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Multi-Objective Optimisation of Integrated Renewable Energy Feedstock Supply Chain and Work-Heat Exchanger Network Synthesis Considering Economics and Environmental Impact

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This work presents a new method for integrating various renewable energy feedstock sources with the utility systems of combined heat and power generation hubs and heat exchanger networks (HENs). The combined heat and power hub of the integrated network involves two turbines fed with high pressure steam. The steam can be generated from fuel sources such as wood, corn stover, and glycerine. The power system is required to produce a fixed amount of shaft power while optimally satisfying the hot utility demand of the HEN of a process plant through the high-pressure steam and intermediate pressure steams exiting the turbines. The superstructure of the integrated system comprises three layers and is synthesised using the utility hub approach. The first layer of the superstructure, which comprises the feedstock supply chain network, is modelled as a mixed integer linear program. The second layer of the superstructure, which comprises the combined heat and power hub wherein are the steam system and turbines for the power plant, is modelled using linear program to represent the material and energy balances of the turbine system. The third layer, which comprises a HEN, is modelled using the simplified stagewise superstructure (SWS) synthesis approach. The objective function of the integrated model comprises operating costs, capital costs, and environmental impact. The newly developed method is applied to a case study using the weighted method of multi-objective optimisation and the results obtained involves the selection of corn stover and glycerine for the generation of heat and power. Also, only high-pressure steam and medium pressure steam were selected for use as hot utilities in the integrated HEN of the system.

1. Introduction

Increasing concerns about climate change has necessitated the design of process plants that are not only economically optimal but environmentally friendly as well. Heat exchanger network synthesis (HENS) has been used over the years by process industries to achieve economically optimal heat integrated systems. However, most of the methods in the literature have failed to consider a holistic view of the benefits inherent in integrating and simultaneously optimising the heat demand of process plants, turbine power systems and renewable energy supply chain. Although the work of Isafiade et al. (2017), which adopted the stage-wise superstructure (SWS) model of Yee and Grossmann (1990) for the synthesis of multiperiod HENs, involves multiple utilities generated from multiple renewable and non-renewable sources, the method did not consider the economics or environmental impact associated with the transportation of the renewable energy feedstocks from their supply locations to the plant site. In terms of combined heat and power generation, a series of studies has been done which incorporates thermodynamic cycles with heat exchanger network synthesis in what can be described as Work and Heat Exchanger Network Synthesis (WHENS). According to Fu et al. (2018), WHENS entails Work Integration and Heat Integration where the requirements for heating and cooling which results from compression and expansion in a thermodynamic cycle can be integrated with the synthesis of HENs. The study of Sun et al. (2019), which incorporated absorption refrigeration cycle with HENS, was aimed at simultaneously optimising the operating parameters of the absorption refrigeration system and the HEN. The HEN component of the integrated system was modelled using the SWS and the objective function comprises capital costs for heat

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exchangers in the HEN, capital costs for the generator, evaporator, absorber, and condenser in the refrigeration cycle. The operating cost component of the objective function of the model comprises the utility costs. Another study that integrates thermodynamic cycles with HENS is that of Elsido et al. (2021) where the HENS component of the system involves multiperiod operating profile and thermal storages. Martinelli et al. (2022) also integrated the synthesis of HENs with refrigeration cycles. One of the novelties of the work involves the ability of the developed model to simultaneously optimise the refrigeration cycle structure, including the pressures and temperatures, with the HEN component of the integrated system.
It is worth stating that for the papers reviewed, the benefits associated with harnessing process heat from one component of the integrated system to satisfy the heat demand of some other component has been established even for problems involving multiple utilities as is the case in the work of Elsido et al. (2021). However, to have a more robust and sustainable integrated resource and energy system, the inclusion of a supply chain involving multiple energy feedstocks from which renewable energy can be generated, while considering the associated environmental impact of the energy sources must be considered and solved simultaneously. One of the few studies that have integrated renewable energy supply chain with the heat demand of process plants through HENS is that of Cowen et al. (2019). In the study, three co-located process plants whose heat demand is multi-period was considered. However, the study did not include power generation and the only criteria for making a choice among the renewable energy sources is economics. This work involves the development of an integrated energy network that comprises a supply chain of renewable energy sources, a steam and power generation system and a HEN. It should be known that the steam and power generation component of the integrated system only involves the boiler and two turbo generators.

2. Problem statement

The problem solved in this paper can be stated as follows. Given a set of biomass and waste-based feedstocks *M*, from which energy can be generated, given a set of transport modes *R* (including unit transport costs) by which the feedstocks, or energy generated from the feedstocks, can be transported from the feedstock locations to a combined heat and power generation plant located at an energy hub. Seasonal availability and unit costs for each of the energy feedstocks, is identified by set *T*, while the distances, including tortuosity factors, between each of the feedstock location and the energy hub is identified by the set *D*. The process plant, whose heat demand is to be integrated with the combined heat and power generation system, has a set of hot *H* and cold *C* process streams with heat capacity flowrates *FCP* and heat transfer coefficients *h*. Other parameters given are the heat exchanger installation and area costs and unit costs for the utilities. The goal is to design a renewable energy supply chain network (SCN) that is integrated with a combined heat and power generation system and the heat exchanger network system of a process plant.

3. Methodology

The superstructure that describes the integrated network is shown in Figure 1. The top layer of the superstructure comprises the SCN of renewable energy feedstocks. This layer is connected to the heat and power hub, which is the middle layer, through various feedstock/energy transport modes. The third layer of the superstructure comprises the process plant where hot and cold utilities are required. The mathematical model for the renewable energy supply chain component of the integrated model is represented as a mixed integer linear program (MILP). The MILP model of this paper differs from that of Cowen et al. (2019) in that the intermediate demand node of the integrated superstructure constitutes the heat and power generation system hub. This is unlike the model of Cowen et al. (2019) where the demand nodes of their superstructure comprise co-located process plants. However, some of the data used for the SCN of this paper were adapted from Cowen et al. (2019). The mathematical model, including data, for the heat and power generation hub of the integrated superstructure is taken from the boiler/turbo-generator model of Edgar et al. (2001). The model comprises a boiler, where high pressure steam (4,378 kPa(g), 382 °C) is generated, and two turbogenerators with turbine 1 being a double extraction turbine while turbine 2 is single extraction. The two turbines have intermediate steams with pressures 1,344 kPa(g) and 427.5 kPa(g) with 54 °C of superheat. According to Edgar et al. (2001), electric power may be purchased from another producer with a base of 12,000 kW. This may be necessary to meet the electric power demand which is 24,550 kW. However, if the additional electric power needed to meet the system demand is less than the purchased 12,000 kW, then the unused power will attract penalty charges. The characteristics of the turbines, details of steam levels, and demand on the system, can be found in Edgar et al. (2001). The model of Edgar et al. (2001) was modified in this paper by the inclusion of additional high-pressure steam (HPS) stream split that links the power hub to the HEN hub. For the HEN model of this paper, the SWS model of Yee and Grossmann (1990) was used. The three models were systematically integrated to obtain a superstructure that contains various options of satisfying the stipulated demand for power (24,550 kW) and utilities by the process streams in the HEN.

The objective function of the integrated model, which is multi-objective, comprises an economic component and an environmental component. The economic aspect involves annual operating and annualised capital costs of the SCN, annual cost of purchased power and penalty associated with unused purchased power, and annual operating and annualised capital cost of the HEN. The environmental component comprises minimisation of Carbon in the flue gas emissions generated from each of the available feedstocks.

$$\text{Min}\, TAC = AF\left\{CF\sum_{i\in H}\sum_{j\in C}\sum_{k\in K} y_{i,j,k} + AC\sum_{i\in H}\sum_{j\in C}\sum_{k\in K} A^{AE}\right\} + \left\{\sum_{i\in H}\sum_{j\in C}\sum_{k\in K} C_j \cdot q_{i,j,k}\right\} + \left\{\sum_{m\in M}\sum_{r\in R}\sum_{t\in T} SCNCost_{m,r,t}\right\}$$
$$+\{(0.0239 \cdot N_{hours} \cdot PP) + (0.00983 \cdot N_{hours} \cdot EP)\} \quad (1)$$

In Eq(1), AF is annualization factor, CF (\$/m) is fixed charge for heat exchanger installation, $y_{i,j,k}$ is the binary variable that indicates whether a heat exchanger is paired between hot stream i and cold stream j in stage k of the stage-wise superstructure, AC (\$/m) is the cost per unit of heat exchanger area, A (m^2) is the size of a heat exchanger, AE is heat exchanger area cost exponent, C_j is the unit cost of cold utility j. The unit cost of hot utility is not included in Eq(1) because the hot utilities are determined by the quantity of energy feedstock selected in the solution network. In Eq(1) $q_{i,j,k,t}$ is the quantity of heat exchanged between hot stream i and cold stream j in stage k of the SWS, $SCNCost_{m,r,t}$ is the annual cost of the SCN, 0.0239 \$/(kW·h) is the unit cost of purchased power PP, 0.00983 \$/(kW·h) is the unit cost of the penalty for excess power EP. The two costs, i.e., PP and EP, were adapted from Edgar et al. (2001). N_{hours} in Eq(1) is the number of operating hours in a year (8,160 h).

$$\min EI = \sum_{r}\sum_{t}\left({x_{m,r,t}}/{\eta \cdot LHV_m}\right) \cdot CUA_m \cdot 3.67 \cdot N_{hours} \quad (2)$$

Eq(2) is adapted from Shenoy (1995). In the equation, EI represent the mass flow of the pollutant (kg/y), $x_{m,r,t}$ is the quantity of energy (in kW) transported from supply m through transport mode r, in season t to the heat and power generation hub. η is the combustion efficiency of the feedstocks, LHV_m is the lower heating value (in kWh/kg) of feedstock m, CUA_m is the mass percentage of the pollutant in non-oxidized form. In this paper, the CUA_m values used for corn stover, glycerine and wood are 47.4% (Kumar et al., 2008), 20.15% (Tamošiūnas et al., 2019) and 53.24% (Shi et al., 2016). The 3.67 was obtained by dividing the molecular mass of CO_2 by the atomic mass of carbon.

The weighted sum method of multi-objective optimisation as presented by Gxavu and Smaill (2012) is adopted in this paper. The multi-objective equation is shown in Eq(3).

$$\min Z = R_g \cdot \left(\frac{TAC}{TAC_{min}}\right) + \left(1 - R_g\right) \cdot \left(\frac{EI}{EI_{min}}\right) \quad (3)$$

In Eq(3), Z is the multi-objective variable, R_g is the weighting factor.

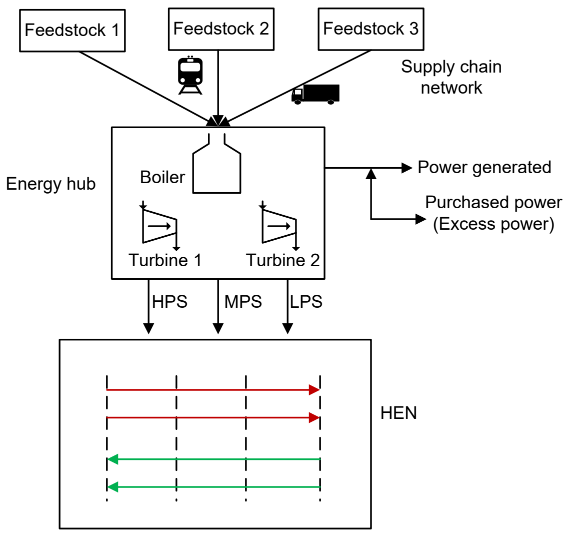

Figure 1: Superstructure of integrated network

4. Case study

The case study involves three kinds of feedstocks (corn stover, glycerine, wood), situated at different locations relative to the heat and power generation hub. The costs, capacity, and seasons of availability of the feedstocks are shown in Table 1 while the various modes of transport, including the cost parameters and tortuosity factors, are shown in Table 2. The HEN component of the case study comprises 2 hot process streams, 4 cold process streams and 1 cold utility. The hot utilities are HPS, medium pressure steam (MPS) and low-pressure steam (LPS). These three hot utility streams form the link between the heat and power generation hub and the HEN hub as illustrated in Figure 1. A split branch of the HPS will flow directly from the boiler to the HEN while the MPS and LPS are exit streams from the turbines that then flow to the HEN. Table 3 shows the parameters for the streams in the process plant.

Table 1: Types of energy feedstocks, unit costs and available capacity

Supply	Feedstock		Season 1		Season 2		Season 3	
		LHV_m (kWh/kg)	Cost ($/kg)	Capacity ($\times10^6$ kg)	Cost ($/kg)	Capacity ($\times10^6$ kg)	Cost ($/kg)	Capacity ($\times10^6$ kg)
Supply 1	Corn stover	4.63	0.024	400	0.022	15	0.027	60
Supply 2	Glycerine	4.75	0.04	500	0.044	50	0.025	50
Supply 3	Wood	4.28	0.05	600	0.030	10	0.070	10

Table 2: Transport options and cost parameters

Transport mode	Transport specific parameter					
	AF	T_r^{FC} ($/(t·km)	T_r^{VC} ($/km)	T_r^{IC} ($/(t·km)	τ_r	tf_r
Truck	0.20	0.002	0.0900	5,000	1.27	2
Railway	0.25	0.005	0.0070	50,000	1.10	2
Pipeline	0.50	0.000	0.0001	1.5×10^5	1.27	1

Table 3: Plant stream data

Hot streams	T_i^s (°C)	T_i^t (°C)	FCP_i (kW/°C)	Cold streams	T_j^s (°C)	T_i^t (°C)	FCP_j (kW/°C)
HU1 (HPS)	257	257	-	C1	25	240	140
HU2 (MPS)	197	197	-	C2	20	250	150
HU3 (LPS)	154	154	-	C3	50	180	70
H1	155	85	150	C4	70	100	120
H2	230	40	285	CU1	5	10	-

For AF in Table 2, the discount rates for truck, railway and pipeline are 15 %, 16.5 % and 24 %, and the capital are annualized over 10 y, 7 y, and 3 y. For the heat exchangers, discount rate is 30 % and capital is annualized over 10 y. In Table 3, it is assumed that all streams, including utilities, have the same heat transfer coefficient which is 0.5 (kW/(m^2·°C)). For this paper, it was assumed that the HPS exiting the boiler and the intermediate streams exiting the two turbines (MPS and LPS), which are all superheated, were desuperheated to temperatures shown in Table 3 through heat losses in the pipes before being fed to the HEN. This is necessary since superheated steam is less effective at transferring heat.

The integrated model, which is a mixed integer non-linear programming model (MINLP) was solved simultaneously using DICOPT solver in General Algebraic Modelling Systems (GAMS) environment. The model comprises 307 equations, 289 variables and 23 discrete variables. To implement the weighting approach of multi-objective optimisation shown in Eq(3), the integrated model was solved for three scenarios. The first is for a case where TAC is the only objective variable being minimised with EI unconstrained. This scenario resulted in a TAC_{min} of $ 2.360 $\times10^7$ with an associated EI of 2.781 $\times10^9$ kg/y. The second scenario is for a case where EI is the only minimised objective in the integrated model. For this case, the solution obtained has an EI_{min} of 1.373 $\times10^9$ kg/y with an associated TAC of $ 5.652 $\times10^7$. For the third scenario, the TAC_{min} and EI_{min} obtained in the first two solution scenarios were substituted into Eq(3) with an R_g value of 0.5. The solution obtained involves a TAC of $ 3.218 $\times10^7$ and an EI of 1.405 $\times10^9$ kg/y. A breakdown of the values for the key variables for each of the three solutions are shown in Table 4. In the table, HEs represents number of heat exchangers. Fig 2 shows the integrated network for the 3rd scenario which is the multi-objective case with equal weightings given to each of the two objectives. In the figure, only corn stover and glycerine are selected as feedstocks for energy generation with corn stover having to be transported by truck while glycerine (converted to biogas) will be transported through pipeline. Corn stover was selected only in seasons 2 and 3 while glycerine was selected in all seasons. At the heat and power generation hub, the total amount of HPS, i.e., HPSTOT, generated from the boiler is 49.21 kg/s. Of this amount, 15.6 kg/s is fed to turbine 1, 30.74 kg/s is fed to turbine 2 while 2.32 kg/s is fed to the HEN as hot utility. For MPS, 3.80 kg/s exits turbine 1 while 29.87 kg/s exits turbine 2. For LPS, 11.8 kg/s exits turbine 1 while 0.87 kg/s exits turbine 2. In turbine 1, 6,250 kW of power is produced while 9,000 kW is produced by turbine 2. In terms of power purchased and excess power, 9,300 kW of power is purchased while 2,700 kW is excess power.

Table 4: Breakdown of costs for the various scenarios investigated

Scenarios	TAC ($\times10^7$ \$)	EI ($\times10^9$ kg/y)	HEs	Feedstock	Transport mode	Feedstock quantity (kW)
1st (TAC_{min})	2.360	2.781	8	Corn stover	Pipeline	629,006
				Glycerine	Railway	198,074
				Wood	Truck	11,989
2nd (EI_{min})	5.652	1.373	10	Corn stover	Truck	22,796
				Glycerine	Truck	809,407
3rd (Multi-objective)	3.218	1.405	10	Corn stover	Truck	31,278
				Glycerine	Pipeline	809,407

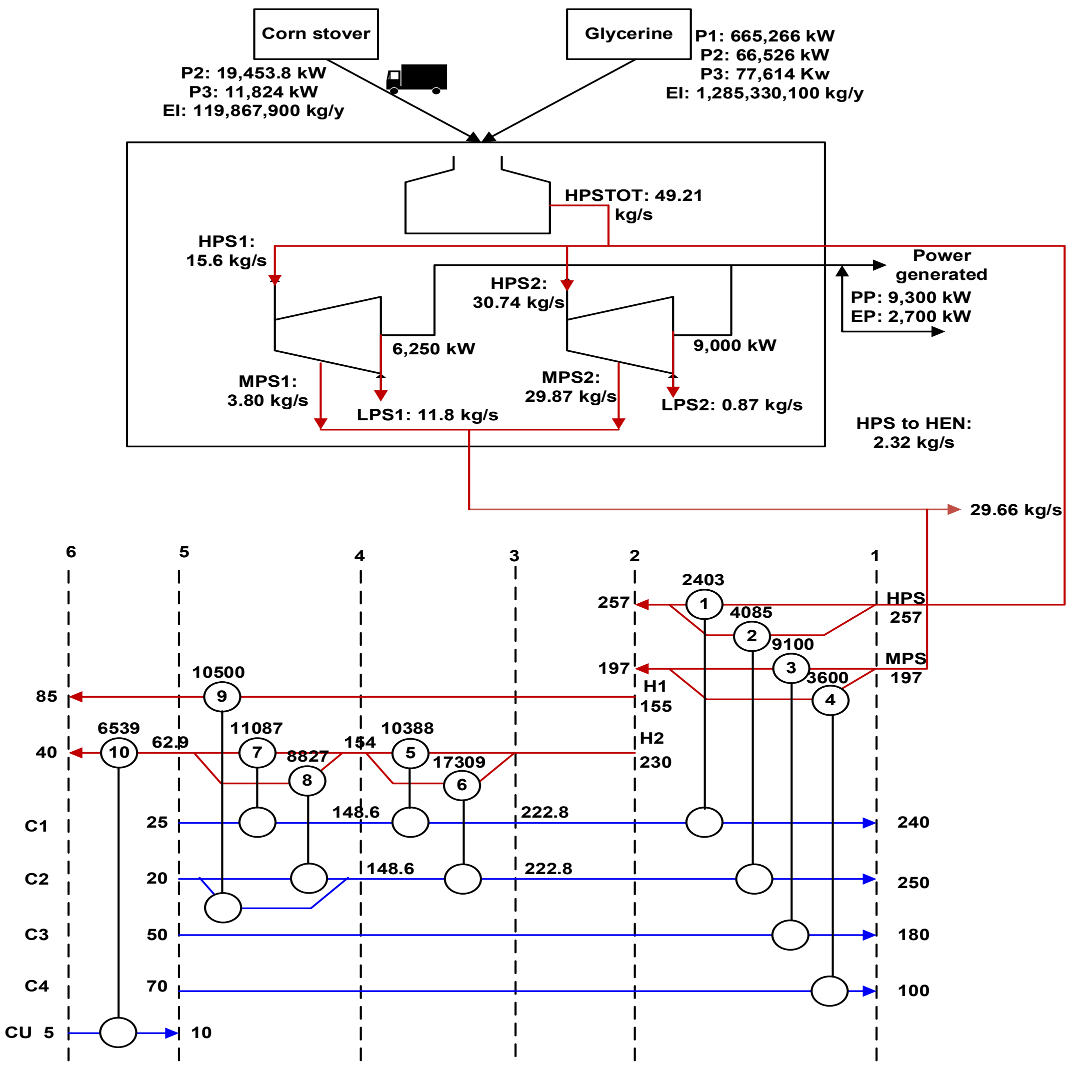

Figure 2: Integrated network for case study involving SCN, power generation and HEN

In the HEN, 10 heat exchangers are selected. Of the 10 exchangers, 4 are hot utility exchangers and 1 is a cold utility exchanger and the remaining 5 are process heat exchangers. In terms of utility usage in the HEN, only HPS and MPS were used as utilities with 6,488 kW coming from HPS while 12,700 kW comes from MPS. It is worthy to note that although HPS has higher temperature driving force compared with MPS, more MPS is still used compared to HPS. This is because the solver tries to minimise the quantity of HPS (with only 2.32 kg/s transported to the HEN) that is generated in the boiler by minimising the quantities of feedstocks selected from the various supply locations. The minimisation of HPS is subject to the stated constraints for the power generation component of the integrated network and these constraints also determine how much of MPS and LPS are generated from the turbines as intermediate streams. Of the total MPS that exits the two turbines, only 4.01 kg/s is transported to the HEN while the LPS is not used in the HEN.

5. Conclusions

This paper has presented a superstructure that illustrates how to systematically integrate various options of renewable energy generation feedstocks with a heat and power generation hub that is then further integrated with the HEN of a process plant. The superstructure also captures the seasonality associated with availability of renewable energy sources. The weighted method of multi-objective optimisation was used to simultaneously evaluate TAC and EI as objectives. The integrated superstructure, which was modelled as an MINLP, gave results that illustrate the benefits of combined heat and power generation using renewable energy sources as feedstocks. Future studies will involve detailed pipe design to account for the associated capital costs and pumping costs of fluids. Other issues that will be considered in future studies are desuperheater design for the various steam levels involved in the heat and power hub, interplant heat integration, environmental impacts associated with the transportation in the integrated network and sensitivity analysis of the solutions obtained to investigate the critical parameters involved in the problem considered.

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