an arbitrary large scalar number, y_i^a is the support lower limit product stream demand for stream i, y_i^b is the core lower limit product stream demand for stream i, y_i^c is the core upper limit product stream demand for stream i, y_i^d is the support upper limit product stream demand for stream i, z^l is the lower limit for the CO_2 emission of the polygeneration plant, z^u is the upper limit for the CO_2 emission of the polygeneration plant, P^l is the lower limit of the economic potential of the polygeneration plant, P^u is the upper limit of the economic potential of the polygeneration plant.

The objective function maximizes the degree of satisfaction λ shown in Eq(1). The net flow of product stream i, y_i, is dependent on the efficiency of processes as indicated by the elements A_{ij} of the technological matrix and the capacity scaling factor x_j for each process j as shown in Eq(2). The environmental footprint z_k of the system as defined by the environmental emission k of process j (D_{kj}) and the technology capacity scaling factor, x_j, as shown in Eq(3). The economic potential of the polygeneration plant is a function of the sales/costs of the product streams, the annualized variable and fixed costs shown in Eq(4). Eq(5) introduces the binary selection function comprising of the topological matrix G_{pi}, the binary variable b_i, and the technology limiting factor Q_p. The binary variable b_i is multiplied by a large arbitrary number M ensuring the technology capacity scaling factor x_j does not exceed the value of the product as shown in Eq(6). The binary variable b_i is represented by the values of 0 and 1 as shown in Eq(7). In Eqs. (8-9), the product demand limits are exogenously defined from the requirements of the community and are desired to be fall within a specific range $y_i^b \leq y_i \leq y_i^c$. The CO_2 emission vector z_k should be minimized within the range of acceptable emissions limits of z_k^l and z_k^u shown in Eq(10). The economic potential P of the polygeneration plant should be maximized within the range of acceptable limits P^l and P^u as shown in Eq(11). The degree of satisfaction λ is ensured to fall within the range from 0 to 1 as shown in Eq(12). The model is then solved using Lingo version 15.0 linked in MS Excel using Object Linking and Embedding (OLE) in a desktop computer with Intel Core i7-4790 CPU at 3.60 GHz processor and an 8 GB of RAM.

4. Case Study

The case study considers a design of a polygeneration plant which addresses the typical requirement of an off-grid rural community basic utility needs for electricity, cooling, and purified water. The community is located within the range of a river basin where a microhydro plant with a capacity of 50 kW has been initially installed to provide power to the community. However, with the growing need for electricity and other utilities, a community-based off-grid polygeneration plant is proposed to provide the required product streams. The utility requirement of the off-grid community is shown in Table 1. Thus, the technologies considered to provide for the needed utilities are shown in Figure 1 together with the input-output process flows for each technological component.

Table 1: The utility requirement of the off-grid community.

Utility Requirements	y_i^a	y_i^b	y_i^c	y_i^d
Power (kW)	60	120	120	180
Cooling (kW)	50	80	100	120
Purified Water (t/h)	20	30	40	50

The microhydro plant installed capacity of 50 kW is insufficient for the requirements of the community with a support lower demand limit of y^a= 60 kW of power shown in Table 1. To provide adequate power with potential back-up power for dry months, a biomass-based Stirling engine and a diesel engine are considered as part of the design of the polygeneration plant since the community has access to biomass and diesel fuel. A vapor compression chiller and a vapor absorption chiller are considered to provide for the cooling load needed to store and prolong the agricultural and aquaculture products. Lastly, a water treatment facility is considered to purify the river water to potable drinking water. A topological constraint is used as part of the mixed-integer linear programming model as shown in Eq(5) to ensure the selection of either biomass or diesel technology and only one chiller technology in the polygeneration plant. Since the microhydro plant has initially been installed and the water treatment facility is needed to produce the purified water, the binary variable, b_i, for these two technologies is set to 1 to ensure the inclusion of the two technologies in the polygeneration plant. The biomass-based Stirling engine has no CO_2 emission as it is assumed that the technology is carbon neutral on the basis that during the growth stage of the biomass as plant, CO_2 was absorbed; offsetting the CO_2 emitted during the combustion of biomass.

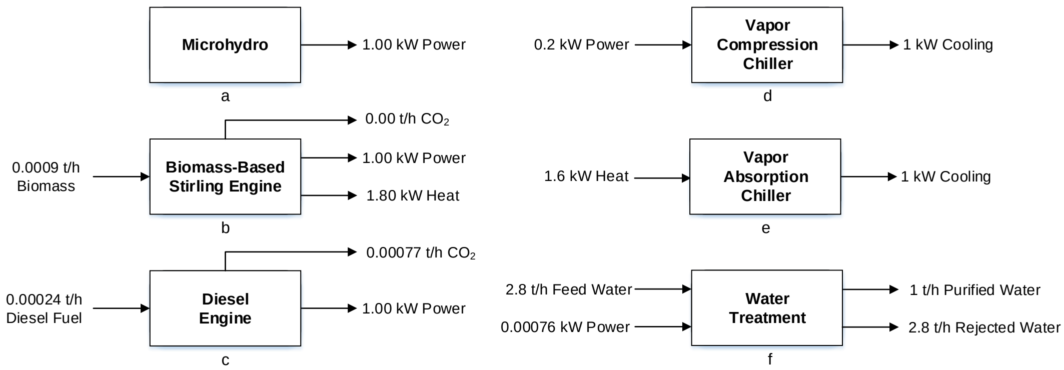

Figure 1: The input-output process flow of the community-based off-grid polygeneration plant.

The prices for the energy and material streams may play a major role in the selection of the technology in the polygeneration system. These are shown in Table 2. It is assumed that the purchasing and selling price for each product stream is the same.

Table 2: The product stream prices.

Product Streams	Prices, C_j
Power (US$ /kWh)	6.71×10^{-9}
Heat (US$/ kWh)	0.00
Cooling (US$/ kWh)	1.80×10^{-8}
Purified Water (US$/ t)	13.00
Biomass (US$/ t)	9.00
Diesel (US$/ t)	808.00

Table 3: The variable and fixed costs of the considered technologies in the polygeneration.

Considered Technologies	Variable Cost (US$), VC_j	Fixed Cost (US$), FC_j	References
Microhydro Plant	555	0	adapted from SATMP (2018)
Biomass-Based Stirling Engine	1,550	31,000	adapted from ProEcoPolyNet (2007)
Diesel Engine	800	28,300	adapted from Kurtz et al. (2014)
Vapor Compression Chiller	2,803	70,083	adapted from Aspen Systems (2018)
Vapor Absorption Chiller	4,020	100,500	adapted from US DoE (2017)
Water Treatment Facility	8,800	220,000	adapted from Sharma (2010)

The variable and fixed costs of the considered technologies for the polygeneration plant is shown in Table 3. The polygeneration plant is assumed to operate 8,000 h annually using an annualizing factor of AF = 0.06 y^{-1}. The conversion factor CF to annualize the sales/costs of the energy streams is 28,800,000 y^{-1} (3600 s/h * 8,000 h/y) and the material streams is 8,000 y^{-1} (8,000 h/y). The polygeneration plant owners allow a breakeven scenario as the worst scenario for the economic potential (P^l= US$ 0/y) while setting a desired economic potential of greater than or equal to P^u = US$ 10 Million/y. Considering the potential CO_2 emissions generated from the polygeneration plant, the upper limit of the CO_2 emission has been set by the local government not to exceed z^u= 0.04 Mt/y with a desired lower CO_2 emission limit of zero if possible (z^l = 0.00 Mt/y).

To test the impact of the discounted price of a product stream such as the purified water, two scenarios were considered in this study. The first scenario uses the price of purified water shown in Table 2. While the second scenario accounts for a 30% discount on the price of purified water. Since purified water is one of the high-valued commodity of the community, a discounted price may spur further livelihood in the community.
Solving for the objective function in Eq(1) and satisfying all constraints from Eq(2) – Eq(12), the results yielded a degree of satisfaction of λ = 0.49 for scenario 1 and λ = 0.36 for scenario 2 achieving the desired multiple design goals for the off-grid polygeneration plant. The resulting optimal configuration of the community-based off-grid polygeneration system is shown in Figure 2. The developed model has chosen the biomass-based Stirling engine over the Diesel engine to generate the back-up and additional power for the community. While the vapor compression chiller was preferred over the vapor absorption chiller to deliver the required cooling load thus prolonging and storing the produce of the community. The resulting net economic potential of scenario 1 is US$ 2.78 Million/y and US$ 1.40 Million/y for scenario 2. The discounted price for the purified water in scenario 2 has decreased the economic potential of the polygeneration system by almost half. However, the discounted price of potable water presents an opportunity to increase the livelihood activities of the community which may lead to the overall economic growth of the community. A zero CO_2 emission has been achieved for both scenarios as the biomass used in the Stirling engine is considered as a carbon neutral fuel offsetting the CO_2 absorbed and released throughout its life-cycle (Ubando et al., 2014). Another opportunity to enhance the economic growth of the community is to utilize the heat generated from the Stirling engine as shown in Figure 2. Currently, the two scenarios used zero pricing for the heat generated as shown in Table 2. Thus, the resulting economic potential of the polygeneration system solved in this model excludes the economic impact of utilizing the generated heat. Micro- and small- enterprise may benefit from the heat generated from the polygeneration plant such as laundry shops, restaurants, and other small processing plants to name a few.

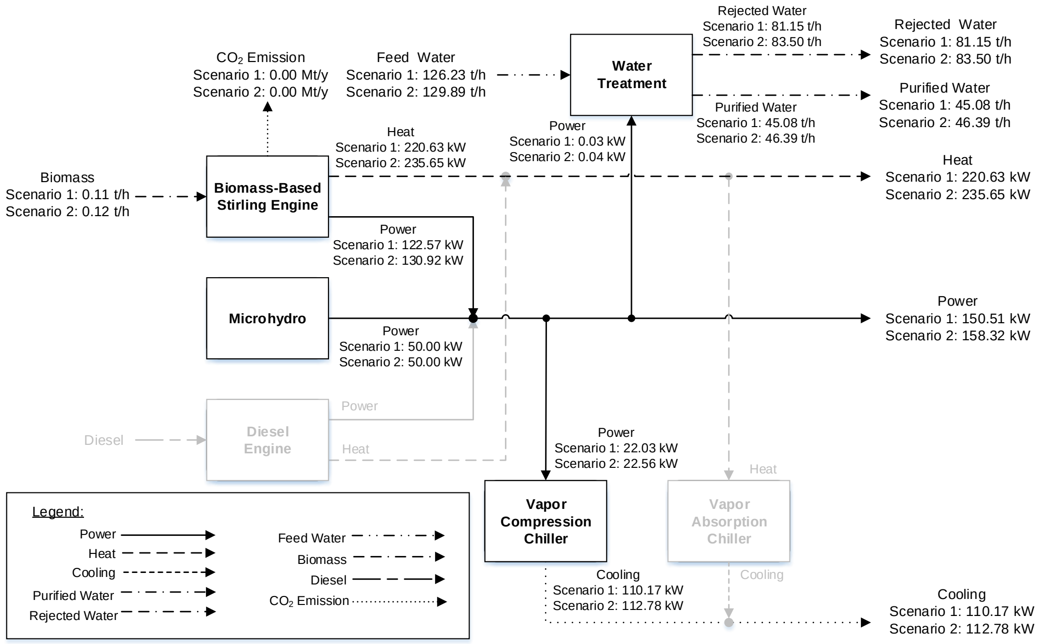

Figure 2: The resulting optimal configuration for scenarios 1 and 2.

5. Conclusions

A fuzzy mixed-integer linear programming model has been developed for the optimal synthesis and design of a community-based off-grid polygeneration plant with emphasis on the production of power, cooling, and purified water. The case study considered a community with an already existing microhydro plant which seeks selection of technology options for back-up and additional power and cooling load capacity. The results yielded an optimal configuration of the polygeneration plant selecting the combination of the biomass-based Stirling engine to provide for the additional power requirement, and the vapor compression chiller to provide the required cooling load. The price discount on the purified water resulted in the decrease of the economic potential of the plant, but, it opens opportunities for economic growth of the community through livelihood activities. In addition, utilization of the heat generated from the polygeneration plant also presents an opportunity for sustainable economic growth of the community. Such insight may be used by policy makers to encourage and influence plant owners to support the sustainable economic growth of the off-grid community.

Future studies may include the consideration of the multi-periodicity of the water source of the microhydro plant and the biomass source in the community.

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