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Electricity demand reduction through waste heat recovery in olefins plants based on a technology-agnostic approach

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ABSTRACT

Developing systematic approaches for the identification of optimal WHR options in industrial applications is key to reducing plant-scale energy demands. In particular, electricity consumption accounts for more than half of industrial energy use, and its share is expected to grow with progressive electrification. In this paper, industrial WHR technologies including organic Rankine cycle (ORC) and absorption systems are investigated, and tools are developed to understand the sustainability and techno-economic impact of integrating these technologies within industrial processes and facilities. We specifically propose a data-driven technology-agnostic approach to evaluate the use of heat engines, which can in practice be ORC systems, and thermally-driven (i.e., absorption) heat pumps in the context of industrial WHR for plant-scale electricity demand reduction. The aim of this work is to explore three pathways for achieving efficiency improvements in bulk chemicals plants, represented here by olefins production facilities: (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 for five different countries representing a diverse portfolio of climates, technical and economic parameters (including utility prices), using fine-tuned thermodynamic and market-based costing models. The results reveal that the proposed approach has the potential to reduce emissions by between 5,000 tCO_2(eq.)/year and 101,500 tCO_2(eq.)/year depending on the scenario. The marginal abatement cost of the proposed solutions ranges from −1,200 $/$tCO_2$(eq.) to −35 $/$tCO_2$(eq.), with a payback time between 1.5 and 8 years depending on the scenario considered.

1. Introduction

The industrial sector is responsible for nearly half of the global energy demand, which is primarily sourced from fossil-fuel sources [1]. Within the industrial sector, according to the International Energy Agency (IEA), chemical and petrochemical processes are the largest consumers of energy, with a slight increase forecasted in the medium term [2]. The IEA estimates that 40% of the contribution required to achieve the Paris agreement two-degree scenario targets are energy efficiency measures, which are also necessary for mitigating other environmental and social burdens, beyond emissions, such as air pollution and energy security [2,3]. Thanks to advancements in industrial energy efficiency technologies and practices, notable improvements have been made to plant energy intensity over the last couple of decades. However, it is estimated that 17% of the UK's industrial energy consumption ends up as waste heat (WH) that is not further utilised. Likewise, WH is estimated to amount to one-fifth of the energy consumed by the industrial sector in the US, and up to 15% of Europe's industrial sector energy consumption could be reduced by exploiting WH [4–7]. Meanwhile, electricity consumption represented around 56% of the EU27 chemical industry's total energy use in 2019, and this is expected to increase as the industry embarks on the electrification transition [8].

In particular, steam cracking olefin plants produce hot condensate equivalent to roughly three to four times their annual olefins production. This hot condensate is typically rejected via condensate return systems without recovering the valuable thermal energy content, and in fact, energy is being spent in the form of electricity to deal with this waste heat stream. In the EU, such streams are found to be responsible for generating around 7,000 TJ of WH annually [9].

1.1. Direct conversion of WH to power

The research of converting low-grade heat into power became a

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Nomenclature

A	area [m^2]
a, b, c	Substance-dependant constants
AF	annualisation factor
C	capital cost [$]
CAPEX	capital expenditure
C_e	electricity tariff [$/kWh]
CEPCI	chemical engineering plant cost index
CGC	cracked gas compressor
COP	coefficient of performance
c_p	specific heat capacity at constant pressure [J/kg/K]
c_v	specific heat capacity at constant volume [J/kg/K]
CW	cooling water
d	gas turbine heat rate-correlating parameter [1/°C]
EF_e	electricity emissions factor [$kgCO_2$(eq.)/kWh]
EF_g	fuel gas emissions factor [$kgCO_2$(eq.)/kWh]
E_{GHG}	emissions reduction potential [tCO_2(eq.)/year]
ETS	emissions trading scheme
GT	gas turbine
h	specific enthalpy [J/kg]
i	interest rate [%]
k	polytropic coefficient or polytropic exponent [-]
LMTD	log-mean temperature difference
M	molecular weight [kg/mol]
$\dot{m}$	mass flow rate [kg/s]
MAC	marginal abatement cost [$/$tCO_2$(eq.)]
MACC	marginal abatement cost curve
n	system lifetime [years]
OH	operational hours [hours/year]
OPEX	operational expenditure
ORC	organic Rankine cycle
P	pressure [bar, Pa]
PBT	payback time [years]
$\dot{Q}$	heat flow rate [W]
R	universal gas constant [J/K/mol]
r_P	pressure ratio [-]
s	specific entropy [J/kg]
SIC	specific investment cost [$/kW]
SRK	Soave-Redlich-Kwong
T	temperature [°C, K]
TAC	total annualised cost [$/year]
U	overall heat transfer coefficient [W/m^2/K]
V	molar volume [m^3/mol]
$\dot{W}$	power [W]
WH	waste heat
WHR	waste heat recovery
Z	compressibility factor [-]

Greek symbols

α	gas turbine power-correlating parameter [-]
β	gas turbine power-correlating parameter [1/°C]
Δ	difference
ε	gas turbine heat rate-correlating parameter [-]
γ	the ratio between c_p and c_v
η	efficiency [-]

Subscripts/superscripts

AbsC	absorption chiller
atm	atmospheric
c	cold stream
comp	compression
cw	cooling water
dis	discharge
er	endoreversible
exp	expansion
g	gas
h	hot stream
in	inlet
int	intermediate stream
k	driving force
out	outlet
p	polytropic
rev	reversible
net	net
0	ambient conditions
"	after cooling state
ZO	zero-th order

classic theme within which several technologies have reached a technology readiness level (TRL) of 9, demonstrating their maturity and applicability to commercial operations [10,11]. These include thermoelectric generators (TEGs) and steam and organic Rankine cycle (ORC) systems. It has been established that ORC systems 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 [6,7,12–14]. Therefore, the focus of this research theme has been shifted to the ORC configuration, working fluids selection, and part-load optimisation [15]. However, other options for the exploitation of industrial WH by indirectly exploiting it to reduce power demand 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.

1.2. Gas turbine performance enhancement through waste heat recovery

Gas turbines (GTs) are becoming favoured over coal-fired plants for power generation due to their high efficiency, low emissions, continuity and flexibility. Therefore, GTs adoption is growing and is not expected to peak before the middle of the 21st century [16]. However, their performance is known to be influenced by ambient conditions, especially in hot climates where it deteriorates. Higher temperatures at a given location can reduce the local air density, resulting in a decrease in the air mass flow entering the gas turbine compressor. This reduction ultimately leads to a decrease in the power output and efficiency of the gas turbine [17–19]. An increase in temperature above international organisation for standardisation (ISO) conditions can result in a significant reduction in power output and efficiency. Studies indicate that the gas turbine power output can decrease by up to 22% and that the thermal efficiency can decrease by approximately 0.06% for every degree Celsius rise in temperature above ISO conditions. This demonstrates the sensitivity of gas turbine performance to changes in ambient temperature [20,21], and why it is essential to consider the various climates and ambient temperatures.

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, Zare [22] found that the impact of cooling GT air intake through the integration with absorption chillers resulted in an increase in the net power and exergy efficiency by 30% and a reduction in the levelised cost of electricity by 23%. Additionally, Kwon et al. studied enhancing a GT combined cycle system by integrating an exhaust-driven absorption chiller system for air cooling [23]. The authors studied two configurations and reported an estimated increase of

8% in the power generation and payback periods of less than three years.

Also, other studies [24,25] proposed novel technologies that improve the relative power output of gas turbines through turbine air inlet cooling. However, it can be noticed that the vast majority of research found in the literature focused primarily on optimising the configuration of GTs by capturing the WH generated by the GT system itself (e.g., Refs. [26–28]), while the opportunity to integrate GTs with WH from wider site utility systems has not been sufficiently addressed. More specifically, an assessment that includes the other comparable WHR pathways is found to be a gap in the literature.

1.3. Multistage compression enhancement through WHR

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 rate exceeds 90 m^3/s and with required discharge pressure up to 700 bar, centrifugal compressors can be found in nearly 60 different petrochemicals manufacturing processes, which leads to a substantial contribution to the total energy consumption [29,30]. Compressors consume a significant amount of energy, and consequently improving their energy efficiency performance remains a compelling area of improvement. For instance, in air separation units, three-fifths of the overall power consumption is allocated to the compressor shaft power [31]. Consequently, the motivation to improve compression efficiency has increased, especially for large-scale systems. Interstage cooling represents a compelling opportunity to reduce power consumption by compression cost-effectively.

As indicated in Ref. [31], a 5% increase in the capacity of interstage cooler could lead to a reduction in shaft power consumption by more than 0.6% for a three-stage compressor. Moreover, Zhang et al. [32] investigated the integration of cryogenic air separation's multistage compression system with thermally-driven refrigeration cycles that recovers heat from the compression process to reduce the power demand. The analysis revealed that when the ambient temperature was 25 °C, a reduction of 7.4% in compression power was achieved. 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 capacities. Therefore, this is also selected as the intended scope of this paper, along with the other opportunities to understand their performance in different scenarios.

1.4. Data-driven technology-agnostic modelling

This paper intends to build and utilise data sets of the performance of commercially available units of the technologies selected within the scope of work. Then, these sets of data are going to be compared and correlated with previously established performance estimation relationships of these technologies with the aim of proposing new ones that tracks the collected data. This atypical approach to the modelling and evaluation of WHR technologies is different from the typical one which focuses on rigorous modelling. Developing such rigours models involves the specification of many factors, such as the configuration, working fluids, and types of equipment used. However, many of these decisive factors are unknown at the concept screening stage, which requires a number of assumptions that inherently lead to 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]. In addition, the use of such data-driven thermodynamic models enables the potential end-users of such technologies to track their market performance values, and helps in accounting for closer-to-reality performance estimation for their intended applications.

Additionally, as the deployment of these technologies has been on an increasing trajectory, the opportunity to improve the accuracy of the performance prediction becomes more evident. This is because modelling results can be correlated with the published performance data. The application of such empirical correlations has not been extensively explored in the literature. An example of such analysis was conducted by Gangar et al. [6]. However, the scope of that study involved only organic Rankine cycle (ORC) systems and mechanical vapour-compression heat pumps for a different scope of applications with a different portfolio of performance indicators.

In summary, this paper brings a unique contribution to the field by highlighting several innovative aspects of its approach. Firstly, it introduces the utilisation of waste heat from sources other than the commonly used for compression or gas turbine systems enhancements, providing a new perspective on the potential for energy efficiency improvement. Secondly, it includes emissions reduction potential in the cost-benefit analysis, providing a more comprehensive assessment of the systems' performance. Thirdly, the study presents a comprehensive analysis of ORC systems with compression and GT systems enhancement by absorption chillers integration, as well as their techno-economic and emission reduction performance for different scenarios. This allows for a more thorough understanding of the potential of these systems. Lastly, the authors have employed a technology-agnostic, data-driven approach rather than traditional modelling techniques to achieve a more market-tracking analysis of ORC and absorption chillers performance estimation. To the best of the authors' knowledge, this study is the first to present a comprehensive and unified framework for evaluating these systems for the minimisation of olefins plants' hot condensate WHR, providing confidence in the conclusions drawn from the analysis. Furthermore, this study serves as a case study of the proposed approach, which can be extended to other applications.

2. 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 olefins plants. Second, the derived energy performance correlations are utilised as inputs for a techno-economic performance appraisal applied to a case study from the bulk chemicals industry to address the advantages of such technologies.

2.1. Heat engines

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

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

and is bound by an upper theoretical limit achieved by an ideal, reversible Carnot cycle, which depends on the available (external) heat source and sink temperatures:

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

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, Carnot efficiency of any heat engine represents the maximum performance of any heat engine operating with the same heat-source and heat-sink temperatures [33,34]. On the other hand, an 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 [35,36]. Novikov [36] and Chambadal [37] proposed an expression to estimate the thermal efficiency of endoreversible heat engines:

$$\eta_{er} = 1 - \sqrt{\frac{T_c}{T_h}}. \tag{3}$$

Once the endoreversible efficiency is estimated, this can be used in a correlation relating it to published performance data, as proposed by Gangar et al. [6], who developed such a correlation after extracting performance data relating to 34 commercially-available ORC systems:

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

Here, an extended range of published performance data of 64 ORC systems with capacities ranging from 1 kW to 10 MW is collected to extend the predictive power of this correlation. In a second step, we can estimate the net generated work by the heat engine after taking into consideration the specific information of the heat delivered to the engine:

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

Despite using a technology-agnostic approach to model the ORC systems without specifying design parameters related to the working fluid state and conditions, it is essential to ensure that the modelled ORC systems are technically feasible. Technical feasibility in the context of this work refers to meeting two key conditions. The first constraint is to adhere to the range of data collected, which is used to derive any correlation that will be discussed later in the paper. Therefore, the heat source temperature must be at least 80 °C and not less than 360 °C. The second constraint is to adhere to the limits of temperature boundaries around the cycle, as shown in Fig. 1, i.e., the difference between the heat-source inlet temperature and cooling-medium outlet temperature must be 20 °C or higher. Similarly, the difference between the heat-source outlet temperature and cooling-medium supply stream temperature is constrained to be 15 °C or higher.

2.2. Absorption chillers

Absorption chillers transform heat into cooling, and their performance can be estimated based on the endoreversible thermodynamics concept described in the heat engine modelling section. Novikov [36], Velasco et al. [6,38] and Yan et al. [39] assessed absorption chillers with the aim of delivering an endoreversible estimation of their performance, and a relationship was proposed after validation. Blanchard [40] 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 (ΔT_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 from:

$$COP_{er} = \frac{\dot{Q}_c}{\dot{Q}_h} = \left(1 - \sqrt{\frac{T_{int}}{T_h}}\right)\left(\frac{1}{1 - \frac{T_c}{T_{int} + \Delta T_k}}\right). \tag{6}$$

A list of 30 chillers ranging from 53 to 530 kW from various manufacturers is considered. Similar to the heat engine process, a comparison between reported performance data and estimated endoreversible *COP*s 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:

$$\dot{Q}_c = COP_{AbsC}\dot{Q}_h. \tag{7}$$

Herold et al. [41] compared the reversible thermodynamic estimation of *COP* of absorption chillers with the zero-order estimation, and found that the expression below was successful in providing reasonable estimates of the *COP* of commercial chillers:

$$COP_{ZO} = \frac{T_c}{T_h}. \tag{8}$$

To ensure that technical feasibility is met in the modelled absorption chiller systems based on the temperature boundaries, the conditions shown in Fig. 2 are imposed. First, the heat source temperature must be at least 70 °C and not greater than 240 °C, to adhere to the range of data collected which is used to derive the correlation that will be discussed later in the paper. Also, the difference between the heat source and cooling medium outlet temperatures must be 20 °C or greater, to ensure technical feasibility is achieved in the different considered cases. For the same reason, the temperature difference between the heat source outlet and cooling medium supply streams' must be 15 °C or greater. Finally, similarly, the temperature differences between the hot and cold sides of the ambient cooling (cooling water) and the heat sink (chilled water) are subjected to be at least 10 °C or greater.

After that, the cooling capacity generated from the absorption chiller systems, which is used to cool down the air intake or compressed gas, is calculated using Eq. (9). These coolers are assumed to be counter-current heat exchangers with temperature differences in the cold and hot sides at least equal to the assumed ΔT_{min}, as illustrated in Fig. 3. The sizes of these coolers are calculated from:

$$\dot{Q}_{cooler} = \dot{m}_c c_p \Delta T_c; \text{ and} \tag{9}$$

$$A_{cooler} = \frac{\dot{Q}_{cooler}}{U_{cooler}\Delta T_{LMTD}}. \tag{10}$$

2.3. Brayton cycle systems with air intake cooling

After determining the potential cooling capacity created from WHR through the absorption chiller system, the cost and benefit of integrating

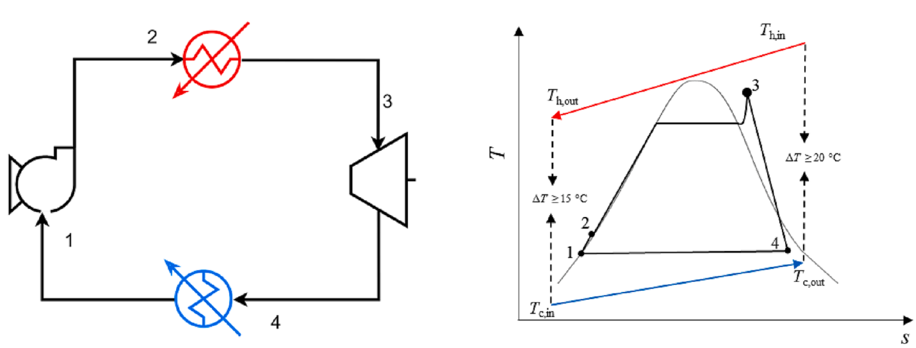

Fig. 1. Simple ORC system (left) and temperature boundary conditions for technical feasibility that ORC systems are subjected to in the modelling approach followed in the present work (right).

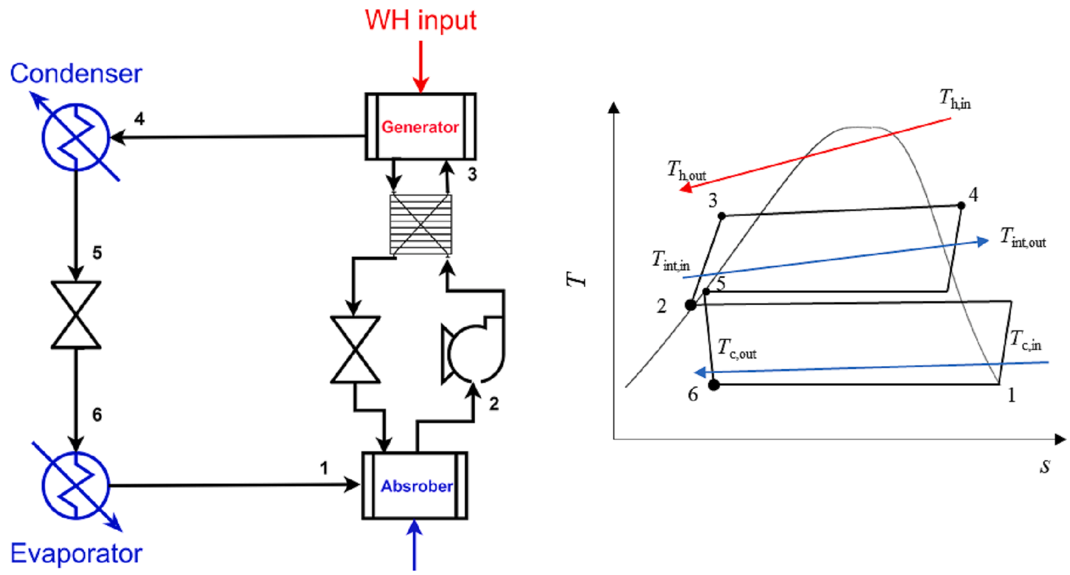

Fig. 2. Absorption chiller system configuration (left) and cycle on a *T-s* diagram (right).

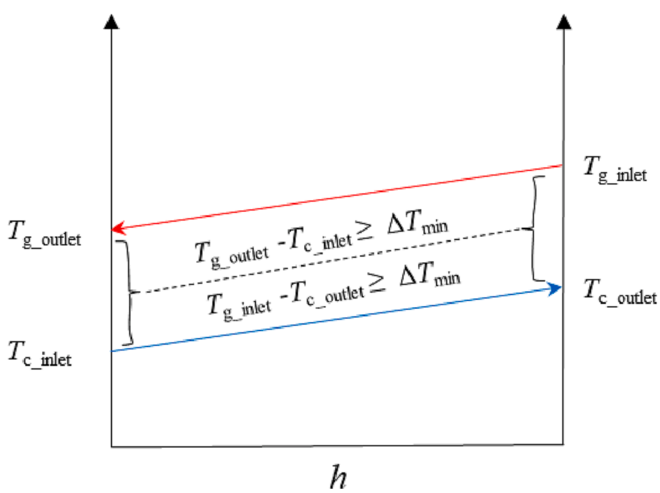

Fig. 3. Assumption followed during the modelling of gas (or air) coolers.

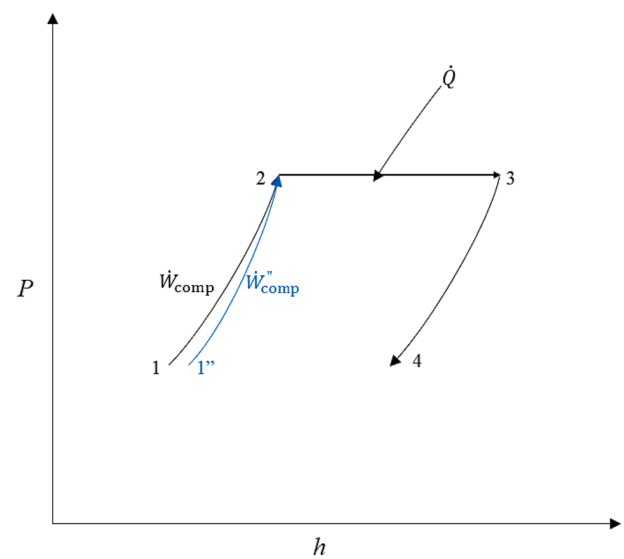

Fig. 4. Illustration of Brayton cycle performance enhancement by air intake cooling on a *P-h* diagram, assuming isentropic compression and expansion processes for constant supply of heat duty.

that capacity into GTs will be studied. The performance impact resulting from air intake temperature variations is typically estimated using GT performance correlations developed by the manufacturers, as different GTs react uniquely due to their system components and control schemes [42].

The improvement in the performance of open-cycle gas turbines at a lower air intake temperature is illustrated in Fig. 4. 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:

$$\eta_{GT} = \frac{\dot{W}_{GT}}{\dot{Q}}. \tag{11}$$

The schematic shown in Fig. 5 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 [29,42]:

$$\dot{W}_{GT} = \alpha + \beta T_0; \text{ and} \tag{12}$$

$$\dot{Q}_{GT} = \frac{\Delta H_{comb}}{\dot{W}_{GT}} = \varepsilon + dT_0, \tag{13}$$

where the constants, α, β, ε and d, are parameters dependent on the performance maps of the GT, which can be obtained from the manufacturer correlations, data fitting or rigorous modelling.

2.4. Gas compression systems with interstage cooling

Gas compression systems are essential in industrial process systems and usually occur in multi-stages of compressors because the single stage is limited to a flow rate of 1 m^3/s and a discharge pressure of 20 bar [29]. Consequently, interstage cooling is employed to protect the machinery integrity and improve the overall compression efficiency, as illustrated in curves in Fig. 6, which show plots of a two-stages compression process.

The compression process can be estimated polytropically, which

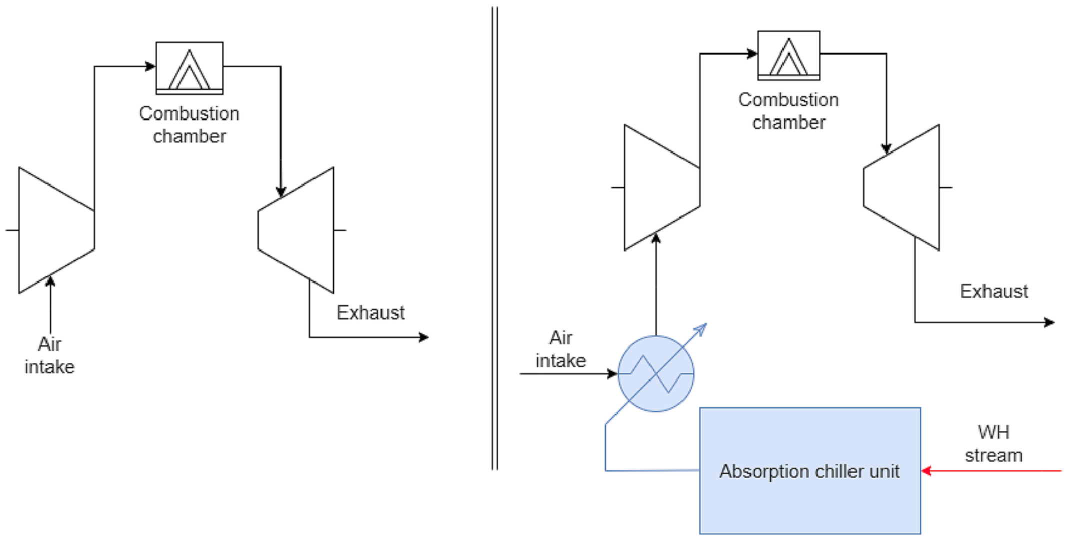

Fig. 5. Schematic diagrams of the base-case GT system (left) where ambient air is directly provided to the system and the proposed scheme (right) where it is integrated with an absorption chiller unit.

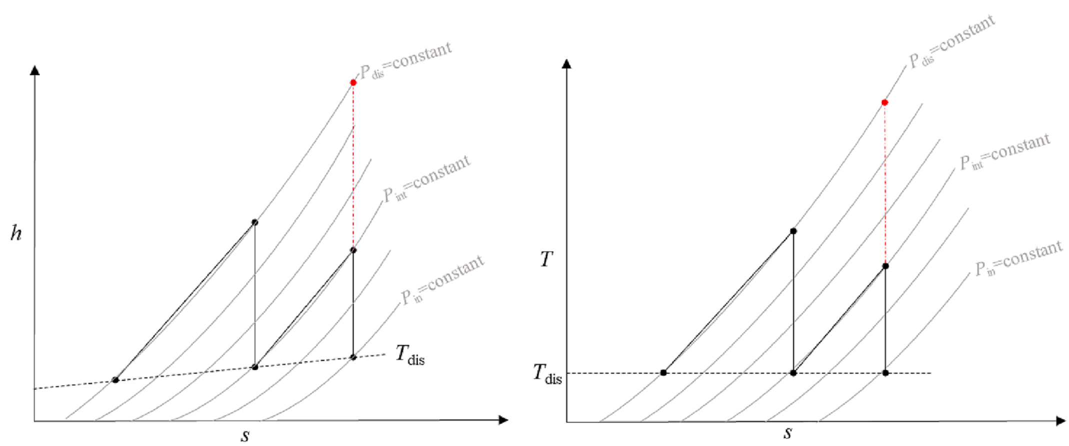

Fig. 6. Schematics illustrating a two-stage isentropic compression process on enthalpy–entropy (*h-s*) and temperature-entropy (*T-s*) diagrams. The red dashed line demonstrates the isentropic compression path for a single-stage compression process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

links the compressor design to the gas properties. It is closer to reality than isentropic compression because it accounts for friction. Equation (14) provides an estimation of the compressor work at different suction temperatures [30,43–48]:

$$\dot{W}_{comp} = \frac{\dot{m}_g}{M} R\, T_g Z_g \frac{k}{k-1}\left[r_P^{\frac{k-1}{k}} - 1\right]. \tag{14}$$

The compressibility factor at 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 [47]. The polytropic exponent (or the polytropic coefficient), *k,* is calculated using Eq. (15), which is a variable that is dependent on both the ratio of the heat capacities, γ, of the compressed gas mixture and the nominal polytropic efficiency, η_p, of the compressor, which typically ranges between 0.76 and 0.78 for most centrifugal compressors [48,49]:

$$k = \frac{1}{1 - \frac{\gamma - 1}{\gamma \eta_p}}. \tag{15}$$

Then, the gained power can be estimated using:

$$\dot{W}_{net} = \dot{W}''_{comp} - \dot{W}^{0}_{comp}. \tag{16}$$

Shaft power of multistage compression systems (also known as machine drive) are typically satisfied by either electrical motors or mechanical coupling with turbines (typically steam turbines). Therefore, the reduction in shaft power requirements can lead to either a direct reduction in the site's power imports or the reduction in fuel imports used to generate steam, which gets expanded through steam turbines for that purpose. In this work, the motor-driven CGC system scenario will be considered to estimate the performance of the proposed integration schemes.

2.5. Technoeconomic performance estimation

As reviewed by Lemmens [50], the existing costing models used in evaluating process technologies are not accurate. 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 specific investment cost (SIC_{ORC}), Arvay et al. [51] 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 a SIC of ~\$2,600/kW. Moreover, an extensive survey by Lemmens revealed that the SICs reported in the literature were scattered and wide-ranged [50], which confirmed that the general trend of ORC SICs decreases as the size increases for the existing ORC units. However, since there is a lack of cost correlations for ORC systems that consider the system size, and by taking a conservative approach, the cost of ORC systems in this work is estimated using an SIC_{ORC} value of \$2,000 per kW, which will be subjected to a sensitivity analysis as part of this work:

$$CC_{ORC} = SIC_{ORC}\dot{W}_{net}. \tag{17}$$

Regarding absorption chillers specific investment cost (SIC_{AbsC}), according to the US department of energy (DOE), SIC_{AbsC} ranges between \$750/kW and \$1,960/kW, with an average value of \$1,730/kW, after adjustment to the 2022 USD value [52]. As a result, the cost of absorption chillers in this work is estimated using Eq. (18). Furthermore, it is estimated that the operations and maintenance costs for both ORC systems and absorption chillers are 1% of the CAPEX. After that, the heat exchangers that transfer the cooling capacity are costed using Eq. (19), which could be applied to up to exchangers with an area of 2,000 m^2 [29]. 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). Finally, the system costs can then be estimated using an SIC_{AbsC} value of \$1,100 per kW, which will be subjected to a sensitivity analysis as part of this work:

$$C_{AbsC} = SIC_{AbsC}\dot{Q}_c; \text{ and} \tag{18}$$

$$C_{cooler} = 156,000\left(\frac{A_{cooler}}{200}\right)^{1.2}; \text{ and} \tag{19}$$

$$C_{total} = C_{cooler} + C_{AbsC}. \tag{20}$$

The system costs can also be combined with the OPEX and get annualised to simplify the estimation of the system economic feasibility using Eq. (21), which generates an annualised factor (*AF*) that can be used to value the system total annualised cost (*TAC*):

$$AF = \frac{i}{(1+i)^n} + i; \text{ and} \tag{21}$$

$$TAC = AF\, C_{total} + OPEX. \tag{22}$$

After estimating the costs of the considered systems, the benefits of these systems are estimated using different metrics. In order to calculate these benefits, the gained benefits from the power savings achieved by either direct conversion through ORC systems, GT air intake cooling, or additional interstage coolers is calculated using Eq. (23), while the change in fuel consumption resulting from air intake cooling in the case of GT enhancement is estimated using Eq. (24). Then, the different performance metrics, such as the annual benefits (*AB*), the payback time (*PBT*), and the net present value (*NPV*), are calculated using Eqs. (25) to (27):

$$B_{power} = \dot{W}_{net}C_e; \tag{23}$$

$$B_{heating} = \dot{Q}_{GT}C_g; \tag{24}$$

$$AB = B_{power} + B_{heating} - OPEX; \tag{25}$$

$$PBT = \frac{C_{total}}{AB}; \text{ and} \tag{26}$$

$$NPV = \sum_{n=1}^{n}\frac{AB}{(1+i)^n} - C_{total}. \tag{27}$$

The technical benefits of these systems are estimated based on the emissions reduction potential, E_{GHG}, measured in metric tonnes of CO_2 equivalent per year, which is obtained as:

$$E_{GHG} = OH\left(EF_g\dot{Q}_{GT} + EF_e\dot{W}_{net}\right). \tag{28}$$

Finally, the systems cost-benefit can be related to the emissions abatement potential using the marginal abatement cost (*MAC*) metric, defined using Eq. (29). The *MAC* relates the cost and the benefits of reducing emissions by one unit and is used to evaluate the cost-effectiveness of studied options:

$$MAC = \frac{-NPV}{E_{GHG}}. \tag{29}$$

3. Case study 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 and power. Fig. 7 shows the typical steps to produce olefins, in which the subsequent stage in the process after the generation of cracked gases is the compression of the cracked gas via centrifugal compressors. The compressors are typically driven by a steam turbine and, in fewer cases, by motors, with four to five compression stages, including intermediate cooling. The number of stages required depends on the cracked gas composition and the cooling medium's temperature level. Switching these compressors drive from steam turbines to motors is one of the most promising opportunities for emissions reduction in ethylene plants, which means that it is foreseeable for these systems to increase the plant power inputs [53,54].

Olefins production by cracking is ranked as the top energy-consuming process within the petrochemical sector [55–57]. The cracked gas compression (CGC) system is estimated to contribute to the specific energy consumption of a olefin plant by 15% to 22%, second only to the thermal energy used for cracking [58,59]. Most interstage coolers yield gas streams at a near-ambient temperature, and such ambient conditions may lead to increased power requirements in 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 evaluation starts by using WH data of an olefins plant quantified in the literature [9]. Then, examples of GT systems within the site's utility system, which satisfies the plant with power requirement, are selected to evaluate GT performance enhancement by integrating a WH-driven absorption chiller system, as shown in Fig. 5. After that, the WH-driven absorption system integrated with the olefins CGC system is also evaluated as part of this study, as shown in Fig. 8. Finally, these two pathways are assessed against standalone power generated by the direct conversion of WH with ORC systems.

Marina et al. [9] conducted an extensive review of the European industrial waste heat, and the data for ethylene plants' waste heat stream, which is hot condensate, was extracted and summarised in Table 1 for use in the present case study. The temperature of this stream is typically between 114 and 125 °C. The production of hot condensate in an olefins process depends on the specific process and operational parameters used. This by-product, produced during the cracking process that converts hydrocarbons such as ethane or naphtha into ethylene and propylene, is generally correlated to the total olefin's steam cracking plant capacity, typically around triple to quadrable of the production.

Regarding the selected GTs, a 26 MW and a 125 MW GE model PG5371 (PA) gas turbine is selected to evaluate the impact of capacity on feasibility. The performance correlations are summarised in Table 2, and the system configuration is illustrated in Fig. 5.

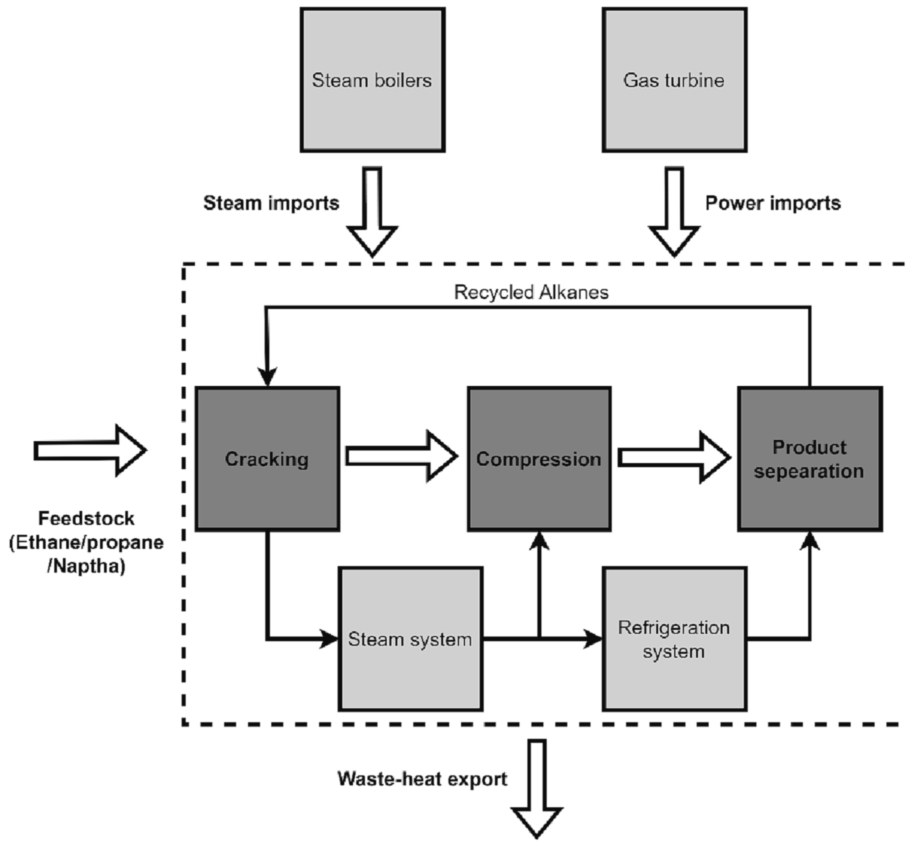

Fig. 7. Schematic of a typical steam cracking plant for the manufacturing of olefins.

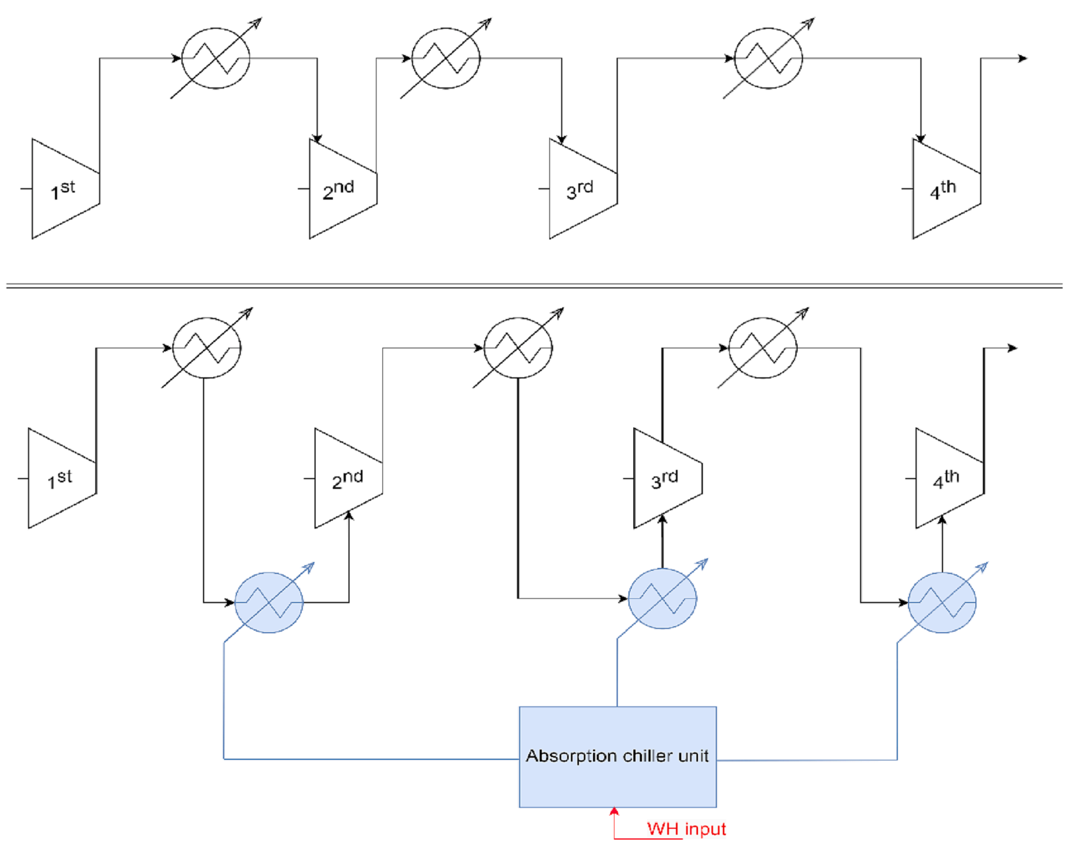

Fig. 8. Schematic diagrams of the base case CGC system (top) where the cracked gas (CG) temperatures are maintained around ambient temperatures and the proposed case (bottom) where the CG temperature drops below ambient levels depending on the absorption chiller unit capacity.

Table 1
Base case WH data [9].

Case study parameters	Value	Units
WH stream	hot condensate (water)	–
T_h	120	°C
$\dot{m}_h$	3 × CGC base case capacity	kg/s

Table 2
GT performance coefficients [42,60,61].

GT system parameters	26 MW GT	125 MW GT	Units
α	29.04	109.4	–
β	−0.19	−0.62	1/°C
ε	3.41	98.7	–
d	0.01	0.13	1/°C

The cracked gas stream data is shown in Table 3, which is taken from the work of Al-douri et al. [48] and Sharifzadeh et al. [62]. The typical nameplate capacity of olefin plants is around 0.5–1.3 million tonnes per year [58]. Therefore, a scenario representing this range of capacities is considered to address the performance of the different WHR schemes using the abovementioned methods, with a base case of a 0.8 million tonnes per year plant. The physical properties of this hydrocarbon mixture can be estimated using the Soave-Redlich-Kwong (SKR) equation of state [63,64]. The SKR equation of state is given by the relationship shown in Eq. (30). The mixture's compressibility factor (Z_g) and specific heat capacity (c_p) at different temperatures and pressures are given by Eqs. (31) and (32), where a and b are substance-dependant constants, respectively, and are plotted in Fig. 9 with the aid of the Aspen plus built-in SKR fluids property package [63].

$$P = \frac{RT}{(V-b)} - \frac{a}{V(V+b)}; \quad (30)$$

$$Z = \frac{PV}{RT}; \text{ and} \quad (31)$$

$$c_p = \left(\frac{\partial h}{\partial T}\right)_P. \quad (32)$$

Consequently, the data required to compute the amount of shaft power at different gas temperatures are obtained and summarised in Table 4.

Finally, the assumptions related to the process systems, ambient conditions, and economic data are summarised in Table 5. The analysis is performed under the steady-state assumption, and sub-zero cooling is not considered in this study due to the limitations this might cause to the use of water due to freezing concerns. 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 crossover heat transfer and violation of the assumed minimum approach temperatures.

Table 3
Composition of cracked gas compressor stream [48,65].

Compressed gas composition	Mass fraction (%)	Mole fraction (%)
Hydrogen (H_2)	5.1	42.0
Methane (CH_4)	8.7	9.0
Acetylene (C_2H_2)	1.1	0.7
Ethylene (C_2H_4)	67.9	40.0
Ethane (C_2H_6)	12.5	6.8
Propylene (C_3H_6)	1.1	0.4
Vinylacytelene (C_4H_4)	0.3	0.1
Butadiene (C_4H_6)	1.5	0.5
Cyclopentadiene (C_5H_6)	0.5	0.1
Benzene (C_6H_6)	1.2	0.3
Hydrogen sulphide (H_2S)	0.1	0.1

4. Results and discussion

The main results and findings are presented and discussed in this section. The analysis starts by investigating the correlations of ORC and absorption chillers energy performance based on the established performance data of commercial systems in Section 3.1. Section 3.2 discusses the technical results related to the impact on plant-level WHR energy flows obtained from modelling the direct conversion of WH to power. Also, the complementation of the direct WHR route with the indirect conversion of WH to power routes through absorption chiller systems integration with power-generating and power-consuming systems is examined. After that, in Section 3.3, a detailed emissions reduction potential benefits analysis is discussed, along with a demonstration of the economic assessment results for the proposed integrated WHR scheme. Also, a sensitivity analysis is conducted in this section to study the impact of some of the primary assumptions used on key performance metrics.

4.1. Data collection of commercial units with thermodynamic estimations

In this work, the performance data of 64 commercial ORC systems ranging from 1 kW to 10 MW in size and operating with heat source temperatures ranging from 80 °C to 350 °C was collected to improve and simplify the correlation shown in Eq. (4). Fig. 10 illustrates the fitting obtained for ORC systems based on the survey. The correlation between the reported efficiencies and their endoreversible efficiencies in Eq. (33) has a coefficient of determination (R^2) value of 0.89, a standard deviation of 0.015, and an average deviation of 0.027. Fig. 11 demonstrates the use of the proposed performance correlation to estimate ORC systems' thermal efficiency compared to other thermodynamic estimation methods:

$$\eta_{ORC} \approx 0.77\eta_{er}. \quad (33)$$

Similarly, a correlation between the absorption chiller units and their respective endoreversible *COPs* is formed, as shown in Fig. 12, by tuning the empirical parameter ΔT_k, which was found to be 27, yielding a linear relationship as illustrated in Eq. (34), with an R^2 value of 0.93, a standard deviation of 0.0657 and an average deviation of 0.0854. Also, the proposed correlation to estimate absorption chiller *COPs* is plotted and compared to other methods in Fig. 13:

$$COP_{AbsC} \approx 1.1COP_{er}. \quad (34)$$

Finally, the country-specific assumptions defined in Table 6 have been taken into account to estimate the performance of absorption chillers and ORC systems when powered by the WH stream defined in Table 1, which yields the thermal efficiencies and *COPs* illustrated in Fig. 14. These results show that both systems' performances improve in locations with colder ambient conditions.

4.2. Technical and emission reduction results

If the WHR from olefins plants is utilised via direct conversion through ORC systems, the amount of power saved can be estimated, as shown in Fig. 15. For our selected base case of a 0.8 million tonnes per year plant, the quantity is estimated to range from 2.3 to 3.5 MW of power in the five locations studied. The varied quantity of recoverable WH and the impact of ambient conditions on the ORC system efficiency mainly cause the variation of this quantity.

Conversely, when analysing the conversion of waste heat to cooling capacities for further process-enhancement utilisation, it should be acknowledged that the potential of this route is limited by the fact that there is a lower temperature limit that cooling cannot be extended beyond. This lower limit implies that there are upper limitations for the amount of cooling duty that can be utilised, especially for large-scale systems. Therefore, the analysis of this scheme starts by quantifying the maximum possible cooling capacity that can be used for the GT

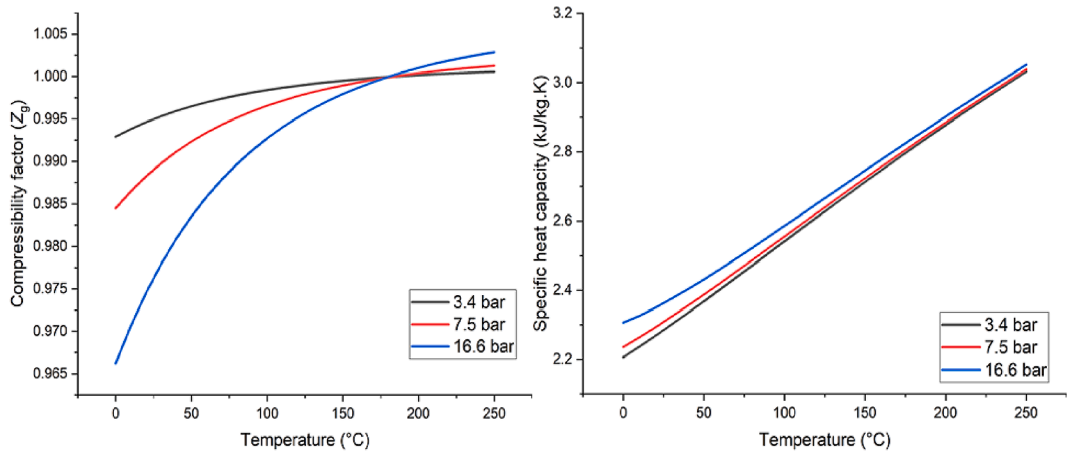

Fig. 9. Compressed gas compressibility factor (Z_g) gas specific heat capacity (c_p) at different temperature and pressure values.

Table 4
Base case cracked gas compression system parameters.

Case study parameter	Value	Units
Number of compression intercoolers	3	–
Compressed gases flow rate ($\dot{m}_{gas}$)	800,000	tons/year
Gases average molecular weight (M)	16.52	kg/kmol
Pressure ratio (r_P)	2.2	–
Heat capacity ratio (γ)	1.29	–
Nominal compressor polytropic efficiency (η_p)	0.78	–

Table 5
Economic and system-level parameters.

Economic assumptions		Process system assumptions	
Plant lifetime	20 years	ΔT_{min}	5 °C
OH	8000 h/year	Heat sink T	T_{atm}
CW cost	6 $/kW/year	Evaporator outlet T	2 °C
CEPCI 2010	534	Max. CW return T	45 °C
CEPCI 2022	701	U_{cooler}	250 W/(m^2.K)

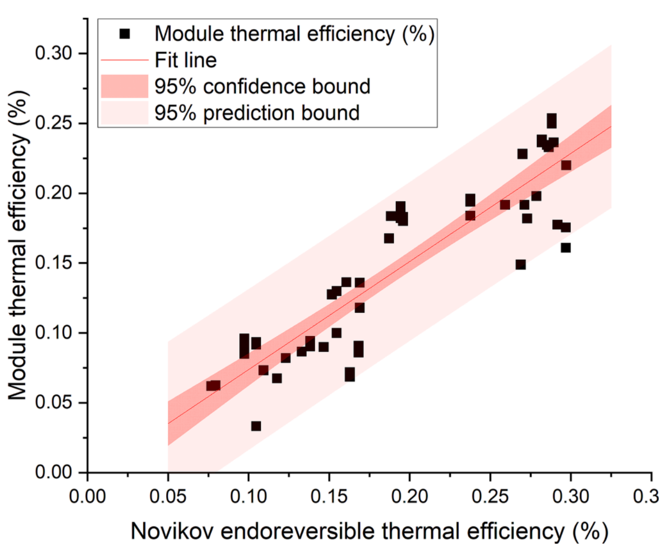

Fig. 10. Fitted line and upper/lower prediction and confidence bands of the estimated thermal efficiency of commercially available ORC systems.

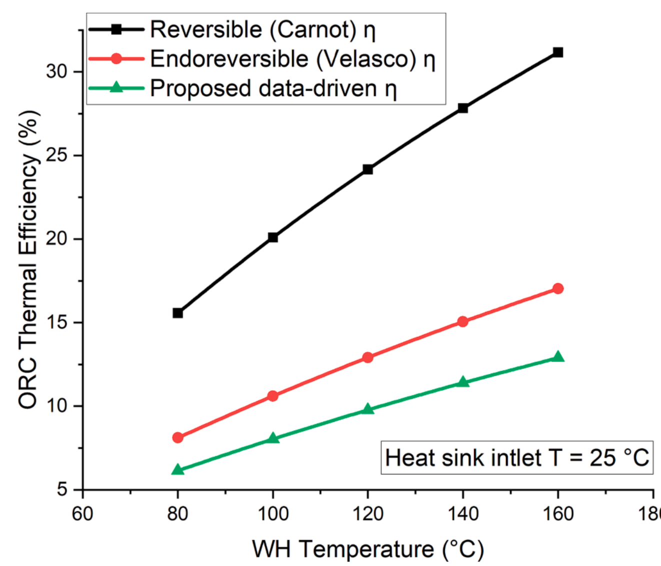

Fig. 11. ORC efficiency using thermodynamic estimations versus the correlation in Eq. (33).

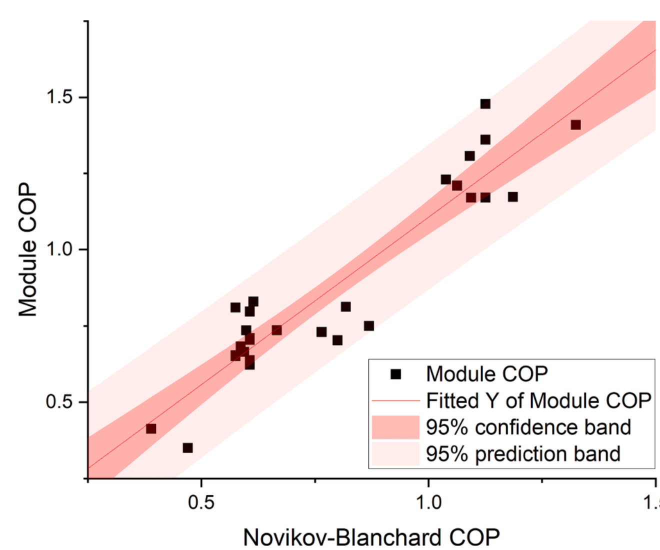

Fig. 12. Fitted line and upper/lower prediction and confidence bands of the estimated *COP* of absorption chillers of commercially available systems.

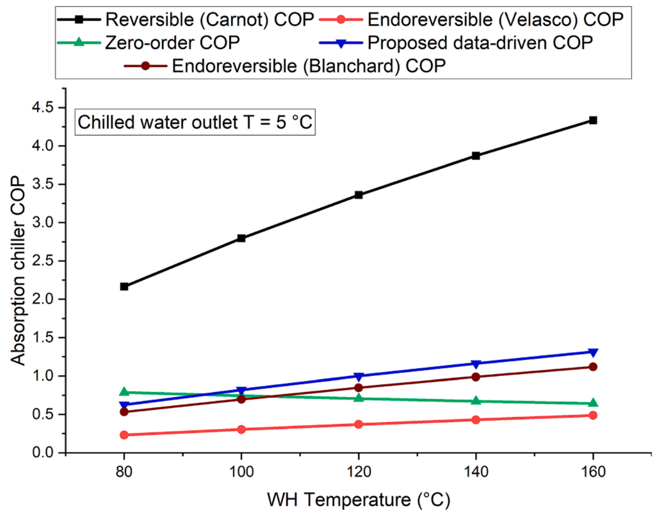

Fig. 13. Absorption chiller *COP* using thermodynamic estimations versus the correlation in Eq. (34).

Table 6
Country-specific assumptions. *Inflation rates are based on historical averages rather than recent (post-2020) figures. Data acquired from Refs. [66–70].

Parameter	Units	Saudi Arabia	UK	China	USA	Germany
T_{atm}	°C	27	12	11	13	9
C_e	$/kWh	0.048	0.37	0.64	0.09	0.28
C_g	$/kWh	0.01	0.06	0.03	0.04	0.15
Inflation rates*	per year	2.5%	2%	2.5%	2%	2%
EF_e	kgCO$_2$(eq.)/kWh	0.812	0.193	0.969	0.388	0.361
EF_g	kgCO$_2$(eq.)/kWh	0.054	0.06	0.050	0.06	0.055

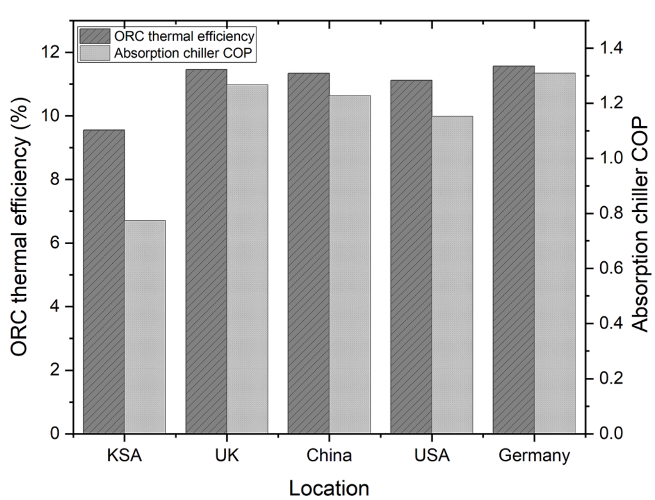

Fig. 14. Estimated ORC thermal efficiency and absorption chiller *COP* for the defined case study at the different studied locations.

enhancement scheme and the CGC enhancement scheme. A demonstration of this conducted analysis for KSA and the UK is presented in Fig. 16 and Fig. 17, respectively. The results are calculated for the defined base case of a 0.8 million tonnes per year olefins plant, and the two cases of GT sizes are shown for each location.

In these figures, it is observed that variation in ambient conditions causes changes to the availability of WH duties, where the hotter the

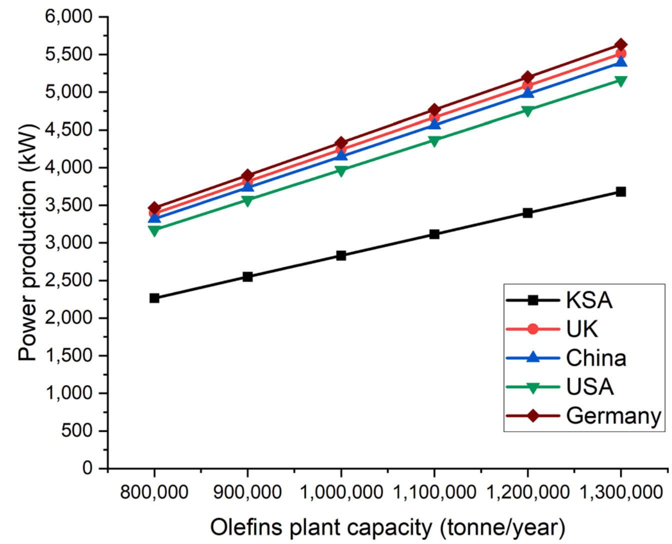

Fig. 15. Power production from a range of olefins plant scales using ORC systems driven by the hot condensate WH stream.

climate, the less energy flow is expected from the same olefins plant. For instance, the plant in KSA is expected to have less available (or recoverable) WH duty than the same plant operating in the UK by around 6 MW of heat. Moreover, the provision for utilising cooling capacities out of WH is higher for hotter locations due to the higher potential for cooling. As a result, the plant in KSA is found to be capable of consuming roughly six times the amount of cooling that can be utilised in the UK, considering the imposed lowest allowable cooling temperature of the 2 °C limit.

Furthermore, the CGC system in the plant in KSA is estimated to be capable of rejecting around 4 MW of interstage heat to the cooling capacity generated by the absorption chiller, which is found to yield a reduction in power requirement for the system by around 1 MW. Simultaneously, 5 MW of cooling is estimated to be usable for GT power generation enhancement through air intake cooling in the plant in KSA. This integration is expected to yield around 12 MW of further power generated from the 125 MW GT, and the GT heating rate demand is reduced by around 3 MW of heat. On the other hand, if the GT system is the 26 MW one gets enhanced by the same 5 MW of cooling, this scheme is expected to yield 4 MW of additional power capacity and 0.2 MW in heating savings.

For the UK plant, out of the available 38 MW of WH, only approximately 2.1 MW of cooling can be utilised by the system, which means that 1.7 MW of WH can be recovered based on the estimated absorption chiller system performance. Then, around 1.5 MW of this cooling capacity is exported to the CGC system, from which around 0.3 MW of power is expected to be saved. However, when it comes to GT, around 0.6 MW of cooling can be deployed, and in the case of the smaller-scale GT, only around 0.6 MW of power is expected to be gained while a small amount of heat demand (around 300 kW) is going to be reduced. In contrast, the bigger GT could yield around 1.9 MW of power gain and 0.3 MW of heat demand reduction. The remaining WH not recoverable indirectly for cooling can then be provided to ORC systems, which is estimated to be around 9 MW for the considered plant in KSA, producing around 1 MW of power through ORC and subsequently dumping around 8 MW, making the total lower-grade residual heat rejected around 10 MW.

In the UK, it is estimated that the vast majority of the plant WH needs to be recovered in ORC systems due to the smaller envelope for cooling. Around 37 MW of WH goes to ORC systems producing around 4 MW of power and dumping the remaining unutilised WH duty of around 33 MW of lower-grade residual heat. An additional amount of lower-grade WH

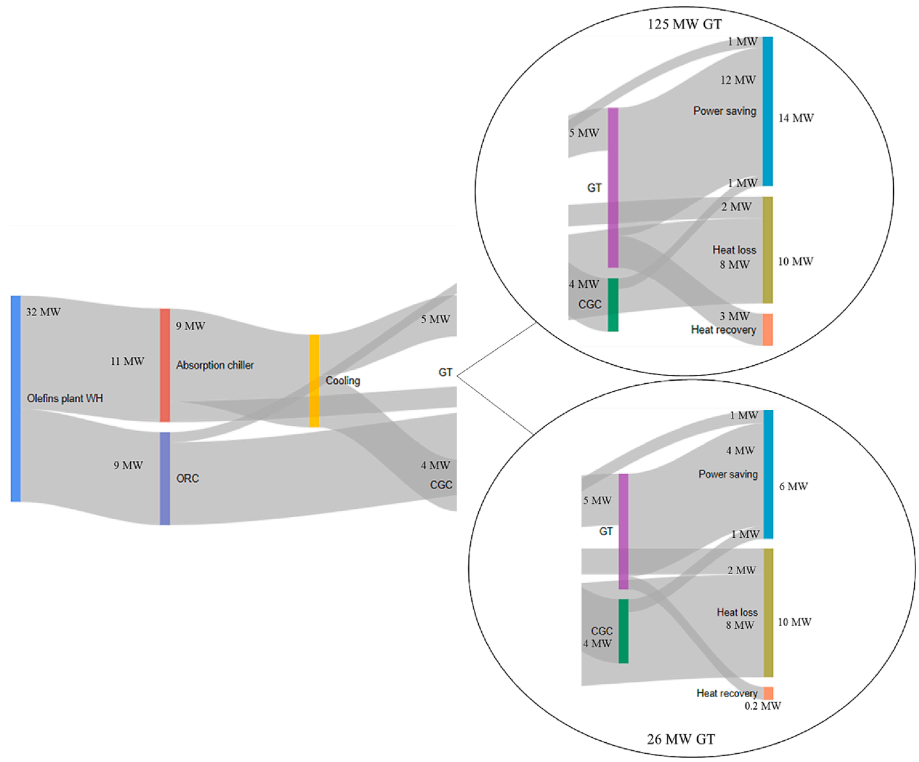

Fig. 16. Energy flows after WHR with GT and CGC enhancement, and ORC systems for an olefins plant in KSA with a 125 MW GT system (top) and a 26 MW GT system (bottom).

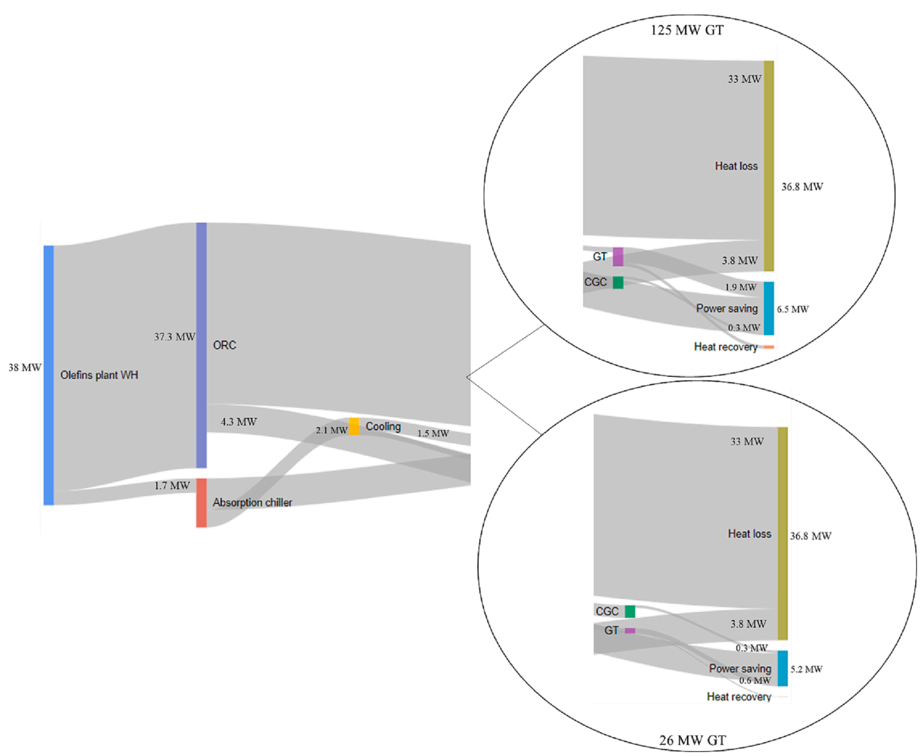

Fig. 17. Energy flows after WHR with GT and CGC enhancement, and ORC systems for an olefins plant in the UK with a 125 MW GT system (top) and a 26 MW GT system (bottom).

will come from the condensation steps in the absorption chiller systems, with a total residual WH around 37 MW.

Therefore, it can be deduced from the conducted analysis that ambient conditions considerably impact the potential for WH discharge reduction in olefins plants through the proposed solution portfolio. Furthermore, it can be noticed from the results shown in Fig. 16 and Fig. 17 that in the indirect conversion of WH to power that in all cases, this scheme has limited potential for recovering the massive amount of

WH generated from the steam-cracking olefins plant. Therefore, in the next section, the option of simultaneously enhancing power generation and consumption through WH-driven cooling integration and using the unrecovered WH duty to generate power through ORCs are examined from emissions and economics standpoints.

4.3. Emissions and economic analysis and results

After addressing the conservation of WH through the identified pathways, in this section, the costs and benefits are evaluated. Table 7 shows the estimated emissions reductions from converting olefins plant WH to power with the proposed portfolio of technologies, including CGC and GT systems enhancement complemented by ORC systems in the considered locations. The highest emissions reduction is expected to occur in China, starting from around 20,000 tonnes of CO_2 equivalent per year for an olefins plant of 800,000 tonnes per year capacity. Meanwhile, the lowest estimates are found for the UK for the smallest considered olefins plant. The deviation in emissions reduction potential is mainly driven by the electricity grid emissions factors (EF_e) in the locations studied, as the highest and lowest values were in line with the obtained estimations.

The economic performance metrics are shown in Fig. 18. From these figures, it can be noticed that the ORC systems performance is expected to have positive financial results across all five locations as the annual net benefits (*AB*) value is estimated to be consistently higher than the total annualised costs (*TAC*). The highest difference between *AB* and *TAC* is observed for the systems in the UK, followed by Germany, while relatively similar economic performance is estimated for USA and China, and the smallest difference between *AB* and *TAC* is estimated for the KSA case. The main reason for these results is the variance in electricity prices (C_e) in the locations studied, as the highest and lowest values were in line with the obtained economic performance estimations.

On the other hand, the power demand reduction opportunities driven by integrating WH-driven absorption chillers from a 0.8 million tonnes per year olefins plant are analysed in the subsequent section. Fig. 19 shows the obtained results from modelling these pathways individually, starting with the top left bar graph, where each of their estimated emissions reduction is illustrated. The highest emissions reduction potential is expected to yield around 80,000 tCO_2(eq.)/year and found to be for the case of integrating absorption chillers with the 125 MW GT in the warmest considered location (KSA). In contrast, the emissions reduction potential tends to drop for the other locations, where the lowest value is estimated for Germany to be around 5,000 tCO_2(eq.)/year due to both the colder climate and the lower grid emissions factor compared to the other locations.

Economically, the remaining graphs in Fig. 19 show each of these pathways *MAC*, *PBT*, *AB*, and *TAC*. It can be seen that the more attractive *MAC*s are observed for the UK, followed by Germany, and relatively similar results in the USA and China, while in KSA, the *MAC*s are relatively less appealing compared to the other locations for the same portfolio of technologies. When breaking down these results from cost and benefit perspectives in Fig. 19-bottom right graph, it is apparent that the *AB* and the *TAC* values are generally closer to each other for

Table 7
Annual emissions reduction potential when converting olefins hot condensate WH stream to power through ORC systems for different plants capacities in the five considered locations.

Olefins plant capacity	KSA	UK	China	USA	Germany
[tonnes per year]	[tCO_2(eq.)/year]				
800,000	11,600	4,100	20,400	7,800	7,900
900,000	13,100	4,700	22,900	8,800	8,900
1,000,000	14,500	5,200	25,500	9,800	9,900
1,100,000	16,000	5,700	28,000	10,700	10,900
1,200,000	17,500	6,200	30,500	11,700	11,900
1,300,000	18,900	6,700	33,000	12,700	12,900

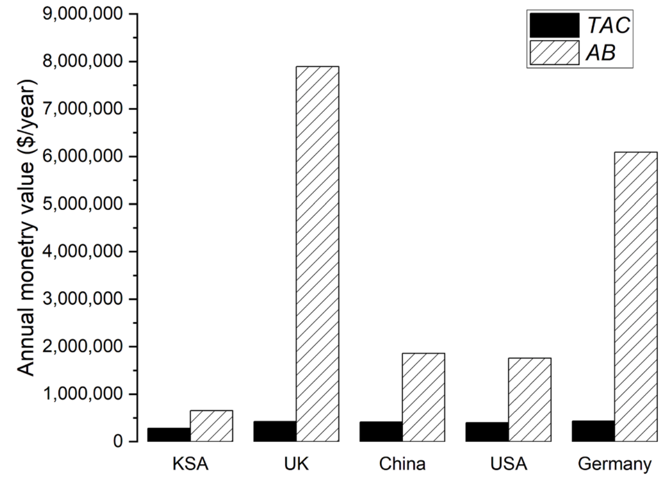

Fig. 18. Total annualised costs and net annual benefits of ORC systems recovering hot condensate waste heat streams in the different studied locations for the base-case olefins plant.

enhancing the CGC system than the GT systems. This indicates that enhancing the CGC alone is less attractive than enhancing either the 26 MW or the 125 MW GT. These factors explain the estimated *PBT*s plotted in Fig. 19-bottom left graph, where the shortest time is noted for enhancing the bigger GT in Germany with as short as four months of payback time and around one year for the smaller GT, and less than four years of the CGC enhancement. The longest estimated *PBT*s are for the KSA case because the power prices there are the cheapest among the five countries. The enhancement of CGC alone is expected to pay back in more than 34 years, while GT enhancement is expected to pay back in less than six years and less than two years for the 26 MW and 125 MW GTs, respectively.

The final part of the analysis is the consolidation of the economic and emissions performance metrics for the proposed solutions by plotting their marginal abatement cost curve (MACC) shown in Fig. 20. This curve illustrates a combination of findings described above: the emissions reduction potential (E_{GHG}) on the horizontal axis and the *MAC* on the vertical axis. Each case shown in this figure includes the results from recovering the WH of the base case olefins plant in the different locations using; absorption chiller systems integrated with CGC, one of the two GTs, and ORC systems to recover the remaining WH. These results provide some support for the generalised conceptual premise that recovering the WH from olefins plants is attractive, and the attractiveness can enormously vary based on location.

Fig. 20 and Table 8 illustrate that the highest E_{GHG} is expected to be found in KSA, driven by the grid emissions factor compared to the other locations, while the *MAC* value is expected to be below zero, driven by the low energy costs there. In contrast, the UK relatively low grid emissions factor limits the relative E_{GHG} value while the relatively expensive power cost supports the *MAC*. This attractiveness ranking is in line with the other overall economic performance metric, *PBT*, illustrated in Fig. 21 and provides a similar ranking of attractiveness between the locations.

According to the international carbon action partnership (ICAP) [71], current CO_2 price in countries with emissions trading schemes (ETS) ranges between 10 and 110 $/$tCO_2$(eq.), as shown in Fig. 22. By comparing these values to the reported values in Fig. 20, it is evident that the proposed measures proposed are expected to be economic from this standpoint, because the *MAC* values are all negative compared to positive carbon prices in the ETS of the different locations considered.

Finally, assumptions such as the SIC_{ORC} and SIC_{AbsC}, ΔT_{min}, and new coolers heat transfer coefficients (U_{cooler}) are subjected to a sensitivity analysis. The results obtained when conducting this analysis for four different locations on the *MAC* of the proposed scheme when integrated

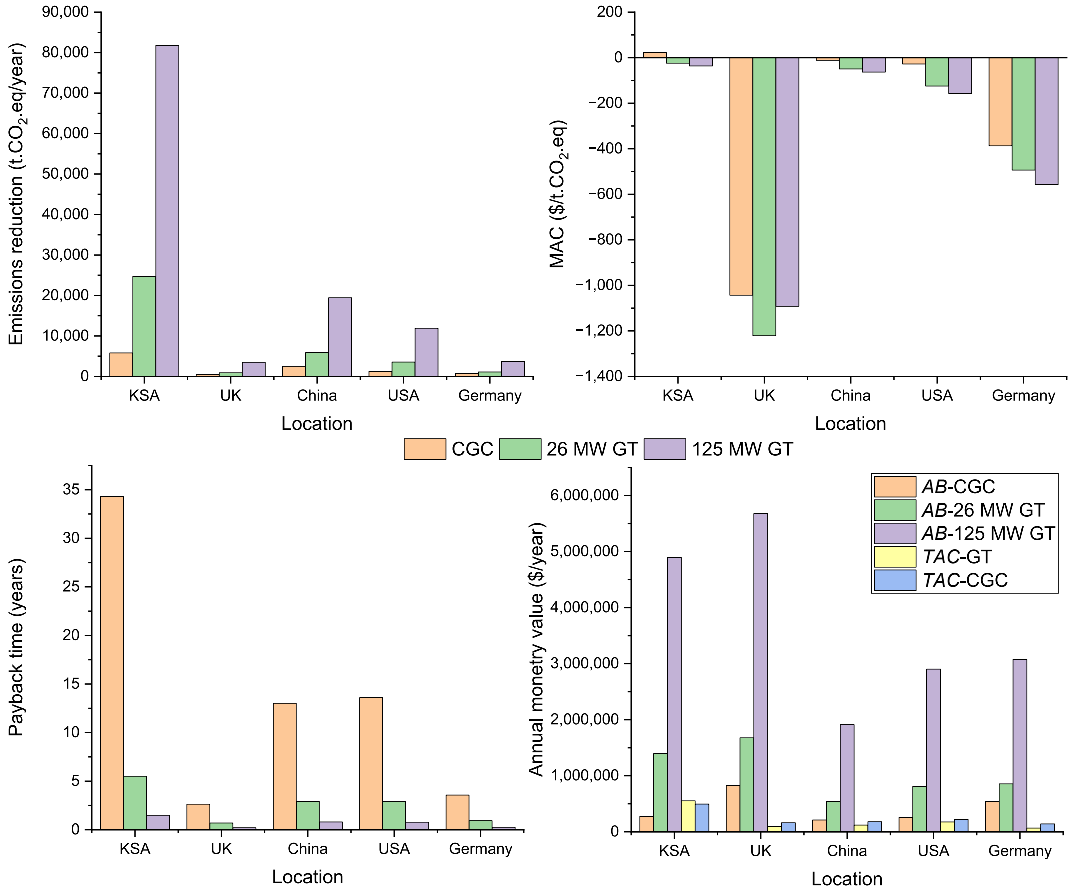

Fig. 19. Illustration of performance indicators for enhancing the CGC system and the two considered GTs in the different locations. Top left: estimated emissions reduction; top right: *MAC*; bottom left: *PBT*; bottom left: *TAC* and *AB*.

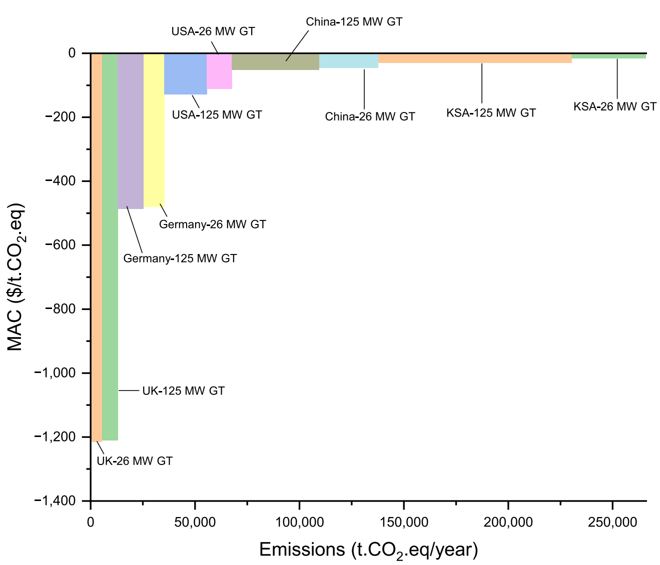

Fig. 20. *MAC* curve for the considered cases and portfolio of solutions.

with a 125 MW GT are shown in Fig. 23. The $\Delta T_{\min}$ was first varied between −20% to +20%, and the impact on the *MAC* was found to be marginal. Then, U_{cooler} values are varied by ±50%, and the impact on the *MAC* is found to be dependent on the amount of cooling deployed in the indirect route. Therefore, halving the U_{cooler} value by 50% in KSA reduces the *MAC* by around 6%. In colder countries, this impact is reduced to less than ±2%. At the same time, increasing U_{cooler} by 50% resulted in increasing the *MAC* by around 2%, which indicates a non-linear relationship between the two variables.

Similarly, a variation of ±50% is imposed on SIC_{ORC} and SIC_{AbsC}, and in the case of KSA, SIC_{ORC} variation marginally impacts *MAC* while SIC_{AbsC} variation is found to change it by around ±10%. When applying the same to colder locations, the assumed *SIC* values have a weaker impact on the base case estimated *MAC* values but a more considerable influence from SIC_{ORC} compared to SIC_{AbsC} values.

Therefore, it can be concluded from this analysis that in locations where cooling will play a more significant role than the direct route for WH conversion to power, it will be worthwhile to ensure that the used values of SIC_{AbsC} are as accurate as possible. For colder locations where most of the WH will utilised with ORC systems, it is advised to verify SIC_{ORC} further.

5. Conclusions

WHR and re-use or conversion and utilisation are appealing solutions to industry as they can be employed to maximise the conservation and promote the better use of energy resources, and can serve these industries by increasing their resilience to environmental sustainability constraints and the economic impact of energy price volatility. A portfolio approach to improving efficiency and reducing emissions especially benefits large, heat-intensive industries with diverse processes. With this overall aim in mind, unconventional modelling techniques have been discussed, and statistical and energy analysis methods have been used to assess and estimate the potential role of selected technologies in terms of their techno-economic performance, considering a portfolio of WHR opportunities based on a proposed data-driven technology-agnostic approach.

Table 8
E_{GHG} values for the for the proposed portfolio of the 3 solutions combined, for the different plant capacities in the five studied locations.

Plant capacity	KSA		UK		China		USA		Germany	
ton/year	tCO_2(eq.)/year									
	26 MW GT	125 MW GT	26 MW GT	125 MW GT	26 MW GT	125 MW GT	26 MW GT	125 MW GT	26 MW GT	125 MW GT
800,000	36,700	92,700	5,400	7,600	28,200	41,700	12.100	20,400	9,800	12,400
900,000	37,400	94,500	6,000	8,200	31,000	44,600	13,200	21,500	10,900	13,500
1,000,000	39,100	96,300	6,600	8,800	33,900	47,500	14,300	22,600	12,000	14,600
1,100,000	41,000	98,000	7,200	9,300	36,800	50,300	15,400	23,700	13,100	15,700
1,200,000	42,700	99,800	7,800	9,900	39,600	53,200	16,500	24,800	14,200	16,800
1,300,000	44,500	101,500	8,300	10,500	42,500	56,000	17,600	25,900	15,300	17,900

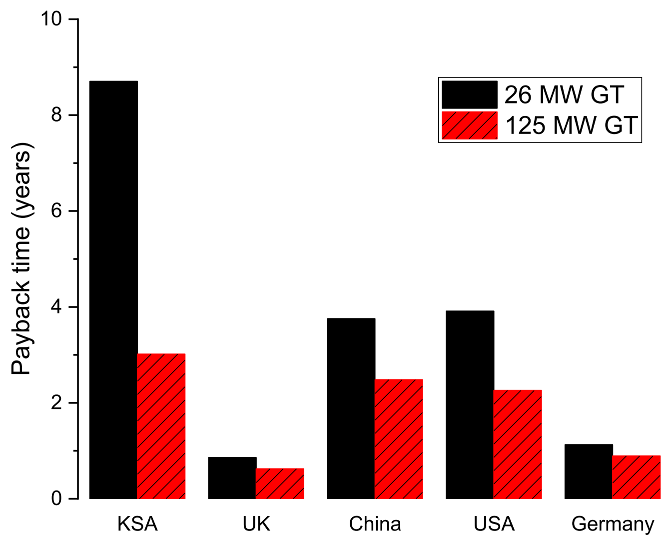

Fig. 21. Estimated *PBT* for the proposed solutions when integrated with different GT sizes.

The objective of this study was to investigate three approaches to reduce power demand in bulk chemicals plants, represented by an olefins plant as a case study, by (i) direct onsite power generation with ORC systems; (ii) enhancement of existing gas turbine (GT) systems; and (iii) reduction in power consumption by compressor efficiency improvements through waste-heat-driven cooling. The results of the conducted analysis demonstrate relatively strong relationships between simple technology-agnostic thermodynamic performance predictions and data provided by ORC and absorption chiller manufacturers. This approach eliminates the need to make detailed design decisions, such as specifying the working fluids and the configuration of these technologies, at this early stage of technology screening. Hence, it is expected to accelerate our understanding of the potential of available WHR opportunities. The method was applied to an olefins plant as a case study, representing the bulk chemicals industries, to assess the proposed portfolio of options to convert WH into power gained by reducing consumption or increasing the production of existing assets.

For this study, it was found that a significant amount of WH from olefins manufacturing processes worldwide is being rejected to the environment without proper utilisation. Multiple options for WHR in these plants were proposed, and many were found to be technically and financially feasible. The economic performance predictions showed that the proposed portfolio of solutions is most attractive for an olefins plant residing in the UK with a *MAC* of approximately −1,200 $/$tCO_2$(eq.), while the lowest *MAC* value was estimated in the KSA plant at around −35 $/$tCO_2$(eq.). From a *PBT* perspective, the estimated payback of these solutions is between 1.5 and 8 years, depending on the location and the size of the GT system being enhanced and integrated with the olefins plant WH stream. Therefore, integration schemes involving larger systems were found to typically outperform the direct routes of WHR, i.e., a standalone WH-driven ORC system, 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 and 7 years for the considered tariffs.

Based on the conducted analysis in this study, it is recommended for olefins plants owners or operators to explore further and potentially invest in such technologies to recover as much as feasibly possible quantities of the hot condensate generated from the steam cracking process. The demonstrated analysis showed that these solutions are

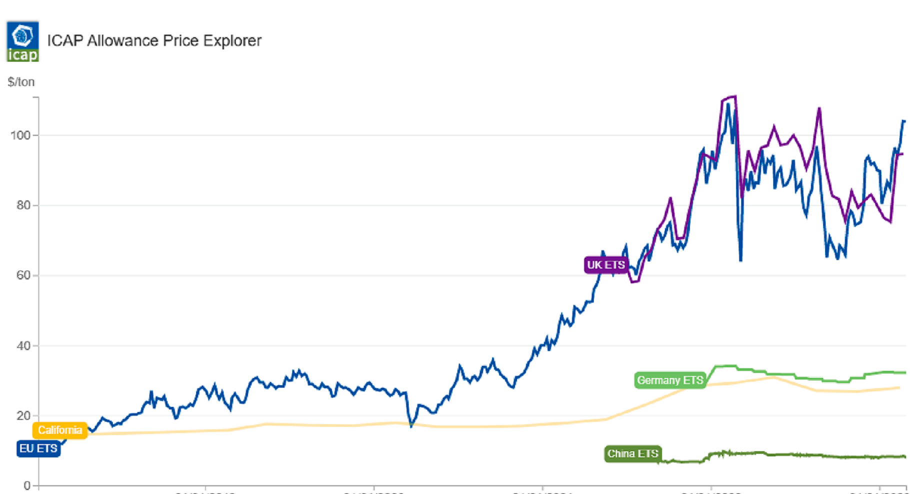

Fig. 22. CO_2 price $/$tCO_2$(eq.) in ETS of various location.

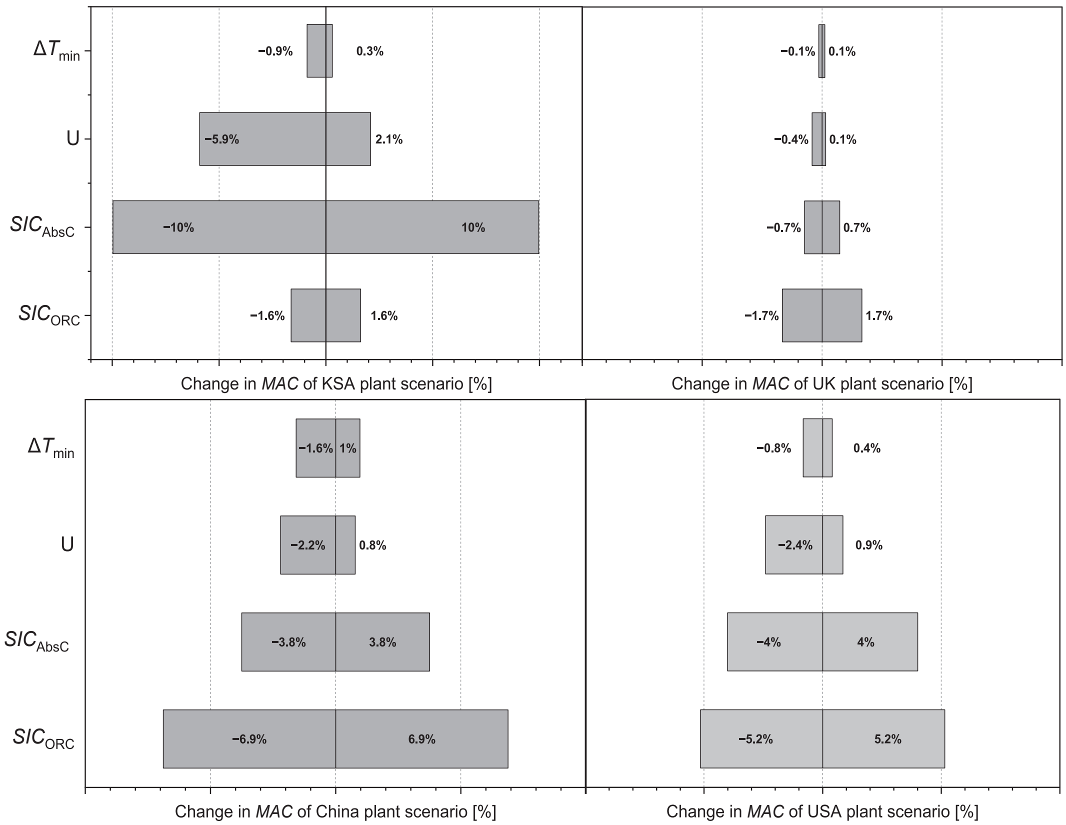

Fig. 23. Impact of varying key assumptions on the *MAC* values at four different locations.

generally economically attractive and technically feasible. More specifically, a combination of direct and indirect conversion of hot condensate into power is expected to provide better economic efficiency relating to monetary investment for emissions reduction and energy savings. The reason for that is that in most studied locations, the indirect conversion of waste heat to power is limited by the lowest-achievable cooling temperature, whilst the amount of available and recoverable waste heat in most cases exceeds these limits.

Finally, a natural progression of this work would be to explore the use of sub-zero cooling levels produced by the WH-driven chillers, the impact of seasonality, and the caused off-design performance variations on the overall techno-economic assessment of the studied technologies in the different locations. Also, it is recommended to extend the analysis for a specific olefins plant in a manner that shows the net power gain using ORC systems as well as the emissions reduction potential as a fraction of the current plant data. Both the plant total power consumption and emissions are required to quantify the power gain and emissions reduction potential against the current plant data. These values strongly depend on the specificity of the process technology, feedstock composition, and grid factor for the plant and cannot be easily generalised in a similar manner as the amount of waste heat estimation conducted in this work. Conducting this work in the future is ought to provide a more sensitive look at the benefits of such systems. Furthermore, comparing the results of the data-driven technology-agnostic approach with the detailed modelling approach would be valuable 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.

CRediT authorship contribution statement

Abdullah M. Maghrabi: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jian Song:** Methodology, Writing – review & editing. **Paul Sapin:** Methodology, Writing – review & editing. **Christos N. Markides:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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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, Markides CN. Recovery and utilization of low-grade waste heat in the oil-refining industry using heat engines and heat pumps: An international technoeconomic comparison. Energies 2020;13(10):pp. https://doi.org/10.3390/en13102560.
[7] Markides CN. The role of pumped and waste heat technologies in a high-efficiency sustainable energy future for the UK. Appl Therm Eng 2013;53(2):197–209. 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] Marina A, Spoelstra S, Zondag HA, Wemmers AK. An estimation of the European industrial heat pump market potential. Renew Sustain Energy Rev 2021;139:110545. https://doi.org/10.1016/j.rser.2020.110545.
[10] Unamba CK, Sapin P, Li X, Song J, Wang K, Shu G, et al. Operational optimisation of a non-recuperative 1-kWe organic Rankine cycle (ORC) engine prototype. Appl Sci 2019;9(15):1–19. https://doi.org/10.3390/app9153024.
[11] 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.
[12] Markides CN. Low-concentration solar-power systems based on organic rankine cycles for distributed-scale applications: Overview and further developments. Front Energy Res 2015;3:1–16. https://doi.org/10.3389/fenrg.2015.00047.
[13] Catalan L, Araiz M, Aranguren P, Astrain D. Computational study of geothermal thermoelectric generators with phase change heat exchangers. Energy Convers Manag 2020;221:113120. https://doi.org/10.1016/j.enconman.2020.113120.
[14] Mulla R, Dunnill CW. Powering the Hydrogen Economy from Waste Heat: A Review of Heat-to-Hydrogen Concepts. ChemSusChem 2019;12(17):3882–95. https://doi.org/10.1002/cssc.201901426.
[15] Wieland C, Schifflechner C, Dawo F, Astolfi M. The organic Rankine cycle power systems market: Recent developments and future perspectives. Appl Therm Eng 2023;224:119980. https://doi.org/10.1016/j.applthermaleng.2023.119980.
[16] International Energy Agency (IEA), Natural Gas-Fired Power, 2021. https://www.iea.org/reports/natural-gas-fired-power.
[17] Mostafa M, Eldrainy YA, EL-Kassaby MM. A comprehensive study of simple and recuperative gas turbine cycles with inlet fogging and overspray. Therm Sci Eng Prog 2018;8(June):318–26. https://doi.org/10.1016/j.tsep.2018.09.006.
[18] Bhargava RK, Meher-Homji CB, Chaker MA, Bianchi M, Melino F, Peretto A, et al. Gas turbine fogging technology: A state-of-the-art review - Part II: Overspray fogging - Analytical and experimental aspects. J Eng Gas Turbines Power 2007;129(2):454–60. https://doi.org/10.1115/1.2364004.
[19] González-Díaz A, Alcaráz-Calderón AM, González-Díaz MO, Méndez-Aranda Á, Lucquiaud M, González-Santaló JM. Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO_2 capture. Energy 2017;134:221–33.
[20] 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.
[21] Pinilla Fernandez DA, Foliaco B, Padilla RV, Bula A, Gonzalez-Quiroga A. High ambient temperature effects on the performance of a gas turbine-based cogeneration system with supplementary fire in a tropical climate. Case Stud Therm Eng 2021;26:101206.
[22] Zare V. Performance improvement of biomass-fueled closed cycle gas turbine via compressor inlet cooling using absorption refrigeration; thermoeconomic analysis and multi-objective optimization. Energy Convers Manag 2020;215:112946. https://doi.org/10.1016/j.enconman.2020.112946.
[23] Kwon HM, Kim TS, Sohn JL, Kang DW. Performance improvement of gas turbine combined cycle power plant by dual cooling of the inlet air and turbine coolant using an absorption chiller. Energy 2018;163:1050–61. https://doi.org/10.1016/j.energy.2018.08.191.
[24] Cha S-H, Na S-I, Lee YH, Kim MS. Thermodynamic analysis of a gas turbine inlet air cooling and recovering system in gas turbine and CO_2 combined cycle using cold energy from LNG terminal. Energy Convers Manag 2021;230:113802. https://doi.org/10.1016/j.enconman.2020.113802.
[25] Dizaji HS, Hu EJ, Chen L, Pourhedayat S. Using novel integrated Maisotsenko cooler and absorption chiller for cooling of gas turbine inlet air. Energy Convers Manag 2019;195:1067–78. https://doi.org/10.1016/j.enconman.2019.05.064.
[26] Popli S, Rodgers P, Eveloy V. Gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry. Appl Therm Eng 2013;50(1):918–31. https://doi.org/10.1016/j.applthermaleng.2012.06.018.
[27] Cao Y, Habibi H, Zoghi M, 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 2021;236:121432. https://doi.org/10.1016/j.energy.2021.121432.
[28] Li B, S-s W, Wang K, Song L. Thermo-economic analysis of a combined cooling, heating and power system based on carbon dioxide power cycle and absorption chiller for waste heat recovery of gas turbine. Energy Convers Manag 2020;224:113372. https://doi.org/10.1016/j.enconman.2020.113372.
[29] Smith R. Chemical process design and integration. Second edition. Chichester: Wiley; 2016.
[30] Bloch HP, Godse A, editors. Compressors and Modern Process Applications. Wiley; 2006.
[31] 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.
[32] Zhang H, Zhou X, Jiang H, Fang S, Zhi X, Qiu L, et al. Performance limit of gas compression processes enhanced by self-utilization of compression waste heat. Energy Convers Manag 2022;273:116414. https://doi.org/10.1016/j.enconman.2022.116414.
[33] Winterbone DE. Advanced thermodynamics for engineers. London: Arnold; 1996.
[34] Rogers GFC, Mayhew YR. Engineering thermodynamics : work and heat transfer. 4th ed. London: Longman; 1992.
[35] Hoffmann KH, Burzler JM, Schubert S. Endoreversible thermodynamics. J Non-Equilibrium Thermodyn 1997;22(4):311–55. https://doi.org/10.1515/jnet.1997.22.4.311.
[36] Novikov II. The efficiency of atomic power stations (a review). J Nucl Energy 1958;7(1–2):125–8. https://doi.org/10.1016/0891-3919(58)90244-4.
[37] Chambadal P. Les centrales nucléaires, no. 4. Paris, Frans: Armand Colin; 1957.
[38] Velasco S, Roco JMM, Medina A, Hernández AC. New performance bounds for a finite-time carnot refrigerator. Phys Rev Lett 1997;78(17):3241–4. https://doi.org/10.1103/PhysRevLett.78.3241.
[39] 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.
[40] Blanchard CH. Coefficient of performance for finite speed heat pump. J Appl Phys 1980;51(5):2471–2. https://doi.org/10.1063/1.328020.
[41] Herold KE, Radermacher R, Klein SA. Absorption chillers and heat pumps. second edition. Boca Raton: CRC Press; 2016.
[42] Varbanov PS, Doyle S, Smith R. Modelling and optimization of utility systems. Chem Eng Res Des 2004;82(5):561–78. https://doi.org/10.1205/026387604323142603.
[43] ASME PTC 10, "Performance Test Code on Compressors and Exhausters." American Society of Mechanical Engineers (ASME), p. 189, 1997.
[44] 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.
[45] 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.
[46] Ul Haq SE, Uddin F, Taqvi SAA, Naqvi M, Naqvi SR. Multistage carbon dioxide compressor efficiency enhancement using waste heat powered absorption chillers. Energy Sci Eng 2021;9(9):1373–84.
[47] Coker AK. Chapter 18 - Compression Equipment (Including Fans). In: Coker AK, editor. Ludwig's Applied Process Design for Chemical and PetroChemical Plants, Fourth Edi. Boston: Gulf Professional Publishing; 2015. p. 729–978.
[48] Al-Douri A, Kazantzi V, Eljack FT, Mannan MS, El-Halwagi MM. Mitigation of operational failures via an economic framework of reliability, availability, and maintainability (RAM) during conceptual design. J Loss Prev Process Ind 2020;67:104261. https://doi.org/10.1016/j.jlp.2020.104261.
[49] Couper JR, Penney WR, Fair JR, Walas SM. Chemical process equipment selection and design, Rev. 2nd ed. Burlington: MA; Elsevier Butterworth-Heinemann; 2009.
[50] Lemmens S. Cost engineering techniques & their applicability for cost estimation of organic rankine cycle systems. Energies 2016;9(7):pp. https://doi.org/10.3390/en9070485.
[51] 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.
[52] United States Department of Energy, "Absorption Chillers for CHP Systems," 2017.
[53] Rissman J, Bataille C, Masanet E, Aden N, Morrow WR, Zhou N, et al. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. Appl Energy 2020;266:114848.
[54] Zimmermann H., and Walzl R., Ethylene, in Ullmann's encyclopaedia of industrial chemistry, vol. 13, pp. 465-530, 2009. https://doi.org/10.1002/14356007.a10_045.pub3.
[55] Woodall CM, Fan Z, Lou Y, Bhardwaj A, Khatri A, Agrawal M, et al. Technology options and policy design to facilitate decarbonization of chemical manufacturing. Joule 2022;6(11):2474–99.
[56] Ozokwelu D, Porcelli J, 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.
[57] Sardarmehni M, Tahouni N, Panjeshahi MH. Benchmarking of olefin plant cold-end for shaft work consumption, using process integration concepts. Energy 2017;127:623–33. https://doi.org/10.1016/j.energy.2017.03.066.
[58] Ren T, Patel M, Blok K. Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. Energy 2006;31(4):425–51. https://doi.org/10.1016/j.energy.2005.04.001.
[59] Hirata K, Kakiuchi H. Energy saving for ethylene process by Adsorption Heat Pump. Appl Therm Eng 2011;31(13):2115–22. https://doi.org/10.1016/j.applthermaleng.2011.03.031.
[60] Brooks F. J., "GE Gas Turbine Performance Characteristics," 2006.
[61] 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.

[62] Sharifzadeh M, Rashtchian D, Pishvaie MR, Thornhill NF. Energy Induced Separation Network Synthesis of an Olefin Compression Section: A Case Study. Ind Eng Chem Res 2011;50(3):1610–23. https://doi.org/10.1021/ie100359a.
[63] Aspen Technology, Aspen Physical Property System: Physical Property Methods, 2013.
[64] Wang T, Ye Z, Wang X, Li Z, Du W. Improved distributed optimization algorithm and its application in energy saving of ethylene plant. Chem Eng Sci 2022;251:117449. https://doi.org/10.1016/j.ces.2022.117449.
[65] AlNouss A, Kazi MK, Mohammed F, Eljack F. Integrated Data (i-Data), Mining and Utilization Approach for Effective Flare Management Strategies. Ind Eng Chem Res 2017;56(10):2789–803. https://doi.org/10.1021/acs.iecr.6b01774.
[66] UK office of Gas and Electricity Markets, Wholesale market indicators, 2022. https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators.
[67] Statista.com, 2023. https://www.statista.com/statistics/1267541/germany-monthly-wholesale-electricity-price/.
[68] Institute for global environmental strategies, List of Grid Emission Factors version 11.0, 2022. https://pub.iges.or.jp/pub/iges-list-grid-emission-factors.
[69] Department for Business, Energy & Industrial Strategy, Greenhouse gas reporting: conversion factors 2022. https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting.
[70] U.S. energy information administration, 2022. https://www.eia.gov/tools/faqs/faq.php?id=74&t=11.
[71] International carbon action partnership (icap), icap allowance price explorer, 2023. https://icapcarbonaction.com/en/ets-prices.