Selecting Energy Carrier Combinations using Energy Hub Model

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Abstract: This paper aims to select the energy-carrier combination for minimal total consumption of 5 processes. Basic multi input-output Energy Hub (EH) concept has been simply modified into multi input-output for multi process purposes. The modified concept affects its matrix model development which represent each combination for multi process. Given 3 scenarios, 3 energy carriers and 5 processes involving effectivity percentages of each energy carrier and process for a certain power plant. Considered energy carriers are natural gas, water, and electricity which are processed by processes P1 to P5. The result shows that minimal energy consumed for the processes is scenario 3with the process of 100% natural gas, 30% water and 30% electricity effectiveness. Scenario 3 has total Natural Gas consumed for 261.63 MMBtu/Ton, 2,069,088.5 m^3 water, and 33,298,620.6 kW electricity.

1 INTRODUCTION

Energy scarcity has remained challenging high-price energy problem. It is evidenced that using various resources of energy generally becomes common approach dealing with high price of electricity. These common problems refer to the term of Energy Hub (EH). It was first presented by (Geidl and Andersson, 2007)to assemble many different energy carriers and assist in obtaining economic combination of those energy.

Energy hub (EH) approach proposes coupling model among different energy carriers. The model combines multi energy-carrier for optimized power consumption (Geidl and Andersson, 2007).Correspondingly, for green manufacturing reasons, EH is also claimed to reduce emission by optimizing energy consumption and combining renewable and unrenewable energy resources. Some studies done by (Pazouki, Haghifam and Olamaei, 2013; Le Guen *et al.*, 2017; Lin *et al.*, 2017; Wang *et al.*, 2018; Miao *et al.*, 2020; Ivatloo, Abapoura and Shafiee, 2021) proposed combinations of renewable and unrenewable energies using EH for green manufacturing reasons. EH concept was also introducedas a system model(Geidl and Andersson, 2007).As a system description, energy hub as a process of integrating, conversing, and combining multi-energy inputs into desirable combinations of outputs (Zhang *et al.*, 2015).

EH concept of coupling various energy carriers have been wide-ranging used to simulate cost and consumed energy carriers. Previous studies in EH were about minimizing cost of multi energy e.g. (Kienzle, Ahčin and Andersson, 2011; Parisio, Vecchio and Vaccaro, 2012; Adamek, Arnold and G. Andersson, 2014), planning and scheduling each energy carriers used done with EH by (Pazouki, Haghifam and Olamaei, 2013). Accommodating uncertainty was also done by (Kienzle, Ahčin and Andersson, 2011). In broader level, combining EH for multi agent such as commercial agent, environmental agent, demand agent, hub-element agent, and integrated dispatch agent was completed by (Lin *et al.*, 2016, 2017).

Combining different energy carriers with EH offers well organized integration of renewable and unrenewable energies as well as lowering total energy operation cost(Jiang and Hong, 2013; Du *et al.*, 2016). However, planning a combination of multi energy carriers requires well-planned and robust scenario to provide the profitable one. An efficient energy carrier combinations outputs depend on each conversion effectiveness within the different processes in the hub.

Given 3 scenarios of natural gas, water, and electricity energy carriers combinations of a generator plant process, this paper aimed to analyze

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and decide most minimal energy consumed by each energy carriers. Therefore, basic multi input-output EH model has been simply modified into that of model for multi-process purpose. Modification has been done on vector matrix of input and output of matrix model to encounter unprocessed energy carrier on any converter. For example, natural gas energy carrier cannot be processed on Cooling Tower which only processes water energy carrier.

Similar study on selecting energy carrier processes was conducted by (Seyyed Mostafa Nosratabadi, Jahandide and Nejad, 2020) which simulated planning of electricity, gas, cooling energy, and water for bus distribution network energy-consumption. The research result proposed minimal cost for bus distribution tes network. A study was also done by (Pazouki, Haghifam and Olamaei, 2013) in planning and scheduling EH research which resulted robust model for amount of each energy, which processes are used, and when processes are done. (Zhang *et al.*, 2015) generated coupled energy carriers models associating with reliability, efficiency and emission. Simplified by given percentage of each energy carriers in scenarios, the research selected optimal model by comparing total energy consumed each scenario model. Optimal planning and strategies for electricity and gas were conducted by (Ghanbari, Karimi and Jadid, 2020) as objectives proposed by the paper.

2 ENERGY HUB (EH)

Figure 1 describes EH as a simple system that processes input L into output P. The process refers to converter assembly box. It is a basic multi input-output EH system developed by(Geidl and Andersson, 2007). Symbol α,β,..ω denotes energy carriers. For the system concept, matrix model also was stated as in (1):

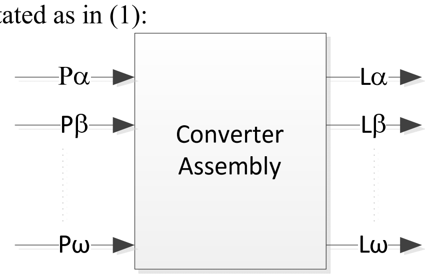

Figure 1. Multi input-output EH system

$$\begin{bmatrix} L\alpha \\ L\beta \\ . \\ . \\ L\omega \end{bmatrix} = \begin{bmatrix} C\alpha{:}\alpha & C\beta{:}\alpha & \cdots & C\omega{:}\alpha \\ C\alpha{:}\beta & C\beta{:}\beta & \cdots & C\omega{:}\beta \\ . & . & \cdots & . \\ . & . & \cdots & . \\ C\alpha{:}\omega & C\beta{:}\omega & \cdots & C\omega{:}\omega \end{bmatrix} \times \begin{bmatrix} P\alpha \\ P\beta \\ . \\ . \\ P\omega \end{bmatrix} \quad (1)$$

Equation (1) expresses matrix model of multi input-output EH system (Geidl and Andersson, 2007). Matrix C is coupling matrix for energy carrier conversion. It represents how effective energy conversion from one energy carrier into another one. In equation (1), $C\alpha{:}\beta$ denotes coupling factor for conversion of energy carrier α to β. For example, $C\alpha{:}\beta = 0.3$ means conversion energy carrier α into energy carrier β is 0.3 effective, therefore $\beta = 0.3\ \alpha$. Generally, this coupling factor represents effectiveness of conversion process. Thus, output Lβ represents conversion output of energy carrier α into β and can be expressed as in equation (2):

$$L\beta = C\alpha\beta \times P\alpha \quad (2)$$

3 RESEARCH FRAMEWORK

Based on EH concept developed by (Geidl and Andersson, 2007), this research framework has been built as a system concept. It begins with problem definition and developing a EH system according to the problem (see Figure 2). Here, entities of the system were identified including inputs, outputs and the processes.

Inputs: Energy carriers involved that will be transformed and/or combined such as electricity, water, and natural gas energy carriers. Inputs were stated as loads or each energy amount. These energies produce electricity power, cooling, and heating which are used as combinations in outputs

Outputs: Energy carriers inputs that have been transformed and/or combined and stated as loads or each combination amount. They are formed as power that is resulted from energies combination.

Process: Process of transforming and/or combination energy carriers. The process works depend on effectiveness of each transformation and combination process. For example, electricity and natural gas are combined as 100% and 30% into power. 100% means electricity is fully transformed into power, while natural gas is only 30% transformed into power.

Next step of the framework is building a matrix mathematical model as stated as equation 1. Matrix L represents outputs of EH system process, matrix P represents inputs, and matric C is effectiveness of the process.

Third step is assessing each combination or energy carriers and determine maximal power result for minimal energy consumed. In this step, some of research may need optimization method added as studies done by (Pazouki, Haghifam and Olamaei, 2013; Seyyed Mostafa Nosratabadi, Jahandide and Nejad, 2020) that used mixed-integer linear programming (MILP), (Vahid Pakdel, Sohrabi and Mohammadi-Ivatloo, 2020) that used fuzzy approach, and (Mansouri *et al.*, 2020) that used particle swarm optimization (PSO). However, this paper does not include the optimation method due to objectives of the paper were completed by the matrix mathematical model.

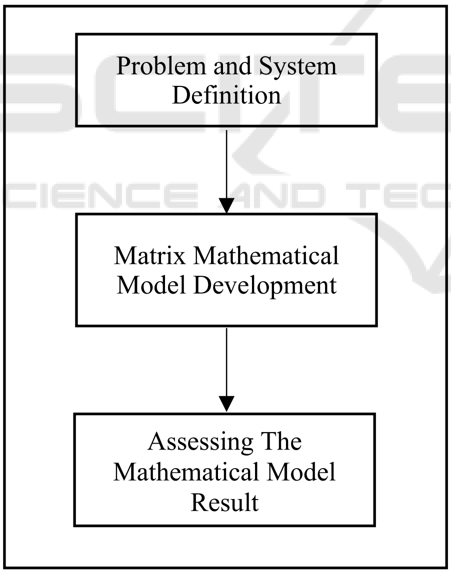

Figure 2 Research Framework

4 EH MATHEMATICAL MODEL DEVELOPMENT

Basic EH mathematical model written as equation (1) and (2) needs to be adapted to existing problem. For the next sub section is developing EH mathematical model in accordance with the problem.

4.1 System and Problem Definition

X company is a green manufacturing committed company in renewable and unrenewable energy resources consumption. Electricity (E), Natural Gas (NG) and Water Energy (WE) carriers which are processed for Lime Softening, Cooling, Demineralize Plant, Gas Generator, and Heat Boiler noted as P1, P2, P3, P4, and P5 respectively. However, for the last two years they have been facing inconsistent water resources that need to be replaced by other energy carriers, i.e. gas and electricity.3 Scenarios of combination of three energy carriers with their percentage of effectiveness were developed by company's engineers for energy generation.These scenarios were defined as:

Scenario 1: Process of 100% natural gas, 30% water, and 50% electricity effectiveness,
Scenario 2: Process of 100% natural gas, 50% water, and 30% electricity effectiveness,
Scenario 3: Process of 100% natural gas, 30% water and 30% electricity effectiveness.

Concerning this interacting energy carrier system problem, the identified problem for this paper is selecting the developed scenarios for minimal consumed energy on outputs. Selected scenario will be planned for the energy carriers combinations.

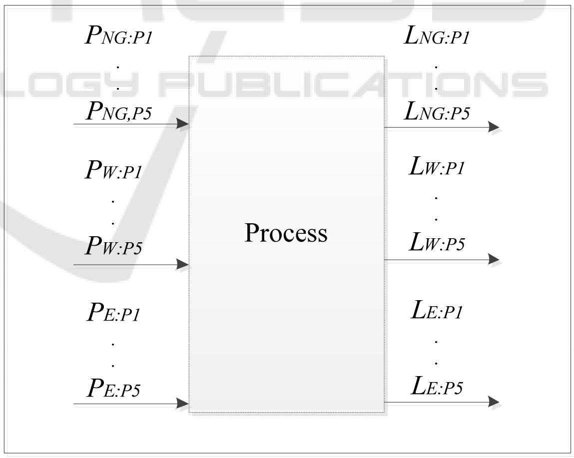

Figure 3 Modified EH system

Referring to EH model built by(Geidl and Andersson, 2007), energy system showed in Figure.1 and Figure 3 is a modified basic EH system adapted for the X company problem. The system converts multi-input energy carriers of PNG, PW, and PE into multi-output energies consumed LNG, LW, LE by combining 5 processes P1 to P5.

On Inputs, PNG:P1,…,PNG:P5, PW:P1,…,PW:P5, and PE:P1,…,PE:P5 denote inputs or available energy carriers which through processes P1 to P5. $P_{NG:P1}$represents input of energy available from Natural Gas that processed through P1.

Outputs represent consumed energies of that on processes P1 to P5while outputs LNG, LW, LE represent consumed energy of Natural Gas, Water, and Electricity by processes P1 toP5. Accordingly, $L_{NG:P1},\ldots,L_{NG:P5}$, $L_{W:P1},\ldots L_{W:P5}$, and $L_{E:P1},\ldots L_{EP5}$ denote inputs or available energy carriers Natural Gas (NG), Water (W), and Electricity (E) on processes P1 to P5.

Table 1 lists available energy-carriers on processes P1 to P5 as input in the system. Number of 0 means that of energy carrier is not available for that of process. For example, Natural Gas is not available on process P1, but then 54.7 MMBtu/Ton of natural gas available for P4.

Table 1: Available Energy for Each Process

Processes	Available Energy Carriers		
	Natural Gas (NG) (MMBtu/Ton)	Water (W) (m^3)	Electricity (E) (kW)
P1	0	3,308,534	628,737
P2	0	3,521,105	98,911,128
P3	0	63,990	3,833,899
P4	54.7	0	7,621,638
P5	206.92	0	0
Total	261.63	6,893,629	110,995,402

4.2 Adapted EH Mathematical Model

According to given scenarios and vector matrix built by (Geidl and Andersson, 2007), mathematical vector model of developed EH system are stated as in equation (3), (4), and (5) respectively for scenario 1,2, and 3.

$$\begin{bmatrix} L_{NG:P1} & L_{NG:P2} & L_{NG:P3} & L_{NG:P4} & L_{NG:P5} \\ L_{W:P1} & L_{W:P2} & L_{W:P3} & L_{W:P4} & L_{W:P5} \\ L_{E:P1} & L_{E:P2} & L_{E:P3} & L_{E:P4} & L_{E:P5} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.3 & 0 \\ 0 & 0 & 0.5 \end{bmatrix} \times \begin{bmatrix} P_{NG:P1} & P_{NG:P2} & P_{NG:P3} & P_{NG:P4} & P_{NG:P5} \\ P_{W:P1} & P_{W:P2} & P_{W:P3} & P_{W:P4} & P_{W:P5} \\ P_{E:P1} & P_{E:P2} & P_{E:P3} & P_{E:P4} & P_{E:P5} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} L_{NG:P1} & L_{NG:P2} & L_{NG:P3} & L_{NG:P4} & L_{NG:P5} \\ L_{W:P1} & L_{W:P2} & L_{W:P3} & L_{W:P4} & L_{W:P5} \\ L_{E:P1} & L_{E:P2} & L_{E:P3} & L_{E:P4} & L_{E:P5} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0.3 \end{bmatrix} \times \begin{bmatrix} P_{NG:P1} & P_{NG:P2} & P_{NG:P3} & P_{NG:P4} & P_{NG:P5} \\ P_{W:P1} & P_{W:P2} & P_{W:P3} & P_{W:P4} & P_{W:P5} \\ P_{E:P1} & P_{E:P2} & P_{E:P3} & P_{E:P4} & P_{E:P5} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} L_{NG:P1} & L_{NG:P2} & L_{NG:P3} & L_{NG:P4} & L_{NG:P5} \\ L_{W:P1} & L_{W:P2} & L_{W:P3} & L_{W:P4} & L_{W:P5} \\ L_{E:P1} & L_{E:P2} & L_{E:P3} & L_{E:P4} & L_{E:P5} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.3 & 0 \\ 0 & 0 & 0.3 \end{bmatrix} \times \begin{bmatrix} P_{NG:P1} & P_{NG:P2} & P_{NG:P3} & P_{NG:P4} & P_{NG:P5} \\ P_{W:P1} & P_{W:P2} & P_{W:P3} & P_{W:P4} & P_{W:P5} \\ P_{E:P1} & P_{E:P2} & P_{E:P3} & P_{E:P4} & P_{E:P5} \end{bmatrix} \quad (5)$$

Differences in scenarios EH model are stated in factor couple matrix which stated each percentage of energy carriers. Here, in equation (3) which represents scenario 1, numbers of 1, 0.3, and 0.5 at factor couple matrix represent effectiveness of natural gas, water and electricity. 1 means that input is full effectively processed into output. 0.3 means only 30% of input is effectively processed into input, while 0.5 is for 50% effective process into output.

Computed using equation (3) and input data in Table.1, output $L_{NG:P1},\ldots L_{NG:P5}$of scenario 1 can be stated as in equation (6).

$$\begin{aligned} L_{NG:P1} &= (1\text{x } P_{NG:P1}) + 0 + 0 = 0 \\ L_{NG:P2} &= (1\text{x } P_{NG:P2}) + 0 + 0 = 0 \\ L_{NG:P3} &= (1\text{x } P_{NG:P3}) + 0 + 0 = 0 \\ L_{NG:P4} &= (1\text{x } P_{NG:P4}) + 0 + 0 = 54.71 \\ L_{NG:P5} &= (1 \text{ x } P_{NG:P5}) + 0 + 0 = 206.92 \end{aligned} \quad (6)$$

Number of 0 for $L_{NG:P1},\ldots L_{NG:P3}$ is a result that natural gas is not processed in P1, P2, P3. Then, total output or energy consumed for process P1 to P5 using natural gas is 261.63 MMBtu/Ton. Accordingly, output L_W and L_E for equation (3) for scenario 1can be also stated as in equation (7) and equation (8):

$$\begin{aligned} L_{W:P1} &= 0+(0.3\text{x } P_{W:P1})+0 = 0.3 \text{ x } 3{,}308{,}534 = 992{,}560 \\ L_{W:P2} &= 0+(0.3 \text{ x } P_{W:P2})+0 = 0.3 \text{ x } 3{,}521{,}105 = 1{,}056{,}331 \\ L_{W:P3} &= 0+(0.3 \text{ x } P_{W:P3})+0 = 0.3 \text{ x } 63{,}990 = 19{,}177 \\ L_{W:P4} &= 0+(0.3 \text{ x } P_{W:P4})+0 = 0 \\ L_{W:P5} &= 0+(0.3\text{x } P_{W:P5})+0 = 0 \end{aligned} \quad (7)$$

Equation (7) calculated scenario 1 for Water (W) energy carrier. First line of the equations represents calculation of input PW 3,308,534 m^3 of water energy carrier processed by P1 into output LW with effectiveness of 30% and resulted output of 992,560 m^3 water energy carrier consumed.

$$\begin{aligned} L_{E:P1} &= 0+0+(0.5\text{x } P_{E:P1}) = 0.5 \text{ x } 628{,}737 = 314{,}368.5 \\ L_{E:P2} &= 0+0+(0.5\text{x } P_{E:P2}) = 0.5 \text{ x } 98{,}911{,}128 = 49{,}455{,}564 \\ L_{E:P3} &= 0+0+(0.5\text{x}P_{E:P3}) = 0.5 \text{ x } 3{,}833{,}899 = 1{,}916{,}949.5 \\ L_{E:P4} &= 0+0+(0.5\text{x}P_{E:P4}) = 0.5\text{x}7{,}621{,}638 = 3{,}810{,}819 \\ L_{E:P5} &= 0+0+(0.5 \text{ x } P_{E:P5}) = 0 \end{aligned} \quad (8)$$

Equation (8) calculated scenario 1 for Electricity (E) energy carrier. First line of the equations represents calculation of input P_E628,737 kW of Electricity energy carrier processed by P1 into output L_E with effectiveness of 50% and resulted output of 314,368.5 kW Electricity energy carrier consumed.

Table 2. EH Output for Scenario 1,2, and 3

Scenario	Process	Energy		
		Natural Gas(MMBtu/Ton)	Water (m^3)	Electricity (kW)
1	P1	0	992,560	314,368.5
	P2	0	1,056,331	49,455,564
	P3	0	19,177	1,916,949.5
	P4	54.7	0	3,810,819
	P5	206.92	0	0
	Total	**261.63**	**2,069,088.5**	**55,497,701**
2	P1	0	1,654,267	188,621.1
	P2	0	1,760,552.5	29,673,338.4
	P3	0	31,995	1,150,169.7
	P4	54.7	0	2,286,491.4
	P5	206.92	0	0
	Total	**261.63**	**3,446,814.5**	**33,298,620.6**
3	P1	0	992,560	188,621.1
	P2	0	1,056,331	29,673,338.4
	P3	0	19,177	1,150,169.7
	P4	54.7	0	2,286,491.4
	P5	206.92	0	0
	Total	**261.63**	**2,069,088.5**	**33,298,620.6**

5 RESULTS

Table 2. lists output of EH Model for scenario 1,2, and 3 as a result of matrix in equation (3) for scenario 1, equation (4) for scenario 2, and equation (5) for scenario 3. It shows results of processes P1,…,P2 for all scenarios as explained as:

a. Natural Gas energy carrier,
   All scenarios resulted the same same consumed natural gas energy carriers 261.63 MMBtu/ton.
b. Water energy carrier,
   Scenario 1 and 3 resulted the same energy consumed of 2,069,088.5 m^3, and higher energy consumed of 3,446,814.5 m^3 for scenario 2
c. Electricity energy carrier,
   For electricity energy carrier scenario 1 resulted highest energy consumed of 55,597,701kW and the same energy consumed of 33,298,620.6 kW for scenario 2 and 3.

For these results, scenario 1 and 3 are chosen for the same water energy consumed. At the same condition, scenario 3 has lowest energy consumed of electricity energy carrier. In context of minimizing energy consumed of all scenarios, it can be concluded that scenario 3 has lowest energy consumed for all energy carrierswith . As listed at Table 2, scenario 3 has total Natural Gas consumed for 261.63 MMBtu/Ton, 2,069,088.5 m^3 water, and 33,298,620.6 kW electricity with process of 100% natural gas, 30% water and 30% electricity effectiveness

6 CONCLUSION

This paper selects minimal energy consumed which involved 3 energy carrier i.e. Natural Gas (NG), Water (W), and Electricity (E) and 5 different processes i.e. Lime Softening (P1), Cooling (P2), Demineralizing Plant (P3), Gas Generator (P4), and Heat Boiler(P5). Combination of energy carriers and processes are provided as 3 scenarios of combination's percentage of effectiveness. Based on EH concept developed by (Geidl and Andersson, 2007), research framework was built to solve the problem.

Problem system were built with amount of energies available as inputs and energies consumed as outputs. Basic mathematical matrix model of EH Model has been extended for multi process purpose based on Table 1.

Using 3 equations of (3), (4), and (5) represented 3 scenarios policies in each energy carrier percentage of effectiveness, the result showed that scenario 3 consumed most minimal energy for total process. scenario 3 has total Natural Gas consumed for 261.63 MMBtu/Ton, 2,069,088.5 m^3 water, and 33,298,620.6 kW electricity with process of 100% natural gas, 30% water and 30% electricity effectiveness.

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