# Data-driven approaches for techno-economic assessment of waste heat recovery and utilisation in the industrial sector

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## ABSTRACT

The industrial sector is a critical element in the sustainability transition as it is currently the largest consumer of fossil fuels, and the consumption is forecasted to continue to increase. Approximately one-fifth of the total industrial primary energy consumption is wasted due to the lack of proven attractive schemes for effective recovery. When addressing the opportunities of industrial waste heat recovery (WHR), it is found that the feasibility depends on multiple factors, including the forms and capacities of the heat sources, the potential heat sinks, and the effectiveness, technological maturity, and economic impact of available technologies. Developing systematic approaches to identify optimal WHR options for different applications is key to effectively reduce plant-scale energy consumption. In particular, power consumption accounts for more than half of the industrial energy use, and its share is expected to grow with the expansion of electrification aspirations. In this paper, industrial WHR technologies are investigated, and tools are developed to understand the sustainability and techno-economic impact of integrating these technologies within industrial processes. We specifically propose a data-driven technology-agnostic approach to evaluate the use of heat engines, which can in practice be organic Rankine cycle (ORC) systems, and of thermally-driven (i.e., absorption) heat pumps in the context of industrial WHR for plant-scale power demand reduction. The scope of this work explores three pathways to achieving efficiency improvements in bulk chemicals plants, represented by olefins production facilities, which are: (i) direct onsite power generation; (ii) enhancement of existing power generation processes; and (iii) reduction in power consumption by compressor efficiency improvements through waste-heat-driven cooling. The techno-economic performance of these technologies is assessed, with particular attention to industrial facilities that reside in hot climates, using fine-tuned technology-agnostic thermodynamic and market-based costing models. Finally, decision-aiding performance maps are derived by varying the quantity and the quality of waste-heat sources and heat sinks, offering application-specific guidelines for selecting appropriate waste-heat recovery schemes. These findings reveal valuable factors for selecting such integration schemes for various industries and scenarios.

## KEYWORDS

Absorption chillers, industrial energy efficiency, organic Rankine cycle, retrofit, techno-economic assessment, waste-heat recovery

## INTRODUCTION

The industrial sector is responsible for nearly half of the global energy demand, primarily sourced from fossil-based sources [1]. Within the industrial sector, according to the international energy agency (IEA), chemicals and petrochemicals processes are the largest consumers of energy and thus are the most emitters of greenhouse gases (GHGs), with a

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forecasted slight increase in the medium-term outlook [2]. The IEA estimates that 40% of the contributions required to achieve the Paris agreement two-degree scenario (2DS) targets are energy efficiency measures, which are also necessary for mitigating other environmental and social burdens, besides the GHG emissions, such as air pollution and energy security [2,3]. Thanks to the advancements in industrial energy efficiency technologies and practices, notable improvements have been made to their energy intensity over the last couple of decades. However, it is estimated that 17% of the UK industrial energy consumption ends up as waste heat that is not utilised. Likewise, it is estimated that one-fifth of the industrial energy consumed ends up as waste heat in the US, and that up to 15% of the primary energy consumed in Europe could be reduced by exploiting waste heat [4–7]. Moreover, power consumption represented around 56% of the EU27 chemical industry's total energy use in 2019, and this is expected to increase further as the industry embarks on the electrification transition [8].

The research of converting low-grade heat into power became a classic theme within which several technologies have reached a technology readiness level (TRL) of 9, demonstrating their maturity and applicability to commercial operations [9,10]. These include thermoelectric generators (TEG) and steam and organic Rankine cycle (ORC) systems. It has been established that ORCs can generally outperform the other two technologies from techno-economic and operability standpoints when driven by low (less than 150 °C) to medium-temperature (150-200 °C) heat sources [6, 7, 11–13]. Therefore, the focus of this research theme shifted to the ORC configuration, working fluids selection, and part-load optimisation. However, other options for the exploitation of industrial WH by indirectly converting it to power have not gained the equivalent level of attention compared to the direct conversion of WH to power route. This can be achieved by integrating thermally driven heat pumps, i.e. absorption chillers, which are further integrated with power-generating or power-consuming processes.

Gas turbines (GTs) are becoming more favoured than coal-fired plants for electricity production due to their performance in terms of efficiency, emissions, continuity and flexibility. Therefore, GTs adoption is growing and is not expected to peak (in a carbon-neutral world) before the middle of the 21st century [14]. However, their performance is known to deteriorate in hot climates. In fact, for every increase by one degree in the ambient temperature, a reduction of power production occurs by about half to one per cent [15, 17]. As a result, studying the integration of several air cooling techniques with GTs has gained increasing attention, especially when driven by free WH. For instance, Kwon et al. studied enhancing a GT combined cycle system by integrating an exhaust-driven absorption chiller system for air cooling [18]. The authors studied two different configurations and reported an estimated increase of power generation by approximately 8% and payback periods of lower than three years. However, it can be noticed that the vast majority of research found in the literature focussed primarily on optimising the configuration of the GTs by capturing the WH generated by the GT system (e.g. [19, 20]), while the opportunity to integrate GTs with the wider site utility system WH has not been sufficiently addressed. More specifically, an assessment that includes the other comparable WHR pathways is found to be a gap in the current work.

Gas compression processes are an essential part of many industrial plants. There are several types of compressors, but for the bulk industries where gas flow rates exceed 90 $m^3/s$ and with required discharge pressures up to 700 bar, centrifugal compressors can be found in nearly 60 different petrochemicals manufacturing processes, which leads to a substantial contribution to their energy consumption [21, 22]. The main drawback of centrifugal compressors is that they consume a significant amount of energy. For instance, in air separation units (ASU), three-fifths of the overall power consumption is allocated to the compressor shaft power [23].

Consequently, the motivation to improve the compressors' efficiency has increased, especially for large-scale systems. Interstage cooling represents a compelling opportunity to reduce compression shaft power requirements cost-effectively. A study on the impact of increasing the capacity of the interstage coolers found that a 5% increase could lead to a reduction in shaft power consumption by more than 0.6% in a three-stage compressor [23]. However, the integration of interstage cooling with process sites' WHR schemes has not been explicitly investigated, which can magnify the potential benefits of WHR due to their large scales of capacities. Therefore, this is selected to be the intended scope that we aim to address in this paper along with the other opportunities to understand their performance in different scenarios.

Furthermore, this paper intends to utilise an atypical approach to modelling and evaluating WHR technologies. This is because the study of the integration of WHR technologies is mainly done by developing rigorous models for these technologies. The creation of such models involves the specification of many factors, such as the configuration, working fluids, and types of pieces of equipment used. However, many of these decisive factors are unknown in concept screening purposes, which frequently leads researchers to make a considerable number of assumptions that inherently increase the inaccuracies of the results. Therefore, reversible and endoreversible thermodynamic models can be advantageous for the early-stage screening of such technologies based on their thermodynamic efficiency [6].

Additionally, as the deployment of these technologies has been on an increasing trajectory, the opportunity to improve the accuracy of the performance predictions becomes more evident. This is because modelling results can be correlated with the published performance data. The application of such empirical correlations has been limited in the literature. An example of such analysis was conducted by Gangar et al. [6]. However, the scope of that study involved only ORC systems and mechanical vapour-compression heat pumps.

## METHODS

As a starting step in our investigation, the computational modelling aspects for the techno-economic performance are discussed for each of the considered technologies, along with a brief description of the configurations when integrated with a conventional energy-intensive process plant. Second, the derived energy performance and investment costs are utilised as inputs for a comparative study for the considered schemes applied to a case study from the bulk chemicals industry to address the advantages of such technologies.

### Heat engine modelling

Heat engines are technologies that convert heat into power, and organic Rankine cycle (ORC) systems are considered in this work. Steam Rankine cycle systems are not covered in this work as it is well established that the performance becomes unattractive for low-grade heat sources [7]. The performance of heat engines can be quantified by the thermal efficiency, defined as the ratio of the useful power output to the heat input:

$$\eta = \frac{\dot{W}}{\dot{Q}}, \tag{1}$$

which is bound by an upper theoretical limit achieved with an ideal, reversible Carnot cycle:

$$\eta_{\mathrm{rev}} = 1 - \frac{T_{\mathrm{c}}}{T_{\mathrm{h}}}. \tag{2}$$

The Carnot cycle is based on the assumption of the absence of internal and external irreversibilities. The first involves viscosity, intermolecular forces and frictions, while the latter accounts for the driving forces for heat transfer in the form of temperature losses. Therefore, the Carnot efficiency of any heat engine represents the maximum performance of any heat engine at operating with similar heat-source and heat-sink temperatures [24, 25]. On the other hand, endoreversible estimation of heat engines' performance was proposed to account for irreversibilities occurring in the heat transfer processes from the source to the engine and from the engine to the sink, while internal processes are assumed to be fully reversible [26, 27]. Novikov [27] and Chambadal [28] proposed the following equation to estimate the endoreversible heat engine's performance:

$$\eta_{\mathrm{er}} = 1 - \sqrt{\frac{T_{\mathrm{c}}}{T_{\mathrm{h}}}}. \tag{3}$$

Once the endoreversible efficiency is estimated, this value can be fed to a correlation relating it to published performance data proposed by Gangar et al. [6]. This correlation was developed after extracting the performance data of 34 different ORC systems:

$$\eta_{\mathrm{ORC}} = -0.93(\eta_{\mathrm{er}})^2 + 0.87\eta_{\mathrm{er}}\,. \tag{4}$$

An extended range of published performance data of 64 ORC systems ranging from 1 kW to 10 MW is collected to improve and simplify this correlation, which is then used in a second step to estimate the net generated work by the heat engine after taking into consideration the specific information of the heat delivered to the engine:

$$\dot{W}_{\mathrm{net}} = \eta_{\mathrm{ORC}}\,\dot{m}\left(h_{\mathrm{h,in}} - h_{\mathrm{h,out}}\right). \tag{5}$$

**Absorption chiller modelling**

Absorption chillers are technologies that transform heat into cooling, and their performance can be estimated using based on the endoreversible thermodynamics concept described in the heat engine modelling section. Novikov [27], Velasco et al. [6, 29] and Chen et al. [30] analysed the performance of absorption heat pumps with the aim of delivering an endoreversible estimation of their performance, and a relationship was proposed after validation. Blanchard [31] later extended this approach to account for the temperature drop across the heat exchangers in the heat pumps needed to act as a driving force for heat transfer through an empirical parameter ($\Delta T_{\mathrm{k}}$), and it was suggested to assign a value of 30 for it based on his review. Subsequently, based on the heat source and sinks temperatures, the COP is calculated based on:

$$COP_{\mathrm{er}} = \frac{\dot{Q}_{\mathrm{c}}}{\dot{Q}_{\mathrm{h}}} = \left(1 - \sqrt{\frac{T_0}{T_{\mathrm{h}}}}\right)\left(\frac{1}{1 - \frac{T_{\mathrm{c}}}{T_0 + \Delta T_{\mathrm{k}}}}\right). \tag{6}$$

A list of 30 chillers ranging from 53 to 530 kW from various manufacturers on the market is considered. Similar to the heat engines process, a comparison between reported performance data and estimated endoreversible COPs is used to obtain a similar correlation. Based on the specific WH data, the performance of the absorption chillers can be calculated. After determining the cooling duty generated in the chiller, the amount of produced coolant can be calculated from:

$$\dot{Q}_{\mathrm{c}} = COP_{\mathrm{AbsC}}\,\dot{Q}_{\mathrm{WH}} \tag{7}$$

### Brayton cycle system air intake cooling modelling

After determining the potential cooling capacity created from WHR through the absorption chiller, the cost and benefit of integrating that capacity into GTs will be studied. The performance impact resulting from air intake temperature variations is typically estimated using GT performance maps developed by the manufacturers, while different GTs react uniquely due to their system components and control schemes [32].

The improvement in performance of open-cycle gas turbines at a lower air intake temperature is illustrated in Figure 1. Operating at a lower air intake temperature corresponds to a slight decrease in heating rate, a reduction in compression shaft power requirements and an increase in power generated in the expansion process. As a result, this integration scheme is expected to yield an overall energy efficiency improvement, which is quantified by:

$$\eta_{\mathrm{GT}} = \frac{\dot{W}_{\mathrm{GT}}}{\dot{Q}} . \tag{8}$$

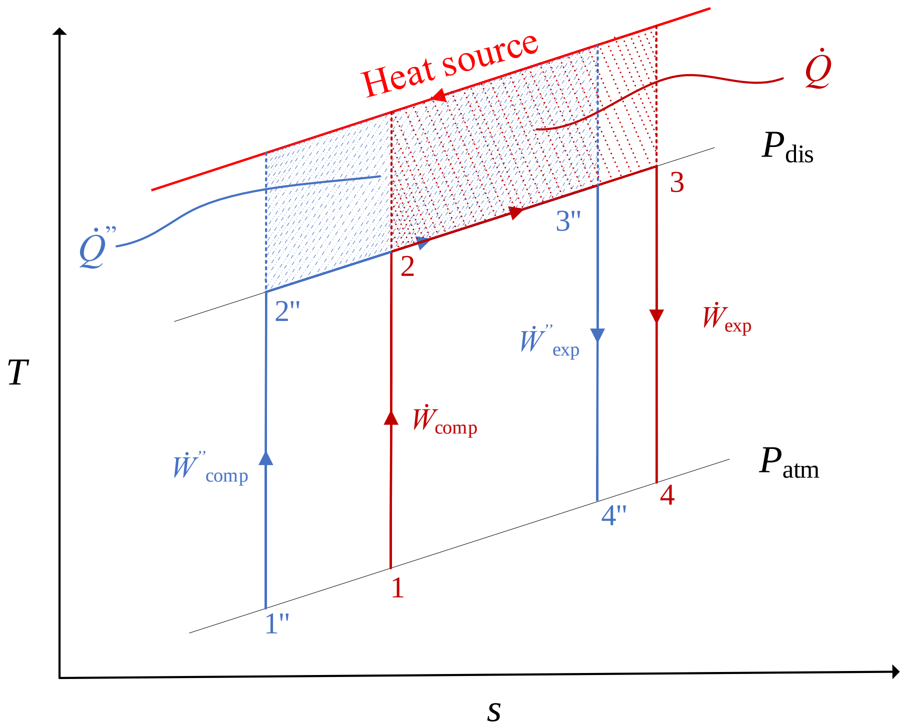


Figure 1. Brayton cycle performance enhancement by air intake cooling on a temperature-entropy (*T*-*s*) diagram.

The process schematic shown in Figure 2 illustrates the proposed configuration. In this process, the ambient temperature variation is known to have a linear relationship with both the work produced and the heat consumed by the GT system, as represented in the following equations [21, 32]:

$$\dot{W}_{\mathrm{GT}} = a + bT_0 , \tag{9}$$

$$\dot{Q} = \frac{\Delta H_{\mathrm{comb}}}{\dot{W}_{\mathrm{GT}}} = c + dT_0 , \tag{10}$$

where the constants, *a*, *b*, *c* and *d*, are parameters dependent on the performance maps of the GT, which can be obtained from manufacturers provided correlations, data fitting or rigorous modelling.

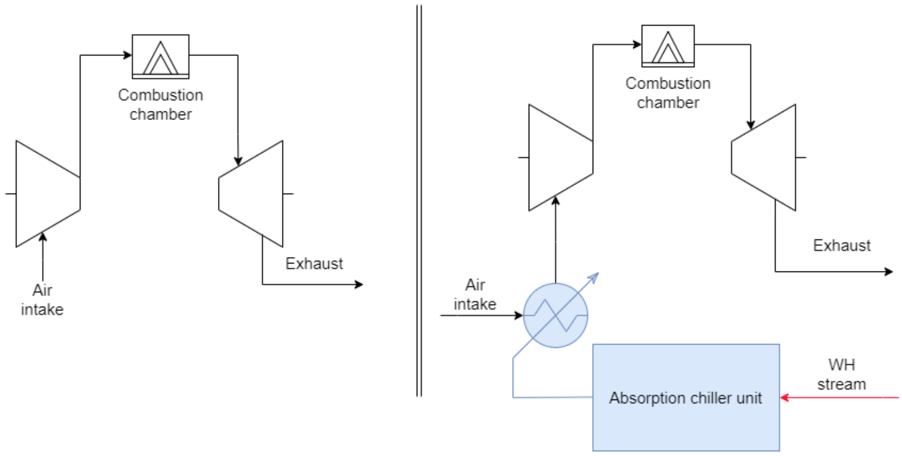


Figure 2. Schematic diagrams of the base-case GT system (left) where ambient air is processed, and the proposed scheme (right) where it is integrated with an absorption chiller unit.

**Gas compression improvement modelling**

Gas compression is essential in industrial process systems, which usually comes as a multistage process because the single-stage is limited to a flow rate of 1 $m^3$/s and a discharge pressure of 20 bar [21]. Consequently, interstage cooling is employed to protect the machinery's integrity and improve the overall compression efficiency, as illustrated in curves in Figure 3, which shows plots of a two-stages compression process.

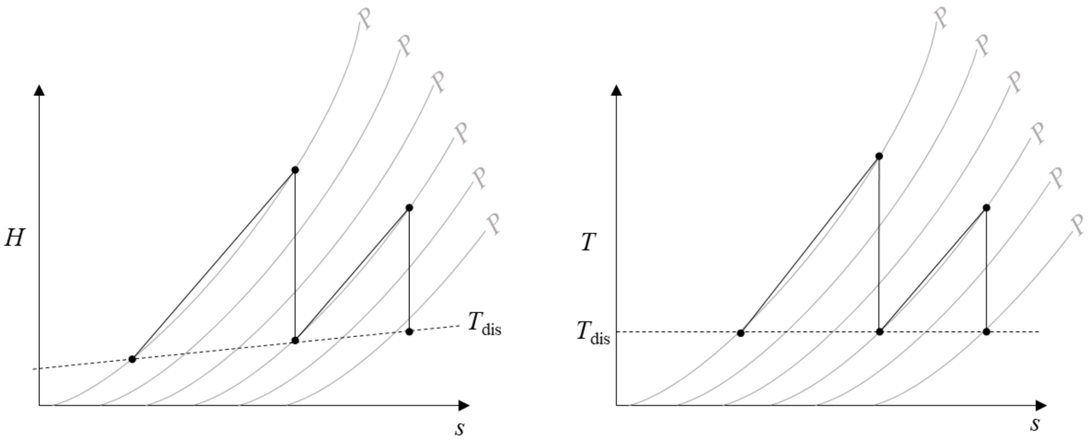


Figure 3. Schematics of a two-stage compression process on enthalpy-entropy (*H*-*s*) and temperature-entropy (*T*-*s*) diagrams.

The thermodynamic process of compression can be estimated polytropically, which links the compressor design to the gas properties. It is closer to reality than isentropic compression because it accounts for friction. The following equation provides an estimation of the compressor work at different suction temperatures [22, 33–38]:

$$\dot{W}_{\mathrm{comp}} = \frac{\dot{m}_{\mathrm{g}}}{M_{\mathrm{W}}} R T_{\mathrm{g}} Z_{\mathrm{g}} \frac{k}{k-1} [P_{\mathrm{r}}^{\frac{k-1}{k}} - 1]/\eta_{\mathrm{p}} \, . \tag{11}$$

The compressibility factor at the different temperatures and pressures can be obtained from the proper equations of state. The variation of this value is insignificant to small changes in temperature and pressure, as in the case of this particular scope [37]. The polytropic exponent (or the polytropic coefficient) ($k$) is a variable that is dependent on both the ratio of the heat capacities ($\gamma$) of the compressed gas mixture and the nominal polytropic efficiency ($\eta_{\mathrm{p}}$) of the compressor, which typically ranges between 0.76 and 0.78 for most centrifugal compressors [38, 39]:

$$k = \frac{1}{1 - \frac{\gamma - 1}{\gamma \eta_{\mathrm{p}}}}. \tag{12}$$

**Economic modelling**

As reviewed by Lemmens, the existing cost models used in evaluating process technologies are not accurate [40]. However, it is observed that studying the relative performance of such process technologies using a consistent economic evaluation methodology provides valuable indications from a comparison standpoint, which is the scope of this paper.

In this paper, the specific investment cost (SIC) is selected to estimate the capital costs (CAPEX) of the WHR systems. First, starting with ORC systems, Arvay et al. [41] provided the SIC from four different manufacturers ranging from $1,800/kW to $2,860/kW with an average of $2,390/ kW. Gangar et al. [6] also performed an economic evaluation for ORC systems against other WHR options and used an ISC of nearly $2,600/kW. Moreover, an extensive survey conducted by Lemmens revealed that the SICs reported in the literature were scattered and wide-ranged [40], which confirmed that the trend of ORC SIC decreases as the size increases for the existing ORC units, as shown in Figure 4.

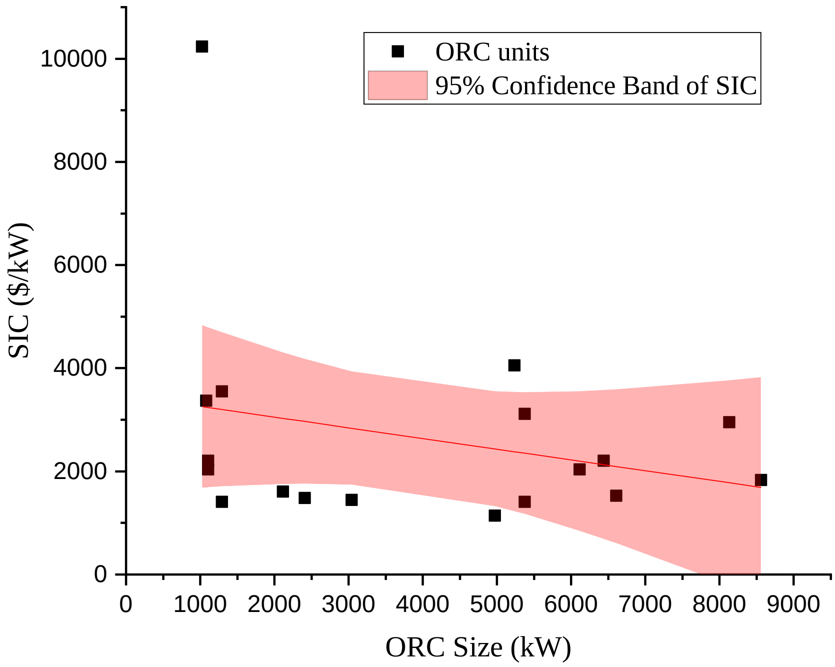


Figure 4. SICs of large-scale ORC units from the literature [40].

Therefore, in this work, two values of SIC are used to illustrate the envelope of ORC economic performance, which are $1,800/kW and $4,000/kW. Furthermore, according to the US department of energy (DOE), absorption chillers' CAPEX ranges between $750/kW and

\$1,960/kW of cooling capacity, with an average value of \$1,730/kW, after adjustment to the 2022 USD value [42]. Furthermore, it is estimated that the operations and maintenance costs for both ORC systems and absorption chillers are 1% of the CAPEX. Finally, the heat exchangers that transfer the cooling capacity are costed using the following equation, which could be applied to up to 2,000 $m^2$ exchangers [21]. This cost is updated from the 2010 USD value to the 2022 USD using the chemical engineering plant cost index (CEPCI) values shown in the assumptions table at the end of this section (Table 5).

$$CAPEX_{\text{cooler}} = 28000 + 54\,(\dot{Q}_{\text{cooler}})^{1.2} \tag{13}$$

**Case study selection and definition**

The case study addresses a scenario of a process site with an olefins plant and a utility system that provides the plant with heat, cooling, and power. The evaluation starts by using WH data of olefins plants quantified in the literature. Then, an illustration of a GT system within the sites utility, which satisfies the plant with power requirement, is selected to evaluate GT performance enhancement by integrating a WH-driven absorption chiller system, as shown in Figure 2. After that, WH-driven absorption system integrated with the olefins cracked gas compression (CGC) system is also evaluated as part of this comparative study, as shown in Figure 5. Finally, these two pathways are compared with power generated by the direct conversion of WH through ORC systems.

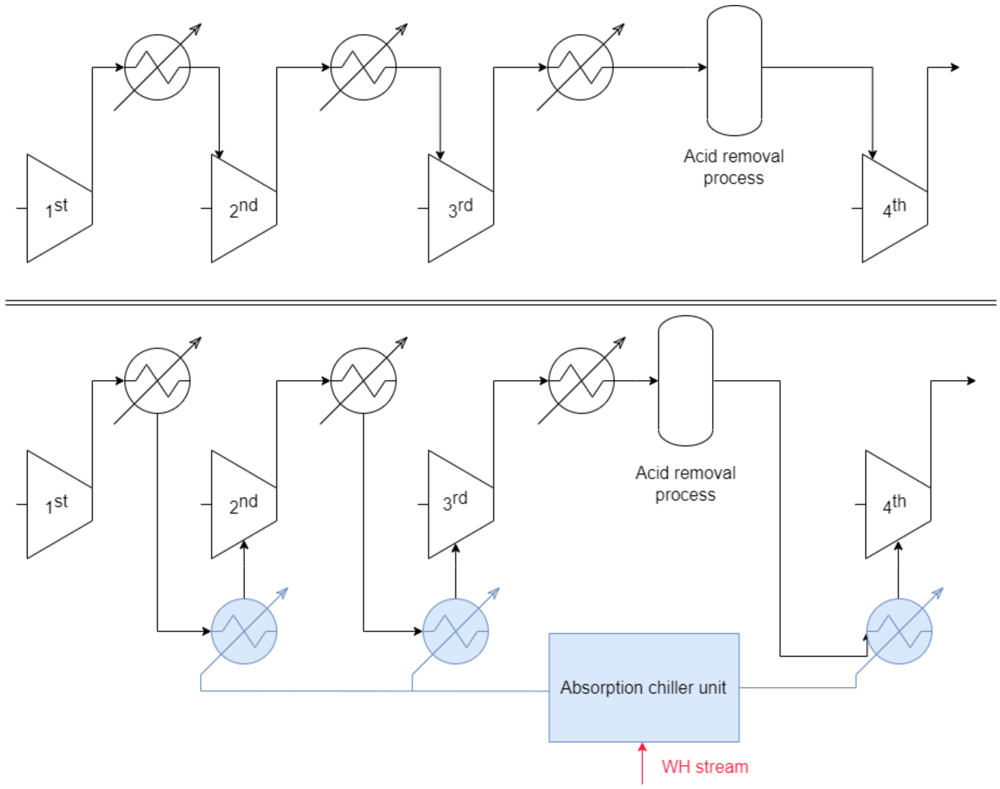


Figure 5. Schematic diagrams of the base case CGC system (top) where the cracked gas (CG) temperatures are maintained around ambient temperatures, and the proposed case (bottom) where the CG temperature drops below ambient levels depending on the absorption chiller unit capacity.

Waste heat data found in the literature is used to assess the alternative WHR pathways discussed in the previous sections. Moreover, data on an industrial gas turbine and industrial multistage compression system is obtained from the literature to conduct the proposed comparative study.

Marina et al. [43] conducted an extensive review on the European industrial waste heat, and the data for ethylene plants is extracted and summarised in Table 1.

Regarding the selected GTs, a 26 MW and a 125 MW GE model PG5371 (PA) are chosen for this case study to understand the impact of their capacities on the feasibility, as GTs sizes vary depending on the site requirements. Their performance correlations are summarised in Table 2 below, while the system configuration that is studied in this work is illustrated in Figure 2.

Table 1. Base case WH data [43].

| Case study parameters | Value | Units |
|---|---|---|
| WH stream | Condensate (water) | NA |
| WH $T$ | 124-114 | °C |
| WH outlet $T$ | 60 | °C |
| WH $\dot{m}$ | 140 | kg/s |
| WH $\dot{Q}$ | 1-10 | MW |

Table 2. GT performance coefficiencts [32, 44, 45].

| GT system parameters | 26 MW | 125 MW | |
|---|---|---|---|
| a | 29.04 | 109.4 | MW/°C |
| b | -0.19 | -0.62 | MW/°C |
| heat rate (c) | 3.41 | 98.7 | dimensionless |
| heat rate (d) | 0.01 | 0.13 | 1/°C |
| Air $C_p$ | 1 | 1 | kJ/kg K |
| Air inlet T | 35 | 35 | °C |
| $U$ | 0.25 | 0.25 | kW/m$^2$/K |

Olefins production by cracking is ranked as the largest energy-consuming process within the petrochemical sector [46, 47]. The cracked gas compression (CGC) system is estimated to contribute to the specific energy consumption of olefins plants by 15 to 22%, second only to the thermal energy used for cracking [48, 49]. Most of the interstage coolers yield gas streams that are at a near-ambient temperature, and such ambient conditions may lead to increased power requirements in regions of hot climates. Therefore, this particular multistage stage compressor system is selected for this case study to represent the compressor power consumption enhancement by WHR opportunities.

The CGC process stream data is shown in Table 3, which is taken from the work of Al-douri et al. [38] and Sharifzadeh et al. [50]. The typical nameplate capacity of olefins plants is around 0.5-1.3 million tonnes per year [48]. Therefore, a scenario representing this range of capacities is considered to address the performance of the different WHR schemes using the abovementioned methods.

The physical properties of this hydrocarbon mixture can be estimated using the Soave-Redlich-Kwong (SKR) equation of state [51, 52]. Consequently, the data required to compute the amount of shaft power at different gas temperatures are obtained and summarised in Table 4.

Table 3. Composition of the cracked gas compressor stream [38, 53].

| Gas composition | Mass flow rate (ton/year) | Mass fraction (%) | Mole fraction (%) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Hydrogen ($H_2$) | 73,400 | 5.1 | 42.0 |
| Methane ($CH_4$) | 124,400 | 8.7 | 9.0 |
| Acetylene ($C_2H_2$) | 15,900 | 1.1 | 0.7 |
| Ethylene ($C_2H_4$) | 969,300 | 67.9 | 40.0 |
| Ethane ($C_2H_6$) | 177,900 | 12.5 | 6.8 |
| Propylene ($C_3H_6$) | 15,900 | 1.1 | 0.4 |
| Vinylacytelene ($C_4H_4$) | 4,400 | 0.3 | 0.1 |
| Butadiene ($C_4H_6$) | 21,700 | 1.5 | 0.5 |
| Cyclopentadiene ($C_5H_6$) | 7,300 | 0.5 | 0.1 |
| Benzene ($C_6H_6$) | 17,300 | 1.2 | 0.3 |
| Hydrogen sulphide ($H_2S$) | 1,500 | 0.1 | 0.1 |
| Total | 1,429,000 | 100 | 100 |

Table 4. Base case cracked gas compression system parameters.

| Case study parameter | Value | Units |
|---|---|---|
| Number of compression stages | 4 | - |
| Compressed gases flow rate ($\dot{\boldsymbol{m}}_{\mathbf{gas}}$) | 1,429,000 | tons/year |
| Gases average molecular weight ($M_W$) | 16.52 | kg/kmol |
| Pressure ratio ($P_r$) | 2.2 | - |
| Heat capacity ratio ($\gamma$) | 1.29 | - |
| Nominal compressor polytropic efficiency ($\boldsymbol{\eta}_{\mathbf{p}}$) | 0.78 | - |

Finally, the assumptions related to the process systems, ambient conditions, and the economic data are summarised in Table 5. The analysis is performed under the steady-state assumption. Also, the heat exchangers used in the considered processes are assumed to be of a counter-current shell-and-tube type with no allowance for cross over heat transfer.

Table 5. Economic and system-level parameters.

| Economic assumptions | | | Process system assumptions | | |
|---|---|---|---|---|---|
| Plant lifetime | 20 | years | $\Delta T_{\mathrm{min}}$ | 5 | °C |
| Operational hours | 8000 | Hours/year | Heat sink T | 35 | °C |
| CW cost | 6 | \$/kW/year | Evaporator outlet T | 12 | °C |
| $C_e$ | 0.10 | \$/kWh | Max. CW return T | 45 | °C |
| CEPCI 2010 | 533 | - | | | |
| CEPCI 2022 | 701 | - | | | |

## RESULTS AND DISCUSSION

Linear fit correlations for ORC systems and absorption chillers data, shown in Figure 6, are produced based on the conducted survey. For ORC systems, the correlation between the reported efficiencies and their endoreversible efficiencies in Equation 14 has a coefficient of determination ($R^2$) value of 0.93, a standard deviation of 0.015, and an average deviation of 0.027. Similarly, a correlation between the absorption chiller units and their respective endoreversible COPs is formed by tuning the empirical parameter $\Delta T_k$, which was found to be

27, yielding a linear relationship as illustrated in Equation 15, with an $R^2$ value of 0.98, a standard deviation of 0.0657 and an average deviation of 0.0854.

As a result, the following simplified correlations are proposed for ORC systems and absorption chillers, respectively:

$$\eta_{\mathrm{ORC}} = 0.8\eta_{\mathrm{er}}\,, \tag{14}$$

$$COP_{\mathrm{AbsC}} = COP_{\mathrm{er}}\,. \tag{15}$$

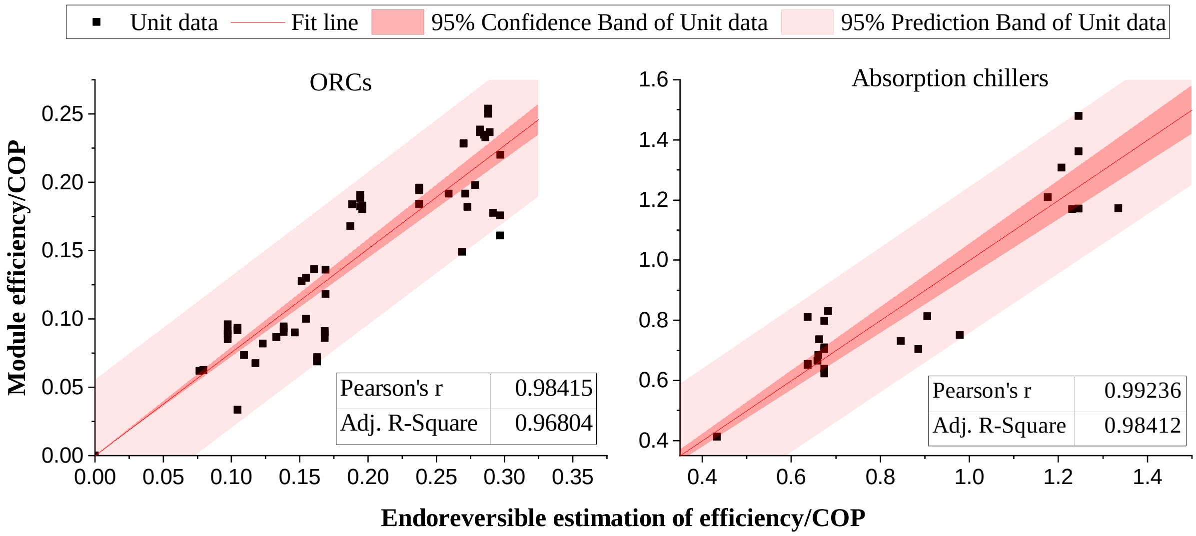


Figure 6. Correlation line fit, prediction and confidence boundaries for the conducted analysis, where the left graph illustrates the reported thermal efficiency of ORC 64 modules versus the estimated endoreversible thermal. The right ones show the same relationship for 24 absorption chiller module COPs.

Using the above relationships, the techno-economic performance of these two technologies for a given WH and heat sink conditions is estimated using the WH data shown in Table 1. To compare the difference between the potential of each of the considered integration schemes, the estimated power gain is illustrated in Figure 7. It can be seen that the enhancement of CGC power consumption through the integration with absorption chillers results in the highest amount of absolute power that can be saved, followed by the scheme of cooling the air intake system of the 125 MW GT. It can also be seen that the amount of absolute power gained from the ORC and air intake cooling of a 26 MW GT are relatively close. These findings align with previous studies that considered these technologies individually, addressed in the earlier sections. For instance, GTs enhancement results in additional power capacities up to 11% depending on the cooling capacities employed to cool the air intake. Also, it can be seen that a difference of 30 °C in the WH stream's temperature does not significantly impact the results. Also, it can be noted that there is a maximum amount of energy that can be recovered at each integration scheme that involves absorption chillers (GT power generation enhancement and CGC power consumption reduction routes). This is justified by the fact that there is always a limit to which the GT air intake and the process gas can be cooled, which is constituted by the cooling medium and the minimum approach temperatures.

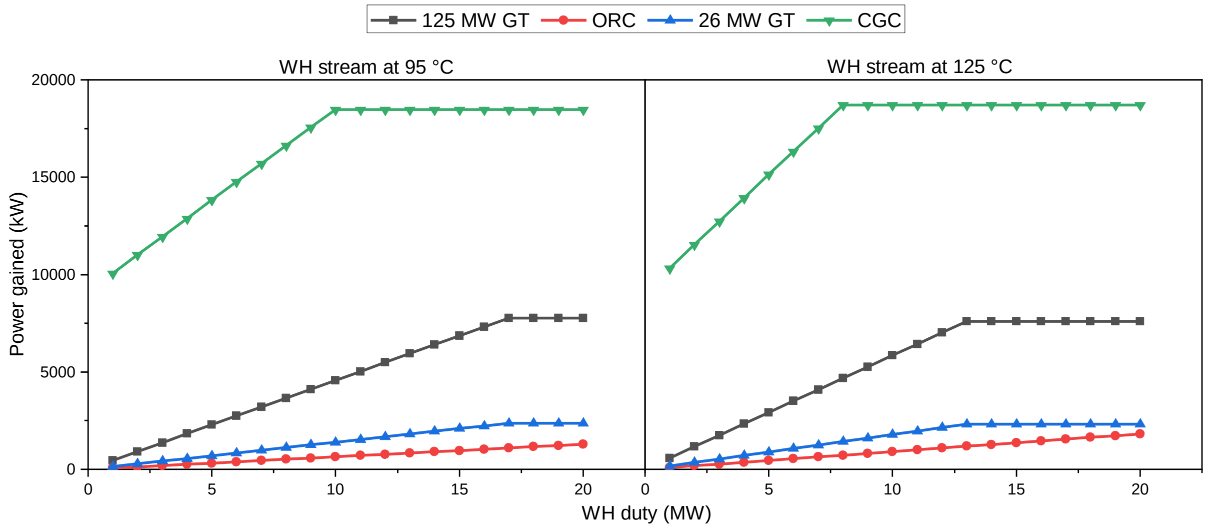


Figure 7. Estimated power gain from the considered WHR technologies at different temperatures and duties of the considered WH source.

After determining the potential of the WHR routes from power gain perspectives, the SICs can be estimated for the range of WH conditions reported in Table 1 for olefins plants. It can be seen from Figure 8 that the enhancement of a typical CGC system has a smaller range of SIC due to the substantial amount of power that can be gained through such an integration scheme. In addition, the GT size is found to have a profound impact on the estimated SIC, where a size of around 26 MW is expected to be the least costly (per kW) compared to the other options. On the other hand, GTs of more than 100 MW capacities are estimated to be more competitive and have the potential to outperform ORC systems from a SIC standpoint.

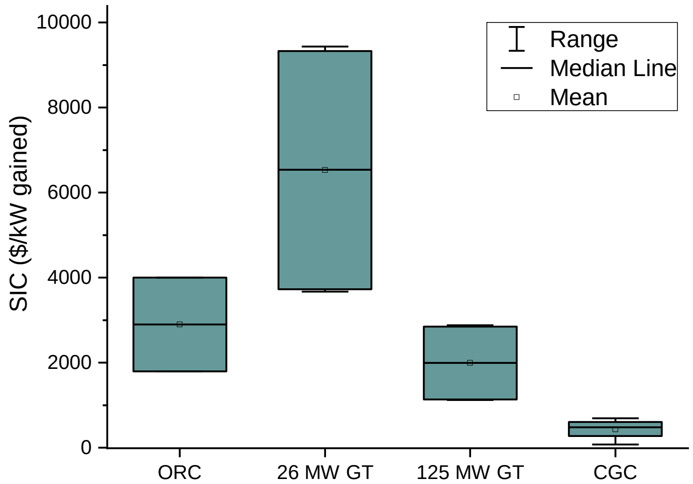


Figure 8. SICs of the considered options for WHR into power from a typical olefins plant.

If we turn now to assess the benefits side of the economic evaluation, Table 6 and Table 7 illustrate the range of the anticipated payback period for the four considered cases. The CGC integration scheme seems to outperform the other routes, while GT can compete when its size increases. It also can be seen that the changes to the WH conditions do not pose any notable impact on the payback periods. Furthermore, since this is a comparative study, if externalities assumptions, like electricity pricing, vary, the overall performance maps developed in this study are unlikely to change. However, such changes are expected to make the considered options more or less attractive depending on the changes to these assumptions.

Table 6. Estimated simple PBP (in years) of the four schemes when driven by a 90 °C WH stream.

| WH duty (MW) | ORC | | 26 MW GT | | 125 MW GT | | CGC | |
|---|---|---|---|---|---|---|---|---|
| | max. | min. | max. | min. | max. | min. | max. | min. |
| 1 | 5.3 | 2.3 | 13.7 | 5.2 | 3.8 | 1.5 | 0.2 | 0.1 |
| 5 | 5.3 | 2.3 | 13.5 | 4.9 | 3.7 | 1.4 | 0.6 | 0.2 |
| 10 | 5.3 | 2.3 | 13.5 | 4.9 | 3.7 | 1.4 | 0.9 | 0.4 |
| 15 | 5.3 | 2.3 | 13.5 | 4.9 | 3.7 | 1.4 | 0.9 | 0.4 |
| 20 | 5.3 | 2.3 | 13.5 | 5.0 | 3.7 | 1.5 | 0.9 | 0.4 |

Table 7. Estimated simple PBP (in years) of the four schemes when driven by a 125 °C WH stream.

| WH duty (MW) | ORC | | 26 MW GT | | 125 MW GT | | CGC | |
|---|---|---|---|---|---|---|---|---|
| | max. | min. | max. | min. | max. | min. | max. | min. |
| 1 | 5.3 | 2.3 | 13.6 | 5.0 | 3.8 | 1.5 | 0.2 | 0.1 |
| 5 | 5.3 | 2.3 | 13.5 | 4.9 | 3.7 | 1.4 | 0.7 | 0.3 |
| 10 | 5.3 | 2.3 | 13.5 | 4.9 | 3.7 | 1.4 | 0.9 | 0.4 |
| 15 | 5.3 | 2.3 | 13.5 | 5.0 | 3.7 | 1.4 | 0.9 | 0.4 |
| 20 | 5.3 | 2.3 | 13.5 | 5.0 | 3.7 | 1.4 | 0.9 | 0.4 |

## CONCLUSIONS

Waste heat recovery is an appealing area for industries to maximise the conservation of energy resources, which serves these industries by increasing their resilience to environmental sustainability constraints and the economic impact of volatility of energy prices. A portfolio approach to improving efficiency and reducing emissions benefits large industries with diverse processes. Therefore, this paper demonstrated the evaluation of a portfolio of WHR opportunities based on a data-driven technology-agnostic approach. This approach eliminated the need to make detailed design decisions, such as specifying the working fluids and the configuration of these technologies, at the stage of technology screening. Hence, it is expected to accelerate understanding of the potential of available opportunities. Moreover, the method was applied to a bulk chemicals plant as a case study to assess a portfolio of options to convert WH into power gained by reducing the consumption or increasing the production of existing assets. Modelling techniques have been discussed, and statistical, and energy analysis methods have been used to assess and estimate the selected technologies techno-economic performance.

In this study, the economic performance predictions showed that the SICs of the small-scale and large-scale GT performance enhancement range from 4000 to 9500 $/kW gained and from 1000 to 3000 $/kW gained, respectively. Also, the predicted SICs of enhancing a typical CGC system range from 100 to 700 $/kW gained. These were compared to the ORC SICs obtained from literature data which ranged from 2000 to 4000 $/kW gained. Moreover, it was found that the uncertainties in the CAPEX of WHR technologies translated into a minimal effect on the overall performance assessment using indicators such as a simple payback period. This can be owed to the large scales of power gains in some opportunities. Consequently, it can be deduced that the focus when evaluating WHR in large industries should be on externalities such as fuel and electricity prices.

Also, the chosen case study yielded performance maps of the opportunities evaluated, indicating that industrial WHR can be significantly advantaged by the large sizes of the systems in many process plants. The study identified that integrating WH-driven absorption chillers with a large-scale multistage compression system (e.g. the CGC) will pay back approximately three times faster than the stand-alone WH-driven ORC. In contrast, stand-alone ORC was found to pay back about three times faster than enhancing a relatively smaller GT that is integrated with WH-driven absorption chillers. Consequently, integration schemes involving larger systems was found to typically outperform the direct routes of WHR, i.e. a stand-alone WH-driven ORC, in energy-intensive industries. Additionally, it can be concluded that if the existing GT system is less than 100 MW, and the interstage cooling of the compression system cannot be further maximised, direct WHR into power through ORCs still represents an attractive option with payback periods between 2 to 5 years for the considered power tariff.

Finally, a natural progression of this work would be to compare the results of the data-driven technology-agnostic approach with the detailed modelling approach to understand the limitation of such an approach compared to traditional first-law modelling approaches. This includes a potential comparison between the used costing models with comprehensive individual component costing models. Furthermore, it is suggested to add performance indicators such as emissions abatement costs to evaluate the options holistically.

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## NOMENCLATURE

### Abbreviations

| | | | |
|---|---|---|---|
| AF | annualisation factor | min | minimum |
| CAPEX | capital expenditure | ORC | organic Rankine cycle |
| CGC | cracked gas compressor | PBP | payback period |
| COP | coefficient of performance | SIC | specific investment cost |
| GT | gas turbine | WH | waste heat |
| max | maximum | WHR | waste heat recovery |

### Symbols

| | | | |
|---|---|---|---|
| $C_e$ | electricity tariff [$/kWh] | $P_r$ | pressure ratio [-] |
| $c_p$ | specific heat capacity at constant pressure [J/kg/K] | $\dot{Q}$ | heat flow rate [W] |
| $c_v$ | specific heat capacity at constant volume [J/kg/K] | $R$ | ideal gas constant [J/K/mol] |
| $h$ | specific enthalpy [J/kg] | $s$ | specific entropy [J/kg] |
| $k$ | polytropic coefficient or polytropic exponent [-] | $T$ | temperature [°C, K] |
| $\dot{m}$ | mass flow rate [kg/s] | $U$ | overall heat transfer coefficient [W/m$^2$/K] |
| $M_W$ | molecular weight [kg/mol] | $\dot{W}$ | power [W] |
| $\eta$ | efficiency [-] | $Z$ | compressibility factor [-] |
| $P$ | pressure [bar, Pa] | $\gamma$ | the ratio between $c_p$ and $c_v$ |

**Subscripts/superscripts**

| | | | |
|---|---|---|---|
| atm | atmospheric | h | heat source |
| c | heat sink | k | driving force temperature difference |
| comp | compression | p | polytropic |
| cw | cooling water | rev | reversible |
| dis | discharge | net | net |
| er | endoreversible | 0 | ambient conditions |
| exp | expansion | “ | after cooling state |
| g | gas | Δ | difference |

## REFERENCES


1. US Energy Information Administration. International Energy Outlook, 2016.
2. International Energy Agency (IEA). Energy Technology Perspectives, 2017.
3. International Energy Agency (IEA). Capturing the Multiple Benefits of Energy Efficiency, 2015. https://doi.org/10.1787/9789264220720-en.
4. BSC Incorporated. Waste Heat Recovery: Technology Opportunities in the US Industry, 2008.
5. Element Energy Limited. The Potential for Recovering and Using Surplus Heat from Industry, 2014.
6. Gangar N., Macchietto S., and Markides C. N., Recovery and utilization of low-grade waste heat in the oil-refining industry using heat engines and heat pumps: An international technoeconomic comparison, Energies, vol. 13, no. 10, 2020. https://doi.org/10.3390/en13102560.
7. Markides C. N., The role of pumped and waste heat technologies in a high-efficiency sustainable energy future for the UK, Appl. Therm. Eng., vol. 53, no. 2, pp. 197–209, 2013. https://doi.org/10.1016/j.applthermaleng.2012.02.037.
8. The European Chemical industry Facts and Figures (CEFIC), Chemical industry - Facts and Figures, 2022. https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/energy-consumption/.
9. Unamba C. K., Sapin P., Li X., Song J., Wang K., Shu G., Tian H., Markides C. N., Operational optimisation of a non-recuperative 1-kWe organic Rankine cycle (ORC) engine prototype, Appl. Sci., vol. 9, no. 15, pp. 1–19, 2019. https://doi.org/10.3390/app9153024.
10. Gokarakonda S., Hennicke P., Moore C., Thomas S., and Venjakob M., Relevant technologies for the energy transition in Germany, with potential relevance for Japan: a preparatory study in the framework of the GJETC project, 2018.
11. Markides C. N., Low-concentration solar-power systems based on organic rankine cycles for distributed-scale applications: Overview and further developments, Front. Energy Res., vol. 3, no. DEC, pp. 1–16, 2015. https://doi.org/10.3389/fenrg.2015.00047.
12. Catalan L., Araiz M., Aranguren P., and Astrain D., Computational study of geothermal thermoelectric generators with phase change heat exchangers, Energy Convers. Manag., vol. 221, p. 113120, 2020. https://doi.org/10.1016/j.enconman.2020.113120.
13. Mulla R. and Dunnill C. W., Powering the Hydrogen Economy from Waste Heat: A Review of Heat-to-Hydrogen Concepts, ChemSusChem, vol. 12, no. 17, pp. 3882–3895, 2019. https://doi.org/10.1002/cssc.201901426.
14. International Energy Agency (IEA), Natural Gas-Fired Power, 2021. https://www.iea.org/reports/natural-gas-fired-power.

15. Bhargava R. K., Meher-Homji C. B., Chaker M. A., Bianchi M., Melino F., Peretto A., Ingistov S., Gas turbine fogging technology: A state-of-the-art review - Part II: Overspray fogging - Analytical and experimental aspects, J. Eng. Gas Turbines Power, vol. 129, no. 2, pp. 454–460, 2007. https://doi.org/10.1115/1.2364004.
16. Chaker M. A. and Meher-Homji C. B., Effect of water temperature on the performance of gas turbine inlet air-fogging systems, in Proceedings of the ASME Turbo Expo: Turbine Technical Conference and Exposition GT2013, 2013, vol. 5 A, no. m, pp. 1–13, https://doi.org/10.1115/GT2013-95956.
17. Mostafa M., Eldrainy Y. A., and EL-Kassaby M. M., A comprehensive study of simple and recuperative gas turbine cycles with inlet fogging and overspray, Therm. Sci. Eng. Prog., vol. 8, no. June, pp. 318–326, 2018. https://doi.org/10.1016/j.tsep.2018.09.006.
18. Kwon H. M., Kim T. S., Sohn J. L., and Kang D. W., Performance improvement of gas turbine combined cycle power plant by dual cooling of the inlet air and turbine coolant using an absorption chiller, Energy, vol. 163, pp. 1050–1061, 2018. https://doi.org/10.1016/j.energy.2018.08.191.
19. Popli S., Rodgers P., and Eveloy V., Gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry, Appl. Therm. Eng., vol. 50, no. 1, pp. 918–931, 2013. https://doi.org/10.1016/j.applthermaleng.2012.06.018.
20. Cao Y., Habibi H., Zoghi M., and Raise A., Waste heat recovery of a combined regenerative gas turbine - recompression supercritical $CO_2$ Brayton cycle driven by a hybrid solar-biomass heat source for multi-generation purpose: 4E analysis and parametric study, Energy, vol. 236, p. 121432, 2021. https://doi.org/10.1016/j.energy.2021.121432.
21. Smith R., Chemical Process Design and Integration, Second edition. Chichester: Wiley, 2016.
22. Bloch H. P., Compressors and modern process applications. Hoboken, N.J: Wiley-Interscience, 2006.
23. Porreca L., Influence of inter-coolers technologies on the performance of isotherm centrifugal compressors, in Asia Turbomachinery & Pump Symposium, 2018. https://hdl.handle.net/1969.1/172510.
24. Winterbone D. E., Advanced thermodynamics for engineers. London: Arnold, 1996.
25. Rogers G. F. C. and Mayhew Y. R., Engineering thermodynamics : work and heat transfer , 4th ed. London: Longman, 1992.
26. Hoffmann K. H., Burzler J. M., and Schubert S., Endoreversible thermodynamics, J. Non-Equilibrium Thermodyn., vol. 22, no. 4, pp. 311–355, 1997. https://doi.org/10.1515/jnet.1997.22.4.311.
27. Novikov I. I., The efficiency of atomic power stations (a review), J. Nucl. Energy, vol. 7, no. 1–2, pp. 125–128, 1958. https://doi.org/10.1016/0891-3919(58)90244-4.
28. Chambadal P., Les centrales nucléaires, no. 4. Paris, Frans: Armand Colin, 1957.
29. Velasco S., Roco J. M. M., Medina A., and Hernández A. C., New performance bounds for a finite-time carnot refrigerator, Phys. Rev. Lett., vol. 78, no. 17, pp. 3241–3244, 1997. https://doi.org/10.1103/PhysRevLett.78.3241.
30. Yan Z. and Chen J., An optimal endoreversible three-heat-source refrigerator, J. Appl. Phys., vol. 65, no. 1, pp. 1–4, 1989. https://doi.org/10.1063/1.342570.
31. Blanchard C. H., Coefficient of performance for finite speed heat pump, J. Appl. Phys., vol. 51, no. 5, pp. 2471–2472, 1980. https://doi.org/10.1063/1.328020.
32. Varbanov P. S., Doyle S., and Smith R., Modelling and optimization of utility systems, Chem. Eng. Res. Des., vol. 82, no. 5, pp. 561–578, 2004. https://doi.org/10.1205/026387604323142603.
33. ASME PTC 10, “Performance Test Code on Compressors and Exhausters.” American Society of Mechanical Engineers (ASME), p. 189, 1997.

34. Sandberg M. R., A More Detailed Explanation of the Sandberg-Colby Method for the Evaluation A More Detailed Explanation of the Sandberg-Colby Method for the Evaluation of Centrifugal Compressor Thermodynamic Performance, 2020. https://doi.org/10.13140/RG.2.2.15841.66401.
35. Golden S. W., Fulton S. A., and Hanson D. W., Understanding centrifugal In a connected process system , expensive changes to the compressor and driver examples of cost effective ways of increasing compressor suction pressure, 2002. https://www.revamps.com/articles/understanding-centrifugal-compressor-performance.
36. Ul Haq S. E., Uddin F., Taqvi S. A. A., Naqvi M., and Naqvi S. R., Multistage carbon dioxide compressor efficiency enhancement using waste heat powered absorption chillers, Energy Sci. Eng., vol. 9, no. 9, pp. 1373–1384, 2021. https://doi.org/10.1002/ese3.898.
37. Coker A. K., Chapter 18 - Compression Equipment (Including Fans), in Ludwig's Applied Process Design for Chemical and Petrochemical Plants, Fourth edi., Coker A. K., Ed. Boston: Gulf Professional Publishing, pp. 729–978, 2015.
38. Al-Douri A., Kazantzi V., Eljack F. T., Mannan M. S., and El-Halwagi M. M., Mitigation of operational failures via an economic framework of reliability, availability, and maintainability (RAM) during conceptual design, J. Loss Prev. Process Ind., vol. 67, no. June, p. 104261, 2020. https://doi.org/10.1016/j.jlp.2020.104261.
39. Couper J. R., Penney W. R., Fair J. R., and Walas S. M., Chemical process equipment selection and design , Rev. 2nd ed. Burlington, MA ; Elsevier Butterworth-Heinemann, 2009.
40. Lemmens S., Cost engineering techniques & their applicability for cost estimation of organic rankine cycle systems, Energies, vol. 9, no. 7, 2016. https://doi.org/10.3390/en9070485.
41. Arvay P., M. Muller R., and Ramdeen V., Economic Implementation of the Organic Rankine Cycle in Industry, in ACEEE Summer Study on Energy Efficiency in Industry, vol. 05, no. 02, pp. 12–22, 2011.
42. United States Department of Energy, "Absorption Chillers for CHP Systems," 2017.
43. Marina A., Spoelstra S., Zondag H. A., and Wemmers A. K., An estimation of the European industrial heat pump market potential, Renew. Sustain. Energy Rev., vol. 139, p. 110545, 2021. https://doi.org/10.1016/j.rser.2020.110545.
44. Brooks F. J., "GE Gas Turbine Performance Characteristics," 2006.
45. Plis M. and Rusinowski H., Modelling and simulation of the effect of ambient parameters on the performance of a combined cycle gas turbine power plant, in Proceedings of the 17th International Carpathian Control Conference (ICCC), pp. 590–595, 2016. https://doi.org/10.1109/CarpathianCC.2016.7501165.
46. Ozokwelu D., Porcelli J., and Akinjiola P., Exergy analysis: A powerful tool for identifying process inefficiencies in the US Chemical Industry, Off. Energy Effic. Renew. Energy US Dep. Energy, 2006.
47. Sardarmehni M., Tahouni N., and Panjeshahi M. H., Benchmarking of olefin plant cold-end for shaft work consumption, using process integration concepts, Energy, vol. 127, pp. 623–633, 2017. https://doi.org/10.1016/j.energy.2017.03.066.
48. Ren T., Patel M., and Blok K., Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes, Energy, vol. 31, no. 4, pp. 425–451, 2006. https://doi.org/10.1016/j.energy.2005.04.001.
49. Hirata K. and Kakiuchi H., Energy saving for ethylene process by Adsorption Heat Pump, Appl. Therm. Eng., vol. 31, no. 13, pp. 2115–2122, 2011. https://doi.org/10.1016/j.applthermaleng.2011.03.031.

50. Sharifzadeh M., Rashtchian D., Pishvaie M. R., and Thornhill N. F., Energy Induced Separation Network Synthesis of an Olefin Compression Section: A Case Study, Ind. Eng. Chem. Res., vol. 50, no. 3, pp. 1610–1623, 2011. https://doi.org/10.1021/ie100359a.
51. Aspen Technology, Aspen Physical Property System: Physical Property Methods, 2013.
52. Wang T., Ye Z., Wang X., Li Z., and Du W., Improved distributed optimization algorithm and its application in energy saving of ethylene plant, Chem. Eng. Sci., vol. 251, p. 117449, 2022. https://doi.org/10.1016/j.ces.2022.117449.
53. AlNouss A., Kazi M. K., Mohammed F., and Eljack F., Integrated Data (i-Data), Mining and Utilization Approach for Effective Flare Management Strategies, Ind. Eng. Chem. Res., vol. 56, no. 10, pp. 2789–2803, 2017. https://doi.org/10.1021/acs.iecr.6b01774.