

Direct and Indirect Integration of Organic Rankine Cycle in Total Site

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Industrial sector is one of the major energy consumers in the world. Energy inefficiency in industry due to energy losses and wastages, which contributes to unnecessary carbon emission and global warming. Various initiatives have been taken for enhancing the energy efficiency in the industrial sector. Pinch Analysis is one of the important systematic tools for improving energy supply and demand in a process plant. Total Site Heat Integration for multiple processes (industrial cluster) has been introduced, as an extension to Pinch Analysis, to debottleneck the limitation of energy recovery in a single process plant. The availability of low temperature waste heat could be found, after considering the maximum heat recovery within the industrial cluster through TSHI. Organic Rankine Cycle (ORC) has been widely used for power recovery from low temperature heat sources. ORC integration is frequently being considered for direct heat transfer from a waste heat stream. In this study, integrating ORC via indirect heat transfer for a site utility system is studied, together with the direct integration of ORC to a waste heat stream. The indirect integration provides more opportunity of energy recovery through cumulating the low temperature waste heat from various stream, which has the potential of generating more power than depending on an individual waste heat stream. Economic comparison between direct and indirect ORC integration has been done in this work through a case study. A simple case study shows direct integration has better energy saving opportunity. Indirect ORC integration could be more efficient when the waste heat sources are distributed in different processes and stream.

1. Introduction

Paris Agreement pushed climate change issues for receiving more awareness from governments, corporates and public. Carbon emission is the most important indicator that has been mentioned in the Paris Agreement, which aims to maintain the global temperature rise at well below 2 °C above pre-industrial levels.

Pinch Analysis establishes for resources (e.g. heat, power, water and mass) conversation in process industry. The conventional Heat Pinch Analysis focuses on individual process heat recovery via heat exchanger network. The saving is limited due to limited potential heat exchange. The concept is extended into Total Site Heat Integration (TSHI), which considers heat recovery via utility system for multiple processes (Liew et al., 2017). TSHI energy targeting considers all possible potential energy recovery through estimating the utility generation and consumption capacities in the Total Site (TS) system, which reduces the overall hot and cold utility requirements, as well as waste heat reduction. Studies found that low grade waste heat at low temperature is still widely available in a TS system. Huge amount of research has been done for waste heat utilisation technologies (Oluleye et al., 2017), such as district heating (Eriksson et al., 2015), district cooling, absorption chiller (Liew et al., 2016) and combined heat and power system (Bandyopadhyay et al., 2010).

Organic Rankine Cycle (ORC) is attractive for its ability in converting low temperature heat (thermal energy) sources into useful shaft work (electrical power). Several recent research has been done for integrating solar thermal system into ORC for harvesting power energy. Desai and Bandyopadhyay (2009) proposed Pinch-based methodology for integrating ORC into process industry for recovering low temperature waste heat as part of cogeneration system. The proposed methodology is based on direct integration of ORC system with individual process stream. In this paper, indirect integration of ORC via utility system for waste heat recovery in TS system is studied, then compared to direct integration of ORC with waste heat stream. This integration requires higher waste heat temperature, waste heat from different streams could be collected in a utility level and recover with ORC system. The direct and indirect integrations of ORC to Total Site system are discussed and compared through a case study.

2. Method

TSHI methodology has been well-established for targeting the energy and utility consumption of an integrated multiple-process system. This paper extended the conventional TSHI targeting methodology for exploring the possibility to integrate ORC system directly to the utility system, which is an indirect integration (Figure 1), for recovering low temperature process waste heat.

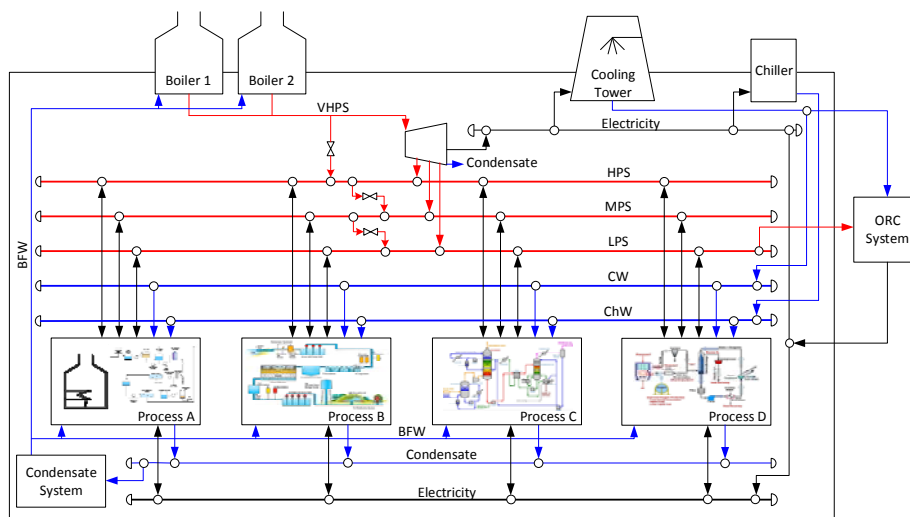


Figure 1: Indirect integration of ORC system to Total Site

The result is then compared with direct integration, which the ORC system is recovering energy from a specify process stream directly. The method is described as following:

2.1 STEP 1: Determination of Single Process Energy Recovery Target

Based on the process streams data available, the minimum energy consumption (hot and cold utilities) are targeted according to process or section using Pinch Analysis. The analysis could be done in graphical (Composite Curves – CC, and Grand Composite Curve - GCC) and numerical (Problem Table Algorithm - PTA) methodologies. The energy recovery opportunity in this level is limited to process level, which the process streams are suggested to be integrated as much as possible in this level.

2.2 STEP 2: Determination of Total Site Energy Recovery Target

Heat recovery between processes through utility system is targeted by TSHI methodologies, include graphical (Total Site Profile – TSP and Site Utility Composite Curve – SUCC) and numerical (Total Site Problem Table Algorithm – TS-PTA) methodologies. The utility generation and consumption potentials are determined using the tools available. The targeted potentials are then matched with each other for satisfying the utility supply and demand between processes. The amount of energy targeted at above the TS Pinch represents the heat deficit, which should be satisfied by the site boiler house. The amount of heat available at below TS Pinch should be cooled down by the cooling utility in the TS system, which represents the waste heat available of the TS. The temperature of waste heat available at below TS Pinch determines the usefulness of the heat available.

2.3 STEP 3: Identification of Waste Heat Source for ORC Integration

2.3.1 Waste Heat Stream for Direct Integration

Based on existing Heat Exchanger Network (HEN) configuration, the highest capacity low temperature waste heat stream is identified for integrating with ORC system. The waste heat stream refers to a stream that could contribute to the utility system, the heat supplied is not going to be used at other part of the TS system as suggested in STEP 2. For grassroots design, the individual waste heat stream should be determined after the design of an optimal HEN as proposed in Liew et al. (2014).

2.3.2 Utility Level with Waste Heat for Indirect Integration

The maximum amount of heat available for indirect ORC system integration is identified through the excess utility generation potential targeting in STEP 2 at below TS Pinch region. The selected utility level should be at below TS Pinch region and higher temperature than required waste heat supply temperature to the ORC's evaporator. Assuming no other suitable waste heat recovery technology available in the plant, higher temperature waste heat is acceptable to be supplied to the ORC system in this work, which reduces the wastage of higher temperature unutilised heat.

2.4 STEP 4: Determination of Energy Recovery of Direct and Indirect Integrated ORC Systems

The waste heat available is simulated in ORC system model (Aneke et al., 2011) for obtaining the net power generation potential from the low temperature waste heat by both direct and indirect integration. The energy discharge by ORC's condenser is also accounted in the model for this work. The power consumption of the ORC includes the pump power consumption and the ORC power generation is contributed by the turbine work output.

2.5 STEP 5: Economic Analysis for Direct and Indirect Integrated ORC Systems

The utility consumptions are summarised for both direct and indirect integration of ORC system and the TS processes. The hot and cold utility requirements, as well as electricity production, are calculated in term of cost for comparing the economics potential of direct and indirect ORC integration.

3. Case Study

A modified literature case study (Liew et al., 2012) is used to illustrate the comparison of the direct and indirect integrated ORC systems in TS. Both configurations of ORC integration are analysed and compared in this case study. The stream data for the case study is shown in Table 1. There are four utilities available in the TS system, which include High Pressure Steam (HPS – 270 °C), Medium Pressure Steam (MPS – 180 °C), Low Pressure Steam (LPS – 134 °C), and Cooling Water (CW – 15 - 20 °C). The minimum temperature difference between utility and process ($\Delta T_{\min,up}$) in this case study is assumed to be 20 °C.

The ORC system is assumed to be integrated direct or indirectly with the TS processes. The excess energy generation potential with temperature higher than ORC's evaporator temperature (80 °C) could be used to evaporate the ORC's working fluid.

Table 1: Stream data for case study (Liew et al., 2012)

Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat duty, ΔH (MW)	Heat capacity, mC_p (MW/°C)	Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat duty, ΔH (MW)	Heat capacity, mC_p (MW/°C)
Process A ($\Delta T_{\min,pp} = 20$ °C)					Process B ($\Delta T_{\min,pp} = 10$ °C)				
A1 Hot	200	100	1,150	10	B1 Hot	200	50	450	3
A2 Hot	150	60	3,600	40	B2 Hot	240	100	210	1.5
A3 Cold	50	120	3,150	45	B3 Hot	200	119	1,860	23
A4 Cold	50	220	2,550	15	B4 Cold	30	200	680	4
					B5 Cold	50	250	400	2

3.1 STEP 1: Determination of Single Process Energy Recovery Target

The energy utilisation in a process must be optimised before considering heat recovery through utility headers at TS level. It is essential to set the energy recovery targets for each individual processes in the system. It is assumed that the energy recovery system, i.e. heat exchanger network, is already in place and properly designed according to Pinch principle. Based on the single process PTA, Process A requires 1,500 MW of hot

utility, which include 750 MW, 200 MW and 650 MW of HPS, MPS and LPS. The cooling utility is supplied by CW at the rate of 400 MW. For Process B, 100 MW of hot utility is required at the HPS level.

3.2 STEP 2: Determination of Total Site Energy Recovery Target

In order to get energy recovery beyond individual process level, the TS energy recovery target is required to be determined for inter-process heat recovery through utility system. The energy generation and demand potentials from the processes are analysed using TS-PTA, as shown in Table 2.

The utility supply and demand potentials match at the same utility level, as shown in the net heat requirement of the TS-PTA. The excess generation potential is then cascaded to satisfy the demand for utility level with lower temperature, which could be seen in the cascades in the TS-PTA. The overall TS system requires 850 MW and 1,093 MW of hot and cooling utility from the utility system, which there are excess MPS, LPS and CW generation opportunities for 15 MW, 339 MW and 739 MW from the processes.

Table 2: Total Site Problem Table Algorithm (TS-PTA) result for case study

Utility	Utility Temp. (°C)	Net heat source (MW)	Net heat sink (MW)	Net heat requirement (MW)	Initial heat cascade (MW)	Final heat cascade (MW)	Multiple utility heat cascade (MW)	External utility requirement (MW)
HPS	270	0	850	-850	0	850	0	850
MPS	180	215	200	15	-850	0	0	-15
LPS	134	989	650	339	-835	15	0	-339
CW	15	739	0	739	-496	354	0	-739
					243	1,093	0	

3.3 STEP 3: Identification of Waste Heat Source for ORC Integration

The HEN for the processes in the Total Site is important in this step. Process A for this case study is different from Liew et al. (2014). The Process A for both case study has energy deficit in LPS level, which means ORC would not be integrating directly to any stream in Process A. Process B in the case study has energy excess at LPS level, which is contributing to the energy deficit in Process A. The remaining of the energy excess in Process B at LPS level would be wasted.

3.3.1 Waste Heat Stream for Direct Integration

For direct integration of ORC system, the HEN design in Liew et al. (2014) for Process B has been improved for effective energy harvesting, without affecting the energy recovery in the case study. In this study, the preheaters, evaporators and super-heaters are treated as steam generator directly. Then, the steam generation opportunity shown in the HEN are first considered for satisfying the TS requirements, before any waste heat stream could be selected for direct integration.

The heat source for producing LPS heat at stream B1 is very limited, it is considered for supplying to the LPS header for supplying to Process A. Stream B2 has reasonable amount of heat source for generating LPS, while there is additional amount of heat source could be considered if it is integrated to ORC system. Stream B3 has very high heat capacity flowrate, which brings highest possibility for beneficial direct ORC integration. Stream B2 and B3 are considered for the direct integration with ORC system. The waste heat that has higher temperature than the evaporator required temperature are also considered in the direct integration. This shows the flexibility given by direct integration of ORC system.

In this study, two cases are assumed for the direct integration of ORC system, as shown in Table 3. Case 1 (optimal case) considers the maximum amount of waste heat for direct integration, which the contribution of this stream to the energy demand of Process A is minimised. In this case, the intra-process heat recovery is assumed at higher temperature. Case 2 is the worst case scenario, which the energy deficit at Process A is completely satisfied by this stream and the intra-process heat recovery exchanger is kept at low temperature. The remaining of the energy are considered for direct ORC integration.

3.3.2 Utility Level with Waste Heat for Indirect Integration

For indirect integration of ORC system, the excess LPS (354.00 MW) is used to operate the ORC system in the case study, as shown in Figure 1. The excess of MPS (15.00 MW) are also considered to be diverted into the ORC system, since the heat quality is capable to evaporate the ORC working fluid.

Table 3: Summary for cases to integrate with ORC system directly

	Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat duty, ΔH (MW)	Heat capacity, mC_p (MW/°C)
Case 1	B3 Hot	141.28	119.00	512.50	23.00
Case 2	B3 Hot	153.24	144.00	212.60	23.00

STEP 4: Determination of Energy Recovery of Direct and Indirect Integrated ORC Systems The case study shows that the ORC system is able to reduce the TS cold utility requirements by 20 to 47 %, while the TS hot utility requirements remained the same. The ORC system requires to operate with a high load condenser, while producing electricity output. The Base Case shows that 1,093 MW of cooling utility is required by the process without ORC integration. When ORC system is directly integrated with stream B3 optimally, a reduction of 46 % for cooling utility demand to 589.50 MW is foreseen, while the ORC condenser requires 459.17 MW of cooling and produces 51.07 MW of electricity. For worst case scenario, both heat sources from stream B1 and B2 (141.40 MW) are wasted and the requirement of Process A is fully satisfied by the heat from stream B3. The amount of waste heat sent to ORC in this case is only 212.60 MW. The ORC produces 21.61 MW of electricity and requires 194.25 MW of cooling utility for the ORC condenser. In the case of indirect integration, the waste heat at MPS and LPS levels (354.00 MW) are both channelled to the ORC system, which produces 35.91 MW of electricity and requires 322.83 MW of cooling utility in the condenser.

3.4 STEP 5: Economic Analysis for Direct and Indirect Integrated ORC Systems

In order to analyse the economic potentials for these integration options, the processes in the TS system are assumed to operate for 335 d annually, while the electricity, fuel and cooling water prices are assumed at 0.1058 USD/kWh, 0.19 USD/kg and 0.0479 USD/m³. The energy recovery and economic analysis of the system are summarised in Table 4.

Table 4: Summary of energy recovery and economic analysis results

		Base Case	Direct Integration Case 1 (Optimal Case)	Case 2 (Worst case)	Indirect Integration
HPS	(MW)	850.00	850.00	850.00	850.00
MPS	(MW)	-15.00	0.00	0.00	0.00
LPS	(MW)	-339.00	0.00	-141.40	0.00
CW	(MW)	-739.00	589.50	-739.00	-739.00
Waste heat for ORC Evaporator	(MW)	0.00	503.50	212.60	354.00
Hot Utilities Requirement	(MW)	850.00	850.00	850.00	850.00
Cold Utilities Requirement	(MW)	1,093.00	589.50	880.40	739.00
ORC Condenser Load	(MW)	0.00	459.17	194.25	322.83
ORC Power Generation	(MW)	0.00	51.07	21.61	35.91
Hot Utility Cost	(million USD/y)	188.51	188.51	188.51	188.51
Cold Utility Cost	(million USD/y)	24.03	23.05	23.62	23.34
Power Cost Saving	(million USD/y)	0.00	43.47	18.39	30.56
Total Utility Cost	(million USD/y)	212.54	168.10	193.75	181.30

The total utility cost for Base Case is found to be 212.54 million USD/y, with 188.51 million USD/y spent for fuel and 24.03 million USD/y for cooling water. The optimal case (Case 1) for direct integration of ORC, is expected to spent 168.10 million USD/y on the hot and cold utility with taking into account the electricity savings (43.47 million USD/y) from ORC system. In the worst case scenario (Case 2), the utility cost is expected to be 193.75 million USD/y with the savings from electricity generation reduces to 18.39 million USD/y. Last but not least, indirect integration of ORC system is consuming 181.30 million USD/y worth of utilities, which includes 30.56 million USD/y savings from the ORC power generation.

3.5 Discussion

The possible integrations schemes are investigated using the simple case study from the thermodynamics and economic point of view. An optimal direct integration of ORC system is able to save more energy through power generation compared to indirect integration. The case study result mainly due to simplicity of the case. The waste heat could be collected easily in one stream (B3) and directly integrated with the ORC system. The direct integration could be able to fully utilise all waste heat at different temperature range from the particular

selected stream. In reality, a TS system includes several processes, which typically consists of more than 10 hot or cold streams in each of the processes. The waste heat sources need to be accumulated or collected from several individual streams from several processes. Poor HEN design in each process also further leads to a poor economic impact of direct ORC integration in TS system. When the major waste heat sources are distributed at different processes and streams, indirect integration could be more beneficial than the direct heat transfer. One major drawback of indirect ORC integration includes the operational flexibility of the process in the TS system. In order to cater this drawback, the plant requires invest in back-up and by-pass systems for empowering the system operational flexibility. This work is very sensitive towards the existing HEN design, cooling tower efficiency and utility prices. When the HEN design is not properly done, the waste heat could not be collected effectively for the utilisation. It could be seen that the ORC is producing more low temperature waste heat from the condenser compared to the waste heat for evaporator from the process. This causes the cooling water efficiency should be high enough to ensure that the ORC electricity generation is contributing to the overall economic benefits.

4. Conclusion

Total Site Heat Integration provides an energy conservation platform for several processes through site utility system. All the waste heat after inter-process energy recovery are collected in the utility headers. In previous studies, ORC is frequently integrated directly with individual process stream. In fact, the ORC could be operated by taking waste heat from the utility headers, which is collected from several processes. This paper compared the direct or indirect integration of ORC system into TS energy system. The result of the case study shows that optimal direct integration of ORC system is able to save more energy compared to indirect ORC integration in a simple TS system. The direct ORC integration provides flexibility in the waste heat temperature based on availability, regardless utility temperature. The result could vary when a complex case study is used due to the distribution of waste heat from different processes. When waste heat sources are well distributed in several processes and steams, indirect ORC integration scheme would be much beneficial than direct integration.

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