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Modelling and Optimization of An Integrated Steam Hub Facility for Brownfield Eco-Industrial Parks

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Eco-Industrial Parks are vital for sustainable development and combating climate change by improving resource efficiency and adopting circular economy practices. Integration of common infrastructure like steam power plants and reutilizing resources collectively are among the crucial steps to achieve these objectives. This study focuses on modeling and optimizing the integration of existing steam utility plants into an integrated steam hub facility through Linear Programming (LP) approach. The optimization goal aims to minimize cost and emission reduction while ensuring a reliable energy supply for industrial operation. The finding demonstrates significant reductions in both cost and emissions. In the scenario involving only fossil fuel-based utility plants, the costs decreased by 2.78 % from 9,544.30 $/h to 9,278.74 $/h, and GHG emissions dropped by 11.8 % from 0.85 t/h to 0.75 t/h. Further integration with a renewable energy-based utility plant reduced GHG emissions by 16.5 % to 0.71 t/h, though with a slight increase in cost to 9,577.66 $/h. Furthermore, this integration strategy allows for the maximization of capital investment for stakeholders while providing a sustainable energy supply and opportunities to transition to greener energy sources through optimized resource utilization.

1. Introduction

Industrial parks encompass various sectors that consume large amounts of energy and emit significant carbon emissions. In 2020, the International Energy Agency (IEA) reported that industries accounted for 37 % of global energy consumption and 24 % of carbon dioxide emissions (IEA, 2020). This report underscores the urgent need for the development of Eco-Industrial Parks that embody circular economy principles, foster resources efficiency, reduce emissions and promote inter-industry collaboration to facilitate resource reuse and sharing. Research has shown intensive efforts through investigations into maximizing waste heat recovery, integrating renewable energy, and optimizing and retrofitting utility networks within industrial parks. However, there remains a notable gap in the reutilization of underutilized existing utility steam plants owned by tenants, which has not been explicitly addressed. Addressing this gap could improve capital investment, particularly within the framework of brownfield Eco-Industrial Parks. An overlooked aspect, which has the potential to be enhanced, is the reutilization of extra boiler capacity by integrating these steam utility plants into an integrated steam hub facility, consolidating the infrastructures that coordinates and optimizes the resources for generating, managing, and distributing steam thus enhance operational efficiency and cost-effectiveness. This integration streamlines operations, reduces redundancy, and minimizes energy losses associated with standalone operation. Additionally, the incorporation also creates opportunities for greener energy sources via integration with renewable energy-based utility plants while addressing the variability and reliability issues associated with renewable energy. The concept of this integration can be visualized in Figure 1. This holistic approach provides a new theoretical framework for optimizing multi-site steam networks by balancing conventional and renewable energy sources, ensuring a sustainable, feasible, and reliable energy supply within the industrial park.

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Therefore, this study aims to demonstrate the feasibility of the integration through operational optimization of selected case study within three possible scenarios. At steady steam demand, scenario 1 (no integration between the integrated steam hub facility and other steam utility plants), while scenario 2 (the integration with multiple steam utility plants), and scenario 3 (the integration of multiple steam utility plants and a renewable energy-based utility plant). Section 2 reviews relevant literature. Section 3 outlines the model formulation and case study. Section 4 presents the results and discussion. Finally, Section 5 concludes with the findings and future work suggestions.

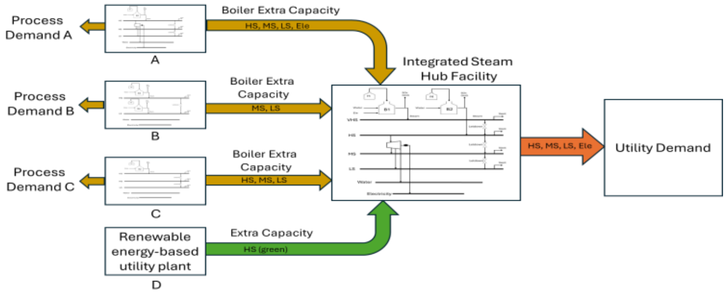

Figure 1: Problem Representation

2. Literature Review

Various literatures have demonstrated intensive efforts on modelling the utility plants within the optimization framework. Varbanov et al. (2004) proposed a successive-MILP procedure for steam turbines and gas turbines modeling. Aguilar et al. (2007a) proposed modeling framework for utility systems and demonstrate it using case study (Aguilar et al. 2007b). These models have since become seminal references and are widely utilized in current research and practice. For the scope of Eco-Industrial Park development, Kim et al. (2010) present a systematic approach to optimize the utility network of Yeosu Industrial Complex covering simultaneous the economic and environmental performance together. An optimization model of waste heat utilization network proposed within the same case study covering the element of wastewater and waste steam (Chae et al., 2010). However, both models are limited to the optimization of utility networks among existing plants and do not emphasize the concept of a centralized system. Luo et al. (2012) focused on operational planning optimization of multiple interconnected steam plants considering environmental cost for petrochemical complex. This model highlights the environmental impact and demonstrates the practicality of interconnected multiple steam systems. Chen and Chen (2014) propose a generic mathematical model for retrofitting steam power plants within an industrial site as total site steam, an extension from the work by Chen and Lin. (2012). Their model is particularly useful for retrofitting and could serve as a key reference for future research, especially after the concept of this integration has been realized. On the other hand, Total Site Heat Integration (TSHI) is an essential methodology for designing efficient utility systems (Dhole and Linnhoff, 1993). Liew et al. (2017) presents a comprehensive review of this methodology and highlighting the planning and design framework of synergizing renewable energy with thermal energy system. Jiménez-Romero et al. (2023) introduced the STYLE methodology, aiming to transition utility systems in industrial settings toward sustainability however the work focuses on the waste heat from processes and does not touch on renewable energy. Pérez-Uresti et al. (2019) propose a superstructure approach for the design of renewable energy-based utility plants and continuously evaluating on the design with various renewable energy technologies (Pérez-Uresti et al. 2023). However, the scope of their model is limited to designing renewable-based utility plants by selecting the best renewable energy technologies. These studies collectively demonstrate the possibility of multi-site utility systems integration, the potential for integrating renewable energy sources, and the importance of retrofitting existing plants. However, there remains a significant gap in addressing the integration of underutilized existing utility steam plants into a centralized hub facility and exploring their combination with renewable energy sources which proposed in this study.

3. Methodology

3.1 Model Formulation

The optimization goal aims to minimize operational costs of the integrated steam hub facility, including fuel and water costs, as well as emissions costs associated with SOx and GHG generation. The optimization problem is subjected to constraints on equipment, their operational capacity, efficiency and type of fuels, and the available extra capacity of each utility plant. The percentage of green source steam in the overall header is introduced as constraints to ensure a specified level of renewable energy integration and to promote the use of sustainable energy sources within the Eco-Industrial Park. Three possible scenarios as mentioned are considered. The optimization was solved using the Linear Programming (LP) solver available in MATLAB software. The mathematical formulation for objective function and constraints of the model are given as follows.

Objective function

Min. Cost = $\sum_f F \times F_c + \sum_e EM_{b,i}gen \times EM_C + \sum_{sp} SP_{l,i} \times SP_c$ (1)

1. Boiler

$$F_{b,i}in + W_{b,i}in = S_{l,b,i}gen + EM_{b,i}gen \quad \forall b \in B, \quad \forall i \in I\ , \tag{2}$$

$$S_{l,b,i}gen = \frac{Cal_f \times F_{b,i}in}{Eff_b} \qquad \forall I \in L \tag{3}$$

$$EM_{e,b,i}gen = EP_e \times F_{b,i}in \qquad \forall e \in E \tag{4}$$

$$Ele_{b,i} = \alpha \times bin_{b,i} + \beta \times S_{b,i}gen \tag{5}$$

2. Turbine

$$Ele_{t,i} = T1_{HS} \times S_{HS,t,i}, in - T2_{MS} \times S_{MS,t,i}, out - T3_{LS} \times S_{LS,t,i}, out - T4_W \times S_{W,t,i}, out \qquad \forall t \in T \tag{6}$$

3. Steam Header

$$S_{l,b,i}gen + SP_{l,i} = SD_{l,i} + S_{l,t,i}, out + SLD_{l,l",i} + SV_{l,i} \tag{7}$$

$$\sum_{sp} SP_{l,i} + \sum_{d} SD_{l,i} \ll S_{l,b,i}gen \tag{8}$$

4. Green Source Steam

$$0.2 < \frac{SP_{l,i(green)}}{SD_{l,i(green)} + SD_{l,i}} < 0.3 \tag{9}$$

3.2 Case Study

A simplified case study consists of an integrated steam hub facility, H and three fossil fuel-based utility plants, plant A, B, C adapted from Kim et al. (2010) together with a range of extra capacity of renewable energy-based utility plant D are considered for demonstrating this integration. The case study data, tabulated in Tables 1 and 2, detail the steam and electricity demands for each utility site and the specifications of their boilers, respectively.

Table 1: Utility demand, $SD_{l,i}$ at each utility site

Steam Level	H	A	B	C
VHS	425			
HS	289	115		85
MS	267	98	223	60
LS	285	95	280	46
Electricity	85	20		

Table 2: Boiler specifications

Utility Site, i	Steam Level, l	Max Capacity (t/h)	Efficiency, Eff_b	Fuel price, F_c ($/t)	Calorific Value, Cal_f	SOx, EP	GHG, EP
Hub	VHS	900	0.59	200	15.19	0.022	0.017
	HS	630	0.57	65	9.79	0.003	0.003
A	HS	480	0.58	76	12.67	0.004	0.005
B	MS	420	0.56	83	9.79	0.003	0.003
	LS	400	0.55	65	9.79	0.003	0.003
C	HS	300	0.58	76	12.67	0.004	0.005

The utility plants have simple configuration of equipment, including boilers, turbines, and steam headers. The boilers produce steam at various pressures and the turbine is an extraction turbine that generates both electricity and steam at different pressure levels.

4. Results and Discussion

The optimization results presented in Tables 3 to 5, illustrate the operational configurations of the integrated steam hub facility for each scenario considered. In scenario 1 in Table 3, the integrated steam hub facility primarily relies on its own boilers to generate steam at various pressure levels to fulfil the demand. However, as the integration introduced in scenarios 2 and 3, the operational dynamics change significantly. In scenario 2 in Table 4, where the integrated steam hub facility utilizes steam from plant A, B, and C, a notable reduction in the load on the VHS boiler at the integrated steam hub facility observed. This reduction ranges from 90 % to 59 %, indicating a significant shift in steam generation towards reutilization strategy rather than self-generation. Meanwhile, plant A, B, and C ramp up their boilers to meet the increased demand, showcasing the flexibility and adaptability of the integrated system. This strategy improves capital investment at both the existing utility plants and the integrated steam hub facility by maximizing their boiler usage, which might otherwise remain underutilized. By reutilizing the extra boiler capacity from individual utility plants (A, B, and C), the integrated steam hub can optimize the use of existing infrastructure, reducing the need for new investments in additional capacity when the steam demand increase. This leads to more efficient resource allocation and enhanced return on investment for the entire industrial area. Furthermore, in scenario 3 from Table 5, where the integrated steam hub facility utilizes green steam from plant D, further reductions in the load on VHS boilers at the integrated steam hub facility observed, showcasing the dual benefit of enhancing operational efficiency and promoting sustainability. This integration not only diversifies the steam sources but also promotes greener energy by incorporating renewable energy into the operational mix.

Table 3: Integrated steam hub facility operation (Scenario 1 - Base Case)

Steam level and electricity	Demand, $SD_{l,i}$ (t/h)	Boiler load, $S_{l,b,i}gen$ (t/h)	Turbine, $S_{l,t,i}, in/out$ (t/h)	Letdown, $SLD_{l,l'',i}$ (t/h)	Vent, $SV_{l,i}$ (t/h)	Purchase electricity from grid (kWh)
VHS	425	809.82	0.00	384.82	0.00	0.00
HS	289	630.00	695.27	30.55	0.00	0.00
MS	267	0.00	236.45	0.00	0.00	0.00
LS	285	0.00	285.00	0.00	0.00	0.00
Electricity (MW)	85	0.00	85.00	0.00	0.00	3.51

Table 4: Integrated steam hub facility operation (Scenario 2)

Steam level and electricity	Demand, $SD_{l,i}$ (t/h)	Boiler load, $S_{l,b,i}gen$ (t/h)	Turbine, $S_{l,t,i}, in/out$ (t/h)	Letdown, $SLD_{l,l'',i}$ (t/h)	Vent, $SV_{l,i}$ (t/h)	Purchase electricity from grid (kWh)	Purchase from A, (t/h)	Purchase from B, (t/h)	Purchase from C, (t/h)
VHS	425	534.79	0.00	109.79	0.00	0.00	0.00	0.00	0.00
HS	289	630.00	695.27	0.00	0.00	0.00	135.48	0.00	109.00
MS	267	0.00	236.45	0.00	0.00	0.00	0.00	30.55	0.00
LS	285	0.00	285.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity (MW)	85	0.00	85.00	0.00	0.00	2.96	0.00	0.00	0.00

Table 5: Integrated steam hub facility operation (Scenario 3)

Steam level and electricity	Demand, $SD_{l,i}$ (t/h)	Boiler load, $S_{l,b,i}gen$ (t/h)	Turbine, $S_{l,t,i}, in/out$ (t/h)	Letdown, $SLD_{l,l'',i}$ (t/h)	Vent, $SV_{l,i}$ (t/h)	Purchase electricity from grid (kWh)	Purchase from A, (t/h)	Purchase from B, (t/h)	Purchase from C, (t/h)	Purchase from D, (t/h)
VHS	425	465.43	0.00	40.43	0.00	0.00	0.00	0.00	0.00	0.00
HS	289	630.00	695.27	0.00	0.00	0.00	135.48	0.00	109.00	69.36
MS	267	0.00	236.45	0.00	0.00	0.00	0.00	30.55	0.00	0.00
LS	285	0.00	285.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity (MW)	85	0.00	85.00	0.00	0.00	2.82	0.00	0.00	0.00	0.00

The comparison of overall boiler loads across all scenarios in Table 6 provides additional insights into the impact of integration on individual plant operations. A varying degrees of boiler utilization across plant, with some plant operating at maximum capacity to meet increased demand, while others adjust their operations in response to the integrated system's dynamics observed. Moreover, the cost and GHG emissions data from Table 6 reveal the economic and environmental implications of the optimization scenarios. Scenario 2, which involves utilization steam from existing utility plants, demonstrates lower costs, 9,278.74 $/h and GHG emissions, 0.75 t/h compared to the base case scenario 1, 9,544.30 $/h and 0.85 t/h. These findings are consistent with the work of Kim et al. (2010), who also observed economic and environmental benefits through multisite steam integration. However, this study expands on this by incorporating an integrated steam hub facility, providing a more streamlined and efficient approach. In scenario 3, with the inclusion of 20 % green steam from plant D, exhibits a further reduction in GHG emissions 0.71 t/h but a slight increase in cost 9,577.66 $/h compared to scenario 1. Although the cost is slightly higher in scenario 3 due to the utilizes steam from plant D, which is renewable energy-based utility plant have higher cost, this approach could potentially be more beneficial than investing in renewable infrastructure at each individual utility plant. The work by Pérez-Uresti et al. (2019) could provide more insight into this aspect of renewable energy-based utility plants. By opting to utilize renewable steam from plant D instead, the individual utility plant can avoid these upfront costs and associated financial risks. This strategic decision not only mitigates financial uncertainty but also accelerates the transition to renewable energy without the need for substantial capital investment. However, further analysis of this aspect would be required, which can be considered in future work.

Table 6: Overall boiler load, cost and GHG emission comparison for all scenarios

Scenario	Hub - VHS boiler (%)	Hub- HS boiler (%)	A- HS boiler (%)	B- MS boiler (%)	B- LS boiler (%)	C- HS boiler (%)	Cost ($/h)	GHG emission (t/h)
Scenario 1	90	100	72	53	70	64	9,544.30	0.85
Scenario 2	59	100	100	60	100	100	9,278.74	0.75
Scenario 3	52	100	100	100	60	100	9,577.66	0.71

5. Conclusions

A simple optimization model was developed to demonstrate the strategy of reutilization of existing utility plants via integration into an integrated steam hub facility within the framework of Eco-Industrial Parks. The findings indicate that the integration leads to a reduction in both cost and GHG emissions. In Scenario 2, which involves integrating fossil fuel-based plants, the costs decreased by 2.78 % and GHG emissions dropped by 11.8 % compared to the base case Scenario 1. Further reduction in GHG emissions was achieved in Scenario 3, which includes 20 % green steam from Plant D, a 16.5 % reduction compared to the base case. However, it was observed that integration with renewable energy sources results in slightly higher costs 9,577.66 $/h compared to 9,544.30 $/h in Scenario 1, albeit achieving further reductions in GHG emissions. By integrating these renewable sources with the more stable fossil fuel-based utility plants, the steam hub facility can ensure a consistent and reliable steam supply, mitigating the risks associated with the inherent variability of renewable energy. This balanced approach not only secures a dependable energy supply but also supports a smoother transition towards increased renewable energy use within the industrial area. While the proposed model presents a significant advancement in enhancing operational efficiency and resource optimization within industrial parks. There are several practical challenges that must be addressed for real-world deployment. Infrastructure compatibility is crucial, requiring a thorough assessment of current infrastructure to harmonize equipment specifications, operational standards, and connectivity. Retrofitting existing plants with compatible interfaces and control systems may be necessary. Ensuring reliability and maintenance is also critical to prevent disruptions. Developing robust maintenance schedules, contingency plans, and redundancy mechanisms can mitigate risks associated with equipment failures or supply interruptions. Addressing these challenges could be the focus of future research, paving the way for successful implementation of integrated steam hub facilities in industrial settings.

Nomenclature

B, b – boiler
EM, e – emissions, t/h
Ec – emissions treatment cost, $/h
Eff_b – boiler emissions
EP – emissions coefficient
F, f – fuel, t/h
F_c – fuel price, $
i – utility site
l – steam level
S – steam t/h
SD – steam demand, t/h
SLD – steam let down, t/h
SP – steam purchase, t/h
SV – steam vent out, t/h
$T1, T2, T3, T4$ – turbine coefficient
α – boiler electricity coefficient
β – boiler electricity coefficient
W – water, t/h

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