Energy Reports 9 (2023) 820–832

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Advanced exergy analysis of the oil and gas processing plant on an offshore platform: A thermodynamic cycle approach

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ARTICLE INFO

Article history:
Received 15 September 2022
Received in revised form 5 December 2022
Accepted 7 December 2022
Available online xxxx

Keywords:
Advanced exergy analysis
Offshore oil and gas processing
Avoidable exergy destruction
Exogenous exergy destruction

ABSTRACT

Ambitious targets on reduction of greenhouse-gas emissions have motivated further studies to improve energy efficiency in offshore gas and oil production. Identifying the causes of inefficiencies and the improvement potentials within these processes is crucial. The oil and gas processing plant on a North Sea platform is evaluated by advanced exergy analysis for a real production day. The study focuses on components and sub-systems with high exergy destruction through conventional exergy analysis in previous research. Splitting the exergy destruction into endogenous and exogenous parts provides information about mutual interdependencies among the system components. The results show that the inefficiencies of compressors are attributed to their inherent irreversibility, while the exergy destruction within the coolers could particularly be reduced by improving the remaining system components. Further, the total exergy destruction avoidable by improving each single component determines the importance of the components. The results indicate that the compressors have relatively large exergy saving potential (14% of total power consumption), while it is relatively low for coolers. Advanced exergy analysis suggests an optimization sequence different from the conventional exergy analysis. The findings indicate that the improvement efforts should be focused essentially on the compressors, especially for the recompression compressors with anti-surge operations.

1. Introduction

Offshore oil and gas production comprises energy intensive processes and this sector is one of the major contributors of greenhouse gas (GHG) emissions for oil and gas exporting countries. In Norway, the share of GHG emissions originating from oil and gas extractions constituted 27% in 2020 (Statistics Norway, 2020). More than 80% of the CO_2 emissions came from gas turbines used to generate power on the installations. In line with the Paris Agreement, the Norwegian national assembly Storting has, by passing the Climate Change Act, set climate targets that include reducing GHG emissions by at least 50% in 2030 (from reference year 1990) and by at least 90% in 2050 (Lovdata, 2021). The launch of ambitious climate targets, and the large share of energy cost in the overall cost of operation, motivate oil and gas industry to improve the energy efficiency of their processes. Therefore, it is crucial to understand the causes of inefficiency and estimate the improvement potentials in the system.

Exergy analysis has proven as a useful tool to detect the inefficiencies within a system (Dincer and Rosen, 2021). By incorporating both the first and second laws of thermodynamics, exergy analysis is able to identify the location and magnitude of the exergy destructions and losses within a system. There are a number of studies that have analyzed the performance of offshore platforms in terms of exergy. De Oliveira Jr. and Van Hombeeck, 1997 published the first exergy analysis of an offshore installation. This was an exergy analysis of petroleum separation processes on a Brazilian platform. The study pointed out that the heating operations preceding the separation of petroleum were the most exergy consuming processes. Recently several investigations have focused on the platforms in the North Sea. Voldsund et al. (2013) used a method similar to De Oliveira Jr. and Van Hombeeck, 1997 to analyze a real production day of the oil and gas processing plant on one of the Norwegian offshore platforms. It was concluded that most exergy destruction took place in processes that increased pressure (compressors and cooling in the compression trains) or decreased pressure (in pressure reduction valves and recycling). Another study by Voldsund et al. (2014) compared the performance of the oil and gas processing plants on four North Sea oil and gas platforms. This study illustrated that the gas treatment and production manifold systems were responsible for most of the exergy destruction in these four processing plants, even

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https://doi.org/10.1016/j.egyr.2022.12.021

though they differed by their operating conditions and strategies. Similar results were obtained by Nguyen et al. (2014b), where a mature oilfield was assessed by exergy accounting. Nguyen et al. (2013) developed a generic model of North Sea oil and gas offshore platforms, which comprised both processing and utility systems. It was found that the shares of exergy destruction between utility systems and the processing plant were about 65% and 35%, respectively, while the variability of the feed composition had little effect on the shares of the thermodynamic irreversibility between the plants. Nguyen et al. (2014a) also investigated the lifespan performance of an offshore platform by comparing three exploitation periods of an oil field, viz. early-life, plateau and end-life production. They discovered that the distribution of exergy destruction per sub-system changed significantly with time. At the beginning of the field exploitation, most exergy destruction took place in the production manifold and gas treatment, while it mainly occurred in the gas recompression as the field had matured.

Although the benefits of exergy analysis have been highlighted in various applications, the results from an exergy analysis can provide even more insights by also:
(i) Considering the interactions between components.
(ii) Considering the real improvement potentials of the components.

To address these points and improve the quality of the conclusions from the exergy analysis, the concept of advanced exergy analysis was proposed by Tsatsaronis and co-workers (Tsatsaronis and Park, 2002; Morosuk and Tsatsaronis, 2008, 2013; Kelly et al., 2009; Morosuk and Tsatsaronis, 2009a,b; Boyano et al., 2012).

In the present study, this method was applied to an offshore processing plant previously investigated by conventional exergy analysis (Voldsund et al., 2013). The aim was to compare the results of the two methods and, potentially, highlight the advantages of each method. This may enable a better understanding of the irreversibilities of the components in the offshore process plant, and thereby focus efforts on the components and subsystems that have the greater potentials for improvement. The study forms an exemplary case related to an important sector of energy industry. The case selected is relatively simple, which offers some possibility of skilled professionals to make evaluations based on their experience for comparison of both conventional and advanced exergy analysis.

In the following, the system will be described (with reference to Voldsund et al., 2013), the theory for the methods is briefly reviewed, with assumptions and necessary adaptions made for the specific case, before results, discussion and conclusions are presented.

2. System description

The system studied in Voldsund et al. (2013) was also employed here in order to investigate potential benefits of advanced exergy analysis. Readers are referred to Voldsund et al. (2013) for a detailed description of the boundary conditions, process characteristics, simulation of the process flowsheet and calibration of process variables.

A simplified flowsheet of the oil and gas processing at the studied platform is given in Fig. 1. The studied platform represents a typical configuration of offshore platforms in the North Sea, in this case without large process heating duties.

Fluids from the reservoirs are transported from subsea wells through the production flowlines and risers to the topside. The pressures of well streams vary between 80 and 170 barg. They are reduced by manifold throttling valves to approximately 70 barg before being mixed and fed to inlet separators.

In the separation system, well streams are separated into gas, oil and water. The separation system consists of one single train, which comprises three separators with a final coalescer for water removal. The 1st and 2nd-stage separators are three-phase separators, and the 3rd-stage separator is a two-phase separator. As the pressure is reduced from 71 to 2.8 bar through the separators, most of the gas is flashed off from oil in the section.

Downstream the electrostatic coalescer are oil export pumps, transferring the stabilized oil to the oil transportation pipeline.

Produced water separated in the 1st- and 2nd-stage separators is purified in the water treatment system in accordance with the discharge requirement of the authorities, whereas the separated water from the electrostatic coalescer is pumped to the 2nd-stage separator.

Gas from the 2nd and 3rd-stage separators is compressed in the three-stage gas recompression train to meet the 1st stage separator pressure. Each recompression stage consists of a suction cooler, a scrubber and the compressor. The suction cooler ensures a stable inlet temperature on the compressor and a low suction temperature, so that the compressor power is minimized. Liquid that condensates in the suction cooler is knocked out in the scrubber to protect the compressor. The platform has been operated for more than 20 years, and due to reduced oil fraction in the feed streams, and thus reduced flows through the 2nd and 3rd-stage separators, the gas flow rate in the recompression train is significantly reduced compared to what it was designed for. Anti-surge recycle is therefore required around each stage to maintain the stable operation and to protect the machine.

The gas reinjection system compresses the gas from the 1st-stage separator and recompression system to 236 bar to provide pressure support in wells in order to maximize oil recovery. There are three parallel trains, where each train is arranged similar to the recompression system, containing a cooler, a scrubber and a compressor. The reinjection compressors are operated within the defined operating envelope. Therefore, there is no need for anti-surge recycling.

A small portion of gas is taken from the 1st-stage separator and treated in the fuel gas system to provide a continuous supply of clean, conditioned and filtered fuel gas at the specified temperature, pressure and flow rates to the main power generator turbines. The liquid collected from the fuel gas system is sent back to the 2nd-stage separator.

3. Exergy analysis

3.1. Conventional exergy analysis

Exergy analysis is based on the first and second laws of thermodynamics and is employed to calculate the maximum theoretical work obtainable from a system as the system comes into equilibrium with the environment, also referred to as the environmental state. Exergy can also be expressed as the theoretical minimum work that is required to bring a system from the environmental state to its real state (Kotas, 2012).

By neglecting the effects of motion and gravity, the molar exergy e is calculated as the sum of molar physical exergy and molar chemical exergy,

$$e = e^{ph} + e^{ch} \tag{1}$$

where

$$e^{ph} = (h - h_0) - T_0(s - s_0) \tag{2}$$

$$e^{ch} = \sum_i x_i e^{ch}_{i,0} + (h_0 - \sum_i x_i h_{i,0} - T_0(s_0 - \sum_i x_i s_{i,0})) \tag{3}$$

Here, h and s are the molar enthalpy and entropy, h_0 and s_0 represent the respective values of these properties evaluated at the ambient temperature and pressure, T_0 and P_0, while x_i is the

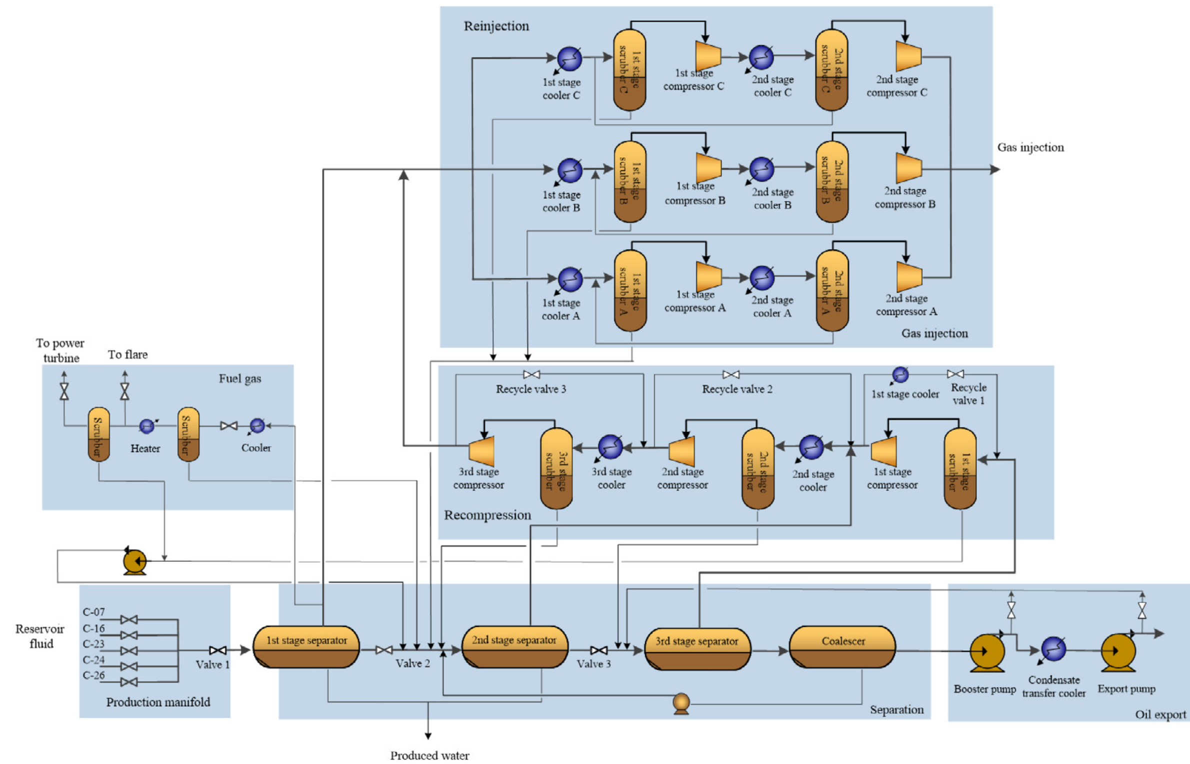

Fig. 1. Simplified process flowsheet of the studied processing plant.

mole fraction and $e_{i,0}^{ch}$ the molar chemical exergy of the individual species i. The last term of Eq. (3) represents the reversible work of separating the mixture to pure species at T_0 and P_0 (Voldsund et al., 2013, 2014).

In conventional exergy analysis the exergy balance of the kth component in a system at steady state is formulated as

$$E_{F,k} = E_{P,k} + E_{D,k} \tag{4}$$

Here, the fuel exergy, E_F, is the exergetic resources expended to generate the desired production exergy, E_P. The exergy destruction, E_D, is the exergy destroyed due to the irreversibility within the kth component. The destroyed exergy represents lost work and can be used to measure the thermodynamic performance of the system. The sum of the exergy destruction in the components of the system is the total exergy destruction of the investigated system.

The exergy destruction ratio for each component is defined as the share of the total exergy destruction occurring in this component,

$$y_{D,k} = \frac{E_{D,k}}{\sum E_{D,j}} \tag{5}$$

This ratio is a useful variable for comparison of dissimilar components. It measures the contribution of the exergy destruction within the kth component to the total exergy destruction of the overall system. The exergy discharged with effluents (cooling water), i.e., the exergy destruction due to its mixing with the environment, was not included in the calculation of the ratio.

3.2. Advanced exergy analysis

Through a conventional exergy analysis, the components with a high irreversibility in a system are identified. However, the origins and inevitability of the exergy destruction in each component are not clearly expressed. In advanced exergy analysis this is addressed by splitting the exergy destruction into endogenous/exogenous and avoidable/unavoidable parts. In the present study, a thermodynamic cycle approach as suggested by Morosuk and Tsatsaronis (2008) was applied to calculate different types of exergy destruction of the components in the offshore oil and gas processing plant.

3.2.1. Endogenous and exogenous exergy destruction

As mentioned, the irreversibility of a component does not only occur due to inefficiencies of the component itself but may also be caused by irreversibilities of other components that are associated with it. Advanced exergy analysis divides the irreversibility into endogenous and exogenous parts, which reveals the causes of the irreversibility.

The endogenous exergy destruction $E_{D,k}^{EN}$ within the kth component is caused by the irreversibility taking place in the component itself. It can be determined by establishing Hybrid Process 1, with the assumption that all other components operate ideally, and the kth component operates under real conditions, i.e. with its current efficiency (Morosuk and Tsatsaronis, 2008). The exergy destruction within the kth component obtained in Hybrid Process 1 represents then the endogenous exergy destruction of this component.

The remaining part of the exergy destruction is the exogenous exergy destruction, which is caused by interaction between the kth component and other components, is acquired from

$$E_{D,k}^{EX} = E_{D,k} - E_{D,k}^{EN} \tag{6}$$

To establish Hybrid Process 1, ideal operating conditions for each component must be determined. These are defined as the conditions where $E_D = 0$ (or $E_D = \min$ with $\Delta T_{pinch} = 0$ for heat exchangers, Morosuk and Tsatsaronis, 2008). The assumptions for establishing the ideal operating conditions will be further discussed in Section 3.4.

3.2.2. Avoidable and unavoidable exergy destruction

In practice only a part of the exergy destruction within a component can be avoided. The unavoidable exergy destruction describes the part of the exergy destruction that cannot be further reduced due to technological constraints and limitation of materials and manufacturing methods (Morosuk and Tsatsaronis, 2013). Two alternative approaches for calculation of avoidable and unavoidable exergy destruction are described in Tsatsaronis and Park (2002) and Morosuk and Tsatsaronis (2008), respectively. In this study, the avoidable part of the exergy destruction is determined based on the methodology described in Morosuk and Tsatsaronis (2008) through Hybrid Process 2. There, the unavoidable conditions, which correspond to the best achievable efficiency, are introduced simultaneously for all components of the overall system. The unavoidable exergy destruction is the exergy destruction within a component with unavoidable conditions.

The difference between the exergy destruction and the unavoidable exergy destruction gives the avoidable exergy destruction,

$$E_{D,k}^{AV} = E_{D,k} - E_{D,k}^{UN} \quad (7)$$

It should be mentioned that the approach described in Tsatsaronis and Park (2002) is the most widely used approach. However, this approach may predict negative endogenous avoidable exergy destruction in some cases. The negative endogenous avoidable exergy destruction is raised by introduction of the quantity $(\frac{E_{D,k}}{E_{P,k}})^{UN}$, which is used to calculate unavoidable exergy destruction per unit of produced exergy of the kth component. This quantity is calculated by isolating the component from the overall system and assuming that the flows entering the component have the same thermodynamic parameters as in the real case and the unavoidable conditions of the component. In this approach (distinguished with superscript * from the approach used in the current study), the value of the unavoidable exergy destruction for the kth component is then calculated from

$$E_{D,k}^{UN*} = E_{P,k}^{real} \times (E_{D,k}/E_{P,k})^{UN} \quad (8)$$

Similarly, the endogenous unavoidable exergy destruction is calculated by

$$E_{D,k}^{EN,UN*} = E_{P,k}^{EN} \times (E_{D,k}/E_{P,k})^{UN} \quad (9)$$

Subsequently, the endogenous avoidable exergy destruction is obtained by

$$E_{D,k}^{EN,AV*} = E_{P,k}^{EN} - E_{D,k}^{EN,UN*} \quad (10)$$

For the components that have more exergy destruction than product exergy, it is obvious that the value of $(\frac{E_{D,k}}{E_{P,k}})^{UN}$ is larger than 1, which further leads to a negative value of endogenous avoidable exergy destruction.

3.2.3. Combination of split exergy destruction

Endogenous and exogenous exergy destruction can be divided further into avoidable and unavoidable parts. The endogenous unavoidable exergy destruction represents the exergy destruction caused by irreversibilities taking place within the component itself that cannot be avoided due to technical constraints. The endogenous unavoidable exergy destruction within the kth component $(E_{D,k}^{EN,UN})$ is calculated by introducing Hybrid Process 3, where the kth component runs at its unavoidable conditions, and the other components operate under ideal conditions. The endogenous avoidable exergy destruction $(E_{D,k}^{EN,AV})$ represents the part of exergy destruction within the kth component reduceable by improving the efficiency of the kth component (Morosuk and Tsatsaronis, 2013). It is then determined by

$$E_{D,k}^{EN,AV} = E_{D,k}^{EN} - E_{D,k}^{EN,UN} \quad (11)$$

The exogenous unavoidable exergy destruction $\left(E_{D,k}^{EX,UN}\right)$ is the effect of other components on the exergy destruction in the kth component, which is inevitable even if all other components are improved as much as practically possible (Morosuk and Tsatsaronis, 2013). It is calculated by

$$E_{D,k}^{EX,UN} = E_{D,k}^{UN} - E_{D,k}^{EN,UN} \quad (12)$$

Exogenous avoidable exergy destruction $(E_{D,k}^{EX,AV})$ can be reduced by improving the efficiency in the remaining components (Morosuk and Tsatsaronis, 2013), and is calculated by

$$E_{D,k}^{EX,AV} = E_{D,k}^{EX} - E_{D,k}^{EX,UN} \quad (13)$$

3.2.4. Importance of the components

From above it is clear that improvements done in one component can both reduce exergy destruction within the component itself, and within other components. The sum of avoidable exergy destruction that can be avoided throughout the system by improving the kth component demonstrates the importance of the component and should be the most important parameter considered when determining the priority for improvement of the components (Morosuk and Tsatsaronis, 2013). Improving the component reduces the effect of interaction between components. This reduction leads to a decrease in the exergy destruction in the remaining components and in the mexogenous exergy destruction, i.e., the part of exergy destruction that is caused by simultaneous interaction of all other components (Morosuk and Tsatsaronis, 2009b). Therefore, the total avoidable exergy reduction by improving the kth component presents the sum of the endogenous avoidable exergy destruction of the kth component, the exogenous avoidable exergy destruction within the remaining components caused by the kth components and the reduction in mexogenous exergy destruction.

$$E_{D,k}^{AV,total} = E_{D,k}^{EN,AV} + \sum_{\substack{r=1 \\ r\neq k}}^{n} E_{D,r}^{EX,AV,k} + E_{D,k}^{AV,mexo} \quad (14)$$

By evaluating the exergy balance of the overall system that incorporates the kth component at its unavoidable conditions and the other components at their real conditions, namely Hybrid Process 4, facilitates estimating the total avoidable exergy destruction $(E_{D,k}^{AV,total})$ by improving the kth component.

3.3. Calculation procedure

The commercial software Aspen HYSYS was used for the simulations. This process simulator is well equipped for industrial processes and can, with a modest user extension, be used for exergy calculations. However, the procedures of advanced exergy analysis were not implemented. Accordingly, these operations had to be done by the user.

The exergy destruction in each process unit was obtained by using the exergy balance of the unit. Physical exergy and the mixing part of the chemical exergy in the material streams were calculated by creating user variables in HYSYS programmed with Visual Basic code described in Abdollahi-Demneh et al. (2011) and Voldsund et al. (2013), respectively. As described in Voldsund et al. (2013), the chosen property package used the equation of state by Peng and Robinson (1976). The chemical exergies of individual species were not taken into consideration, since the fluid only flowed through the offshore platform, and no chemical reactions took place.

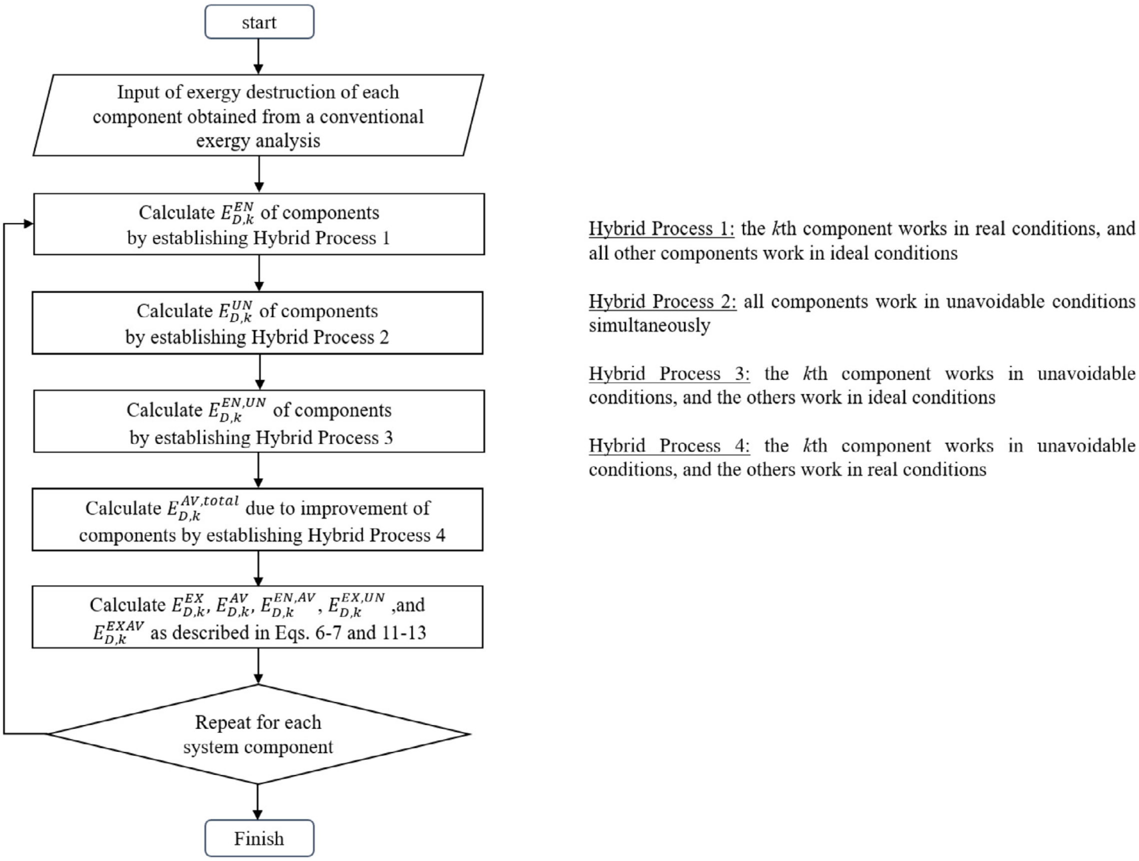

Fig. 2. Flow chart of calculation of different types of the exergy destruction of system components. There is one simulation with each of HP1, HP2, HP3 and HP4 for each component.

Table 1
Assumptions for calculation of exergy destruction rate under real, unavoidable and ideal conditions.

System	Component	Real	Unavoidable	Ideal
Production manifold	Choke valves	Isenthalpic	NA	Isentropic
Recompression train	1st stage compressor	η_{is} = 46.52%	η_{is} = 80%, no anti surge recycle	η_{is} = 100%, no anti surge recycle
	2nd stage compressor	η_{is} = 68.99%		
	3rd stage compressor	η_{is} = 56.38%		
	Recycle valves 1,2,3	Isenthalpic	Mass flow = 0	Mass flow = 0
	1st stage cooler	T_{out} = 39.9 °C, Δp/p =9.4%	Mass flow = 0	Mass flow = 0
	2nd stage cooler	T_{out} = 21 °C, Δp/p = 9.0%	T_{out} = 21 °C, Δp/p = 1%	T_{out} = 17 °C, Δp/p = 0%
	3rd stage cooler	T_{out} = 24 °C, Δp/p = 2.4%	T_{out} = 22 °C, Δp/p = 1%	T_{out} = 17 °C, Δp/p = 0%
Reinjection A	1st stage cooler A	T_{out} = 28 °C, Δp/p = 1.7%	T_{out} = 22 °C, Δp/p = 1%	T_{out} = 17 °C, Δp/p = 0%
	1st stage compressor A	η_{is} = 63.85%	η_{is} = 80%	η_{is} = 100%
	2nd stage cooler A	T_{out} = 28 °C, Δp/p = 0%	T_{out} = 22°C, Δp/p = 0%	T_{out} = 17 °C, Δp/p = 0%
	2nd stage compressor A	η_{is} = 54.40%	η_{is} = 80%	η_{is} = 100%
Reinjection B	1st stage cooler B	T_{out} = 28 °C, Δp/p = 1.6%	T_{out} = 22 °C, Δp/p = 1%	T_{out} = 17 °C, Δp/p = 0%
	1st stage compressor B	η_{is} = 63.77%	η_{is} = 80%	η_{is} = 100%
	2nd stage cooler B	T_{out} = 28 °C, Δp/p = 0.5%	T_{out} = 22 °C, Δp/p = 0.5%	T_{out} = 17 °C, Δp/p = 0%
	2nd stage compressor B	η_{is} = 56.89%	η_{is} = 80%	η_{is} = 100%
Reinjection C	1st stage cooler C	T_{out} = 30 °C, Δp/p = 5.6%	T_{out} = 22 °C, Δp/p = 1%	T_{out} = 17 °C, Δp/p = 0%
	1st stage compressor C	η_{is} = 68.75%	η_{is} = 80%	η_{is} = 100%
	2nd stage cooler C	T_{out} = 30 °C, Δp/p = 2%	T_{out} = 22 °C, Δp/p = 1%	T_{out} = 17 °C, Δp/p = 0%
	2nd stage compressor C	η_{is} = 64.34%	η_{is} = 80%	η_{is} = 100%

The procedure for calculation of the different types of exergy destruction are summarized in Fig. 2. Table 1 shows the assumptions of real, ideal and unavoidable conditions constituting the hybrid processes. These assumptions are elaborated in Section 3.4. As indicated, the conventional analysis was run first. Then, for each component, k, the system was set up as a Hybrid Process 1, with all other components in ideal conditions, to establish the endogenous exergy destruction of the kth component. Subsequently, Hybrid Processes 2, 3 and 4 were set up and run to calculate the unavoidable, endogenous unavoidable and total avoidable exergy destruction of this component. This procedure, with 4 different simulations, was repeated for each component. Altogether, with K components, a total of $4K$ simulations had to be conducted for the system, in addition to the initial one of the conventional analysis. Presumably, future software can take care of the operations of the method.

3.4. Assumptions

3.4.1. Ambient conditions

To calculate exergy quantities for the conventional and advanced exergy analyses, ambient conditions of $T_0 = 8$ °C and $p_0 = 1$ atm were assumed. These were regarded representative for North Sea locations.

3.4.2. Ideal conditions

For defining the ideal conditions of each component, reversible conditions where $E_D = 0$ were assumed. When this was not possible, the conditions with a minimum value of E_D were used, as suggested by Morosuk and Tsatsaronis (2008).

At 100% efficiency, the compressor would have an exergy destruction equal to zero. Thus, the isentropic efficiencies of all compressors were assumed to unity. In addition, for those compressors that were protected by anti-surge recycle, no anti-surge recycle was assumed under the ideal conditions.

In the heat transfer process, it was not possible to define ideal conditions with $E_D = 0$. The minimum exergy destruction is attainable when temperature difference between the cooling medium and the process stream is reduced to minimum ($\Delta T_{pinch} = 0$) (Morosuk and Tsatsaronis, 2008), and no pressure drop occurs in the heat transfer process. These conditions were therefore defined as ideal conditions for heat exchangers.

Valves were evaluated differently depending on their locations in the system. Ideal conditions for the manifold throttling valves was defined as isentropic expansion. Exergy destruction within the anti-surge valves was caused by off-design operating conditions of associated compressors. Ideal conditions for the anti-surge valves were therefore defined as zero flow rate through these valves.

3.4.3. Unavoidable conditions

Unavoidable conditions are the operating conditions constrained by physical and economic limitations. They are based on the authors' knowledge and experience (Morosuk and Tsatsaronis, 2013).

In the present analysis, the compressors were assumed operated at 80% isentropic efficiency. Similar to the definition of ideal conditions, compressors that had a majority of gas recycled for anti-surge protection were assumed to be revamped to fit the current flowrate. Consequently, exergy destruction taking place in the anti-surge valves can theoretically all be eliminated.

The avoidable exergy destruction of a cooler depends on the stream outlet temperature, which is constrained by the cooling medium inlet temperature. For each cooler, a 5 °C temperature difference was assumed between the stream outlet temperature and the cooling medium inlet temperature. An exception was made for coolers that already had a temperature difference less than 5 °C. Then, the temperature in the real system was used.

The manifold throttling valve functions only to decrease the pressure of the well streams, and no meaningful exergy efficiency can be defined for the valves alone (Lazzaretto and Tsatsaronis, 2006). Replacing the valves with other devices such as expanders, reduces the exergy destruction. However, the application of such devices faces some challenges considering the state-of-art technology. Hence, the exergy destruction in these valves was regarded unavoidable.

4. Results

4.1. Conventional exergy analysis

Exergetic assessment based on real process data for the investigated platform was performed by Voldsund et al. (2013).

Table 2
Results for conventional exergy analysis of the oil and gas processing plant.

System	Components	$E_{D,k}$ (kW)	$y^*_{D,k}$ (%)
Production manifold	Valve @ Manifold C-07	853	4.6
	Valve @ Manifold C-16	934	5.0
	Valve @ Manifold C-23	1634	8.8
	Valve @ Manifold C-24	383	2.1
	Valve @ Manifold C-26	364	2.0
	Valve 1	253	1.4
	Other components	196	1.1
	Total	4617	24.9
Separation train	Valve 2	414	2.2
	Valve 3	39	0.2
	Other components	370	2.0
	Total	823	4.4
Recompression train	1st stage compressor	380	2.1
	2nd stage compressor	398	2.1
	3rd stage compressor	638	3.4
	Recycle 1	300	1.6
	Recycle 2	655	3.5
	Recycle 3	738	4.0
	1st stage cooler	141	0.8
	2nd stage cooler	199	1.1
	3rd stage cooler	276	1.5
	Other components	125	0.7
	Total	3851	20.8
Reinjection train A	1st stage compressor	736	4.0
	2nd stage compressor	815	4.4
	1st stage cooler	265	1.4
	2nd stage cooler	396	2.1
	Other components	0.11	0.001
	Total	2211	11.9
Reinjection train B	1st stage compressor	803	4.3
	2nd stage compressor	769	4.2
	1st stage cooler	279	1.5
	2nd stage cooler	451	2.4
	Other components	0.12	0.001
	Total	2302	12.4
Reinjection train C	1st stage compressor	1160	6.3
	2nd stage compressor	1178	6.4
	1st stage cooler	671	3.6
	2nd stage cooler	821	4.4
	Other components	0.17	0.001
	Total	3830	20.7
Reinjection train[a]	Other components	134	0.7
	Total	8477	45.8
Fuel gas system	Heater	139	0.8
	Valve 4	140	0.8
	Valve 5	182	1.0
	Other components	48	0.3
	Total	508	2.7
Export pumping	Booster pump	38	0.2
	Export pump	77	0.4
	Cooler	81	0.4
	Other components	47	0.3
	Total	244	1.3
	Total exergy destroyed	18 520	
	Exergy discharged	2188	

[a]Total exergy destruction for Reinjection train is the sum up of exergy destructed in trains A, B, C and mixer, splitter (denoted as "Other components") upstream the reinjection train.

There, the exergy destruction rates were reported by type of components and system, while in this study, the exergy destruction rate is calculated and presented on component level, as summarized in Table 2. Viewing the exergy destruction on component level enables the comparison between components and makes it possible to conclude the priority of main components for improvement.

The total power consumption was 23 800 kW, including 18 640 kW for the reinjection trains, 4700 kW for the

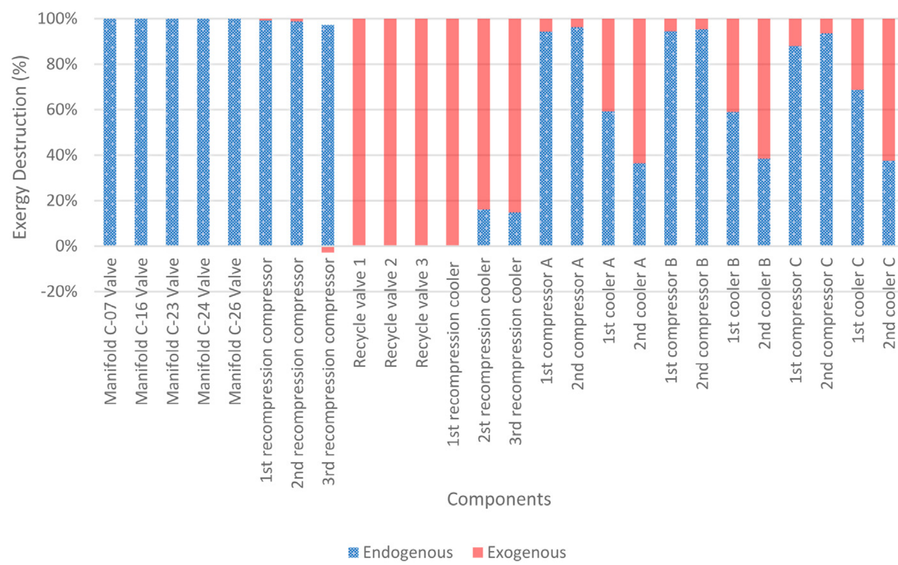

Fig. 3. Breakdown of exergy destruction into endogenous and exogenous exergy destruction for main components.

recompression train, 320 kW for the export section and 156 kW for the fuel gas system (Voldsund et al., 2013).

It is worth mentioning that some minor changes were made for the calculation of exergy destruction rates for all coolers in the system compared to Voldsund et al. (2013). In this study, we distinguished between exergy destruction within the coolers and exergy loss due to irreversible mixing of the discharged cooling medium into seawater, while in Voldsund et al. (2013) this was calculated as one value.

It is clear, as indicated by the exergy destruction ratio in Table 2, that the throttling valve at manifold of well C-23 had the largest exergy destruction rate: 1634 kW exergy was destroyed due to a significant pressure drop over the valve. Moreover, both compressors in the Reinjection train C had a high exergy destruction rate. Totally, 2338 kW exergy was destroyed in these two compressors due to a high flow rate in Reinjection train C and low isentropic efficiency of the compressors. Apart from the components mentioned above, most of the exergy destruction in the system was distributed among valves, compressors and coolers, ranging from 300 kW to 935 kW.

Pumps, however, had relatively low exergy destruction. This was also reported for separators, mixers and splitters, and the exergy destruction of these components is grouped as "other components" in the table. The low exergy destruction implies that these components do not have a significant effect on the overall system efficiency.

For the perspective of the overall system, the gas treatment train gave the biggest portion of exergy destruction and accounted for 45% of the total exergy destruction. The production manifold and recompression train followed with relatively large exergy destruction values, while those for the separation and export train were low.

It should be noted that since valves are dissipative components, these are not taken into consideration when prioritizing the components for improvement. Therefore, based on the results obtained from conventional analysis, the overall system should be improved following priorities for components with higher exergy destruction: the compressors in Reinjection train C should be improved first, the second priority is the 2nd stage cooler in Reinjection train C, and the third priority is simultaneously the improvement of 2nd stage compressor and 1st stage compressor in Reinjection trains A and B, respectively. Pumps and separators were less important with respect to improvement of the overall system.

4.2. Advanced exergy analysis

As suggested by the conventional exergy analysis, it is more meaningful and advisable to focus on the components and the sub-systems with a large exergy destruction. Thus, advanced exergy analysis was performed on the systems of production manifold, recompression train and reinjection train, which provided the greatest opportunities for improvement. The detailed results of advanced exergy analysis for the main components are presented in Table 3 and Figs. 3–5.

As shown in Fig. 3, the proportion of endogenous exergy destruction differed significantly from component to component. Compressors had always a high percentage of endogenous exergy destruction, amounting to 88% or more. This implied that the greatest contribution to the exergy destruction rate was the internal irreversibilities of the compressors themselves. A negative value of exogenous exergy rate was observed for the 3rd-stage recompression compressor. Such negative values can occur when introducing ideal conditions, changing the mass flow rate and stream composition for the compressor in the hybrid processes used to determine the parts of exergy destruction. Indeed, the exergy destruction itself (sum of all parts) will be positive.

The proportion of endogenous destruction rate varied for coolers. Some coolers had a higher value of endogenous exergy, while some had a higher value of exogenous destruction. Exogenous exergy destruction dominated within coolers in the recompression train. This could be explained as these coolers were under the influence of other components, specifically the recompression compressors. Eliminating operation of anti-surge recycle around the compressor would result in a declined flow through these coolers and consequently, reduce the exergy destruction. In the reinjection trains, the first-stage coolers had more endogenous exergy destruction than exogenous, while in the second-stage coolers the exogenous exergy destruction was the larger part. A higher value of exogenous exergy destruction indicated that to reduce the exergy destruction, it is more effective to improve the performance of remaining components.

Considering the valves installed on the anti-surge recycle lines, the exergy destruction was exclusively exogenous as explained in Section 3.4.1. Zero exergy destruction for anti-surge valves was attainable by improving the associated compressors. Conversely, valves at the production manifold were exclusively endogenous. The exergy destruction within the manifold throttling valves can only be decreased by replacing them with other devices.

Table 3
Results for advanced exergy analysis of oil and gas processing plant.

System/Component	$E_{D,k}$ (kW)	$E^{EN}_{D,k}$ (kW)	$E^{EX}_{D,k}$ (kW)	$\frac{E^{EN}_{D,k}}{E_{D,k}}$ (–)	$E^{AV}_{D,k}$ (kW)	$E^{UN}_{D,k}$ (kW)	$\frac{E^{AV}_{D,k}}{E_{D,k}}$ (–)	$E^{EN,AV}_{D,k}$ (kW)	$E^{EN,\ UN}_{D,k}$ (kW)	$E^{EX,AV}_{D,k}$ (kW)	$E^{EX,UN}_{D,k}$ (kW)	$E^{AV,\ total}_{D,k}$ (kW)
Production manifold												
Manifold C-07 Valve	853	853	0	1	0	853	0	0	853	0	0	–
Manifold C-16 Valve	934	934	0	1	0	934	0	0	934	0	0	–
Manifold C-23 Valve	1634	1634	0	1	0	1634	0	0	1634	0	0	–
Manifold C-24 Valve	383	383	0	1	0	383	0	0	383	0	0	–
Manifold C-26 Valve	364	364	0	1	0	364	0	0	364	0	0	–
Recompression train												
1st stage compressor	380	377	3	0.99	374	6	0.98	370	7	4	−1	880
2nd stage compressor	399	394	5	0.99	320	78	0.80	315	79	5	0	1244
3rd stage compressor	639	658	−19	1.04	579	60	0.91	586	72	−7	−12	1670
Recycle valve 1	300	0	300	0	300	0	1	0	0	300	0	0
Recycle valve 2	655	0	655	0	655	0	1	0	0	655	0	0
Recycle valve 3	738	0	738	0	738	0	1	0	0	738	0	0
1st stage cooler	141	0	141	0	141	0	1	0	0	141	0	0
2nd stage cooler	200	32	168	0.16	183	17	0.92	26	5	157	11	140
3rd stage cooler	277	41	236	0.15	217	59	0.79	4	36	213	23	40
Reinjection A												
1st stage compressor	736	694	42	0.94	404	332	055	384	310	20	22	525
2nd stage compressor	815	784	31	0.96	563	252	0.69	547	237	16	15	560
1st stage cooler	265	157	108	0.59	22	244	0.08	17	140	4	103	50
2nd stage cooler	396	144	252	0.36	160	236	0.40	6	138	154	98	−9
Reinjection B												
1st stage compressor	803	759	44	0.95	442	362	0.55	422	338	20	24	577
2nd stage compressor	769	732	36	0.95	503	265	0.65	488	245	15	21	502
1st stage cooler	280	165	115	0.59	20	260	0.07	15	149	5	110	57
2nd stage cooler	451	173	278	0.38	172	278	0.38	3	170	169	109	−15
Reinjection C												
1st stage compressor	1160	1020	140	0.88	562	598	0.48	455	565	107	34	669
2nd stage compressor	1161	1086	75	0.92	627	533	0.54	592	494	35	39	644
1st stage cooler	671	461	210	0.69	200	471	0.30	189	271	10	200	531
2nd stage cooler	821	308	513	0.37	383	438	0.47	40	267	342	171	27

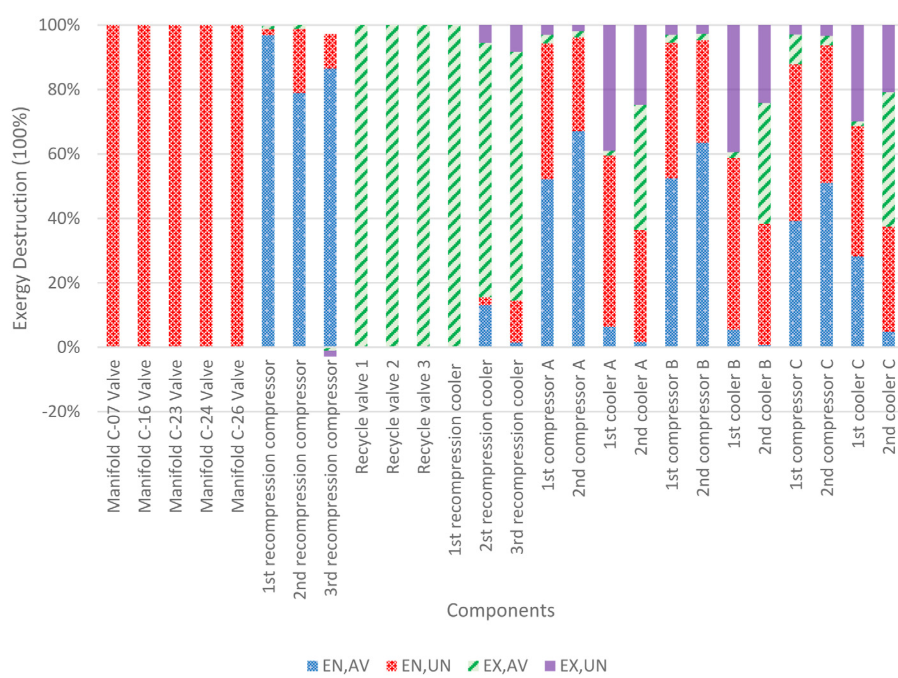

Fig. 4. Breakdown of exergy destruction into endogenous avoidable, endogenous unavoidable, exogenous avoidable and exogenous unavoidable parts for main components.

Fig. 4 outlines the percentages of exergy destruction further split into endogenous avoidable, endogenous unavoidable, exogenous avoidable, and exogenous unavoidable exergy destruction. Endogenous avoidable and exogenous avoidable exergy destruction indicate the influence of irreversibility of the component itself, and of the remaining components, on improving potential for the investigated components. As shown in Table 3, the endogenous avoidable part of the exergy destruction within most of the compressors was higher than the other parts. This meant that efforts should be made to improve each compressor's performance in order to reduce the exergy destruction rate. For components such as anti-surge valves and coolers in the

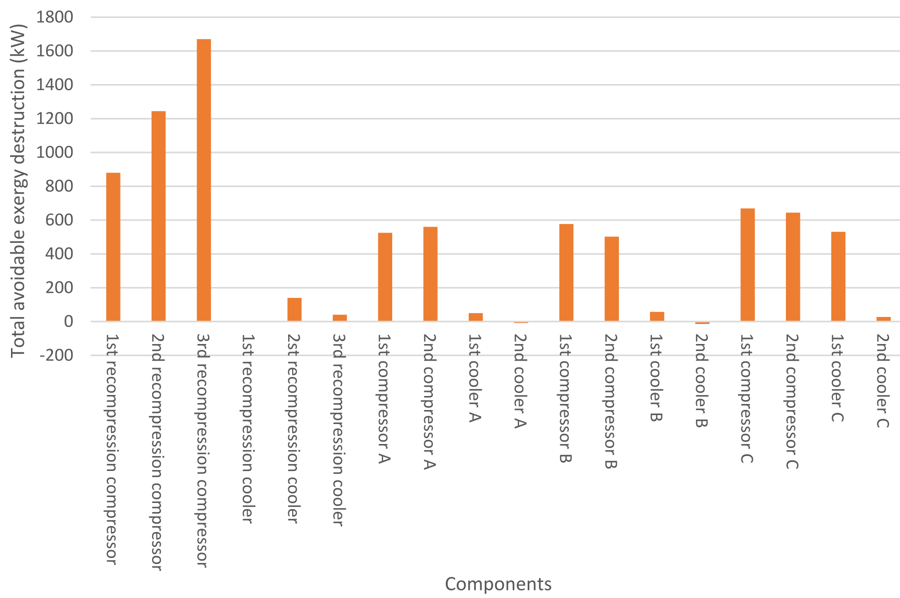

Fig. 5. Total avoidable exergy destruction by improving the main components.

recompression train and 2nd-stage coolers in the reinjection train, the value of exogenous avoidable exergy destruction was greater than the values of endogenous avoidable and exogenous unavoidable. Therefore, it can be concluded that to reduce the exergy destruction within these components, it is more efficient to improve the conditions of other components. The first stage coolers in the reinjection train, on the other hand, had higher values of endogenous unavoidable and exogenous unavoidable exergy destruction. This indicated that the effect is insignificant when it comes to any improvement to reduce the exergy destruction in the coolers.

However, to reveal the real improvement potential and determine the priority for improvement, the total avoidable exergy destruction associates to the improvement of the components, $E_{D,k}^{AV,\ total}$, gives the best indication. It is noticeable from Fig. 5 that the compressors had relatively large exergy saving potential, especially for the compressors with anti-surge operations. This also implies that the compressors operate far from their optimal point at current operating conditions. Coolers, on the other hand, have relatively low exergy saving potential. Improving the coolers will not lead to improvement of the overall system.

4.3. Comparison with conventional exergy analysis

By splitting the exergy destruction into different parts, the advanced exergy analysis provides more insight than the conventional exergy analysis. For offshore oil and gas processes, the improvement priorities suggested by the advanced exergy analysis can be useful, especially for retrofit projects. For instance, when revamp of a compressor is necessary to limit anti-surge recycle, the improvement priorities can provide a more effective way for improving the overall system.

The improvement priorities based on the advanced exergy analysis of the studied process are presented in Table 4, with comparison to the results obtained from the conventional exergy analysis. For the conventional exergy analysis, the improvement priorities were sorted based on the values of exergy destruction in each unit without considering the valves. The sequence for optimization based on the advanced exergy analysis was determined from the total avoidable exergy destruction by improving the component (Fig. 5).

The advanced exergy analysis suggested the three compressors in the recompression train to be optimized first. The benefit of optimization of the compressors on power consumption were demonstrated by running the simulation that assumed the recompression compressors to be operated within the operation envelope, i.e., no need for anti-surge recycle. The simulation showed that 3500 kW power, meaning 14% of total power consumption were saved by avoiding the anti-surge operation around the recompression compressor.

4.4. Comparison between alternative approaches

As part of the investigation, the studied platform was previously analyzed by the approach applied by Tsatsaronis and Park (2002) to evaluate the avoidable part of exergy destruction, and the results were presented by Sheng et al. (2019). In Table 5, the avoidable and endogenous avoidable exergy destruction obtained from the approach of Morosuk and Tsatsaronis (2008) are compared to those of the approach described by Tsatsaronis and Park (2002). It was seen that the avoidable and endogenous avoidable exergy destruction obtained by both approaches were in good agreement for components where endogenous exergy destruction governs. On the other hand, large deviations were observed for components with large exogenous exergy destruction. Moreover, the approach of Morosuk and Tsatsaronis (2008) predicted a positive endogenous exergy destruction for the components that had negative values by using the approach of Tsatsaronis and Park (2002).

5. Discussion

5.1. Sensitivity study

During the calculation of avoidable and unavoidable exergy destruction, no unavoidable conditions were assumed for the manifold throttling valves. Thus, a sensitivity analysis was conducted to investigate the effect of this assumption on the results of the analysis. Since the throttling valve is the first component in the process, it will not be influenced by other components.

For the sensitivity analysis, manifold throttling valves with large pressure drop were assumed to be substituted with multiphase expanders, with an efficiency ranging from 30% to 50%. It

Table 4
Suggested optimization sequence from conventional and advanced exergy analysis.

Improvement priority	Conventional exergy analysis	Advanced exergy analysis
1	2nd stage reinjection compressor C	3rd stage recompression compressor
2	1st stage reinjection compressor C	2nd stage recompression compressor
3	2nd stage reinjection cooler C	1st stage recompression compressor
4	2nd stage reinjection compressor A	1st stage reinjection compressor C
5	1st stage reinjection compressor B	2nd stage reinjection compressor C

Table 5
Comparison of results based on alternative approaches.

System/Component	Approach of Morosuk and Tsatsaronis (2008)	Approach of Tsatsaronis and Park (2002)	Relative deviation	Approach of Morosuk and Tsatsaronis (2008)	Approach of Tsatsaronis and Park (2002)	Relative deviation
	$E^{AV}_{D,k}$ (kW)	$E^{AV*}_{D,k}$ (kW)	(%)	$E^{EN,AV}_{D,k}$ (kW)	$E^{EN,AV*}_{D,k}$ (kW)	(%)
Recompression train:						
1st stage compressor	374	372	−0.5	370	371	0.3
2nd stage compressor	320	324	1.3	315	314	−0.3
3rd stage compressor	579	569	−1.7	586	583	−0.5
2nd stage cooler	183	87	−55.5	26	−2	−107.7
3rd stage cooler	217	49	−77.4	4	24	500.00
Reinjection A:						
1st stage compressor	404	385	−4.7	384	380	−1.0
2nd stage compressor	563	542	−3.7	547	538	−1.6
1st stage cooler	22	42	90.9	17	2	−88.2
2nd stage cooler	160	9	−94.4	6	−81	−1450
Reinjection B:						
1st stage compressor	442	421	−4.8	422	417	−1.2
2nd stage compressor	503	489	−2.8	488	483	−1.0
1st stage cooler	20	59	195.0	15	−1	−106.7
2nd stage cooler	172	9	−94.8	3	−85	−2933.3
Reinjection C:						
1st stage compressor	562	489	−13.0	455	471	3.5
2nd stage compressor	627	611	−2.6	592	600	1.4
1st stage cooler	200	268	34.0	189	189	0.0
2nd stage cooler	383	88	−77.0	40	−71	−277.5

should be noted that substitution of valves with expanders will influence the outlet temperature, which again will influence the phase separation in the separation train. These effects are not investigated here. Fig. 6 presents the effect of the assumption on the exergy destruction of the overall system: A total of 1200–2000 kW power was generated for expander efficiencies between 30%–50%. The reduced exergy destruction by replacing the throttling valves was slightly less than the produced power, meaning that the exergy destruction increased within other components. This increase was due to the changed flowrate through the downstream process, caused by marginal drops in temperature through the expanders. However, this effect of other components was insignificant, indicating the assumption with respect to the manifold throttling valves only had a small impact on the obtained results.

The specific power consumption, defined as consumed power per unit oil produced, is one of the performance indicators used to assess the offshore oil and gas processes (Voldsund et al., 2013). A parametric study on compressor efficiency was conducted to show how the specific power consumption responses to the improvement of compressors. For each compressor, the isentropic efficiency was increased stepwise by 5%, 10% and 15% from the real values in Table 1. Only one compressor was investigated at a time, while the operating parameter of other components were kept constant at the value of the real processes (Table 1). The dependencies of specific power consumption on compressor isentropic efficiencies is shown in Fig. 7. It can be seen that the improvement of recompression compressors effectively reduced the specific power consumption. The decline of specific power consumption was mainly attributed to the avoidance of the anti-surge recycles, while the compressor efficiency itself was less important. The reinjection compressors had similar effects on the specific power consumption, and the benefit of enhancement of compressors in Reinjection train C become obvious with increasing compressor efficiency. It is also noted that the capability of reducing power consumption by improving the single compressor followed the improvement priorities from the advanced exergy analysis. This can be seen as confirming the improvement priorities proposed by the advanced exergy analysis.

5.2. Uncertainty

Advanced exergy analysis was performed based on the results of the conventional analysis; thus the input data are destroyed exergy of each system component. An uncertainty analysis was performed by Dincer and Rosen (2021) to investigate the uncertainties in calculated destroyed exergy originating from measurement and inaccuracies in the equation of state. The results implied that the uncertainties of exergy destruction related to the gas processing, as the subject of this study, were small, and did not exceed 5% for the exergy destruction.

5.3. Suggestion of process improvement

An advanced exergy analysis was performed for a specific North Sea platform. Mapping the irreversibility causes and improvement potentials gave indications for process improvement. The evaluation suggested that the compressors have the highest improvement potential, particularly the compressors that are operated with anti-surge recycle as a consequence of off-design operation. Measures to minimize the recycle on reduced gas

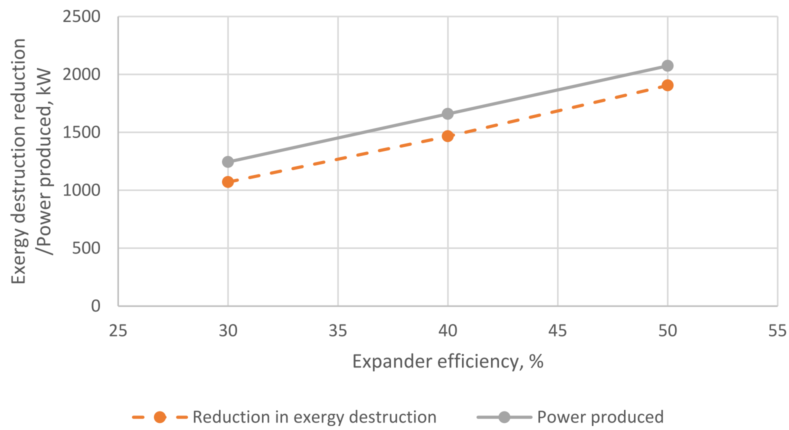

Fig. 6. Effect of replacing throttling valves with multiphase expanders.

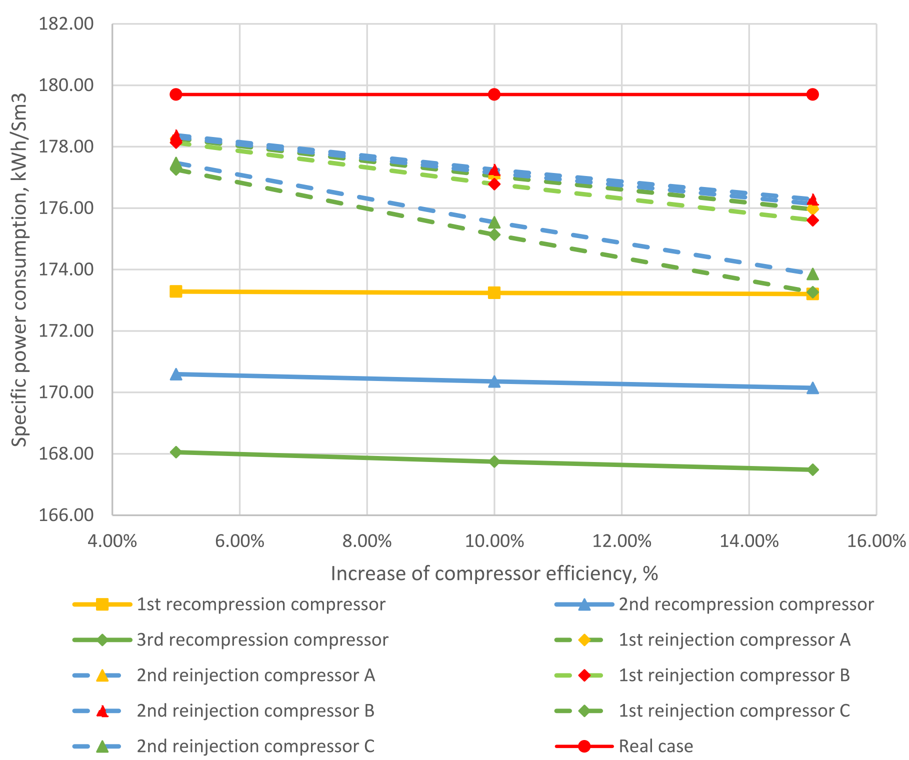

Fig. 7. Effect of increasing compressor efficiency (% points from real values of Table 1) on specific power consumption. One compressor is changed at the time, while others are kept at their real values. The Real case value is included for reference.

flowrate, and to maintain high compressor efficiency, are of importance to reduce the power consumption. An example is revamping the compressors for current and future production when recycle cannot be avoided. Measures proposed by Svalheim and King (2003), such as integration of variable speed drives when significant flowrate changes are anticipated over the field lifetime, and installation of compressors of different capacity in parallel, can effectively reduce the power consumption and improve the performance of the overall system.

Attention should also be paid to the exergy destructed in the production manifold caused by pressure drops over the production throttling valves. For high-pressure wells, a multiphase expander might be an option to recover exergy from the well streams, leading to smaller exergy destruction rates (Rawlins and Ross, 2002). However, this technology is not yet matured, and it faces some challenges for offshore application. The efficiency of such devices will suffer from the instable flowrate of reservoir fluid, and from decreased well pressure as the field is aging. The presence of significant amounts of impurities, and potentially sand, also hinders the practical application of the device. An example of a successful improvement was the application of a multiphase ejector for boosting production and bringing shut-in wells back into production (Andreussi et al., 2003). The demonstrated benefit of such devices should be further examined. It should be noted that installing expanders will impact the downstream temperature, that might affect the separation process in the 1st stage separator.

Exergy losses related to dissipation of heated cooling water into the sea was not part of the advanced exergy analysis. However, as it accounted for approximately 10% of the total destroyed exergy (Voldsund et al., 2013), it should be investigated. Utilization of warm process streams will lead to saving of cooling water and reduce the exergy loss to the environment. Nevertheless, this temperature is relatively low, and waste heat from gas turbines is the preferred heating source for the platforms that have such turbines. However, for electrified platforms, with no waste heat from turbines, warm process streams may be the candidate to provide heat to different heat consumers through heat pumps.

6. Conclusions

Advanced exergy analysis based on a thermodynamic cycle approach has been performed on oil and gas processing to reveal the causes of inefficiencies and improvement potentials of components and the overall system. The main conclusions that can be drawn from the results are summarized as:

- The improvement priorities obtained using advanced exergy analysis differ from those obtained with conventional exergy analysis.
- For the investigated system, the advanced exergy analysis prioritizes improvement of the recompression compressors, whereas the conventional exergy analysis indicates that reinjection compressors and a reinjection cooler are more important. A parametric study on compressor efficiency confirms the improvement priority from the advanced exergy analysis.
- The shares of endogenous and exogenous exergy destruction vary considerably from component to component. Compressors have more endogenous than exogenous exergy destruction. Thus, the influence from other components is low. The proportion of exogenous exergy destruction within the coolers is relatively higher, which means that the irreversibility in a cooler strongly depends on the other components.
- The results show that compressors have higher energy saving potential. On the contrary, the energy saving potential for coolers is relatively low.
- A reduction of 14% in power consumption of analyzed production day is achievable by optimizing the components with highest exergy saving potential, i.e., the recompression compressors.

It should be noted that the results obtained in the advanced exergy analysis are valid for current operating conditions, and they may change due to varying conditions over field lifetime. A further study with more focus on the extension to different operation stages is therefore suggested.

CRediT authorship contribution statement

Juejing Sheng: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mari Voldsund:** Conceptualization, Data curation, Methodology, Resources, Software, Supervision, Writing – review & editing. **Ivar S. Ertesvåg:** Conceptualization, 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

The underlying data are available in previous articles, in particular Voldsund et al. (2013).

Acknowledgments

This study has been funded by HighEFF - Centre for an Energy Efficient and Competitive Industry for the Future, an 8-years' Research Centre under the FME-scheme (Centre for Environment-friendly Energy Research, 257632/E20). The authors gratefully acknowledge the financial support from the Research Council of Norway and user partners of HighEFF.

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