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# Oil and gas platforms with steam bottoming cycles: System integration and thermoenvironomic evaluation

Tuong-Van Nguyen [a,b,*], Laurence Tock [b], Peter Breuhaus [c], François Maréchal [b], Brian Elmegaard [a]

[a] Section of Thermal Energy, Department of Mechanical Engineering, Technical University of Denmark, Building 403, Nils Koppels Allé, 2800 Kongens Lyngby, Denmark
[b] Industrial Process and Energy Systems Engineering Laboratory, École Polytechnique Fédérale de Lausanne, Station postale 9, 1015 Lausanne, Switzerland
[c] Department of Energy, International Research Institute of Stavanger, Professor Olav Hanssens vei 15, 4021 Stavanger, Norway

## HIGHLIGHTS

- The energy demand of a North Sea platform is systematically analysed.
- The integration of steam bottoming cycles is investigated, considering energy, economic and environmental criteria.
- The fuel gas consumption and total $CO_2$-emissions can be reduced by more than 15%.

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## ABSTRACT

The integration of steam bottoming cycles on oil and gas platforms is currently regarded as the most promising option for improving the performance of these energy-intensive systems. In this paper, a North Sea platform is taken as case study, and a systematic analysis of its energy requirements is conducted. The site-scale integration of steam networks is evaluated, based on thermodynamic, economic and environmental performance indicators. The penalties induced by operational restrictions such as (i) the use of a heat transfer loop, (ii) the demand for a heat buffer, (iii) the selection of a specific cooling utility, and (iv) the weight limitations on the platform are quantitatively assessed. The results illustrate the benefits of converting the gas turbine process into a combined cycle, since the fuel gas consumption and the total $CO_2$-emissions can be reduced by more than 15%. Using the cooling water from the processing plant reveals to be more profitable than using seawater, as the additional pumping power outweighs the benefit of using a cooling medium at a temperature of about 8 °C lower. This study highlights thereby the importance of analysing energy savings and recovery options at the scale of the entire platform, rather than at the level of the utility plant solely.



## 1. Introduction

The extraction of oil and gas from petroleum fields is generally energy-intensive and associated with a significant environmental impact. Offshore oil and gas processing consumes from 10 to several hundreds MW power, depending on the properties of the oil field, the system design set-up, and the export specifications. The combustion of diesel and fuel gas for on-site power generation releases large quantities of $CO_2$ to the atmosphere. Similarly, flaring and venting practices may result in non-negligible $CH_4$-emissions, which are more harmful than $CO_2$-emissions, with regards to the global warming potential. The treatment of the produced water effluents and cooling water can meanwhile lead to a discharge of chemicals such as biocides and methanol to the sea.

These offshore facilities are designed for peak productions of oil and gas [1–4] and they suffer from inherent performance losses, when the hydrocarbon production declines and the water production rises [5,6]. The equipments may also be run at different loads, implying that they are not operated at their nominal points.

Although the petroleum throughput decreases, the total power consumption of the facility may increase because of the use of oil recovery techniques, such as water injection, and the operation of several process components at part-load conditions. A possible operational strategy for local power production on offshore plants is to share the electric load generation between several but redundant gas turbines, while keeping one on standby. This control strategy allows for a greater operational flexibility and a faster response

* Corresponding author at: Section of Thermal Energy, Department of Mechanical Engineering, Technical University of Denmark, Building 403, Nils Koppels Allé, 2800 Kongens Lyngby, Denmark. Tel.: +45 4525 4129; fax: +45 4588 4325.
*E-mail addresses:* tungu@mek.dtu.dk, tuong-van.nguyen@epfl.ch (T.-V. Nguyen).

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**Nomenclature**

| | |
|---|---|
| $I$ | environmental impact, kg/FU |
| $T$ | temperature, °C or K |
| $\dot{Q}$ | heat rate, kW |
| $\dot{W}$ | power, kW |
| $\dot{m}$ | mass flow rate, kg/s or t/h |
| $h$ | specific enthalpy, kg/kg |
| $p$ | pressure, bar |
| *Abbreviations* | |
| ACD | acidification |
| CC | combined cycle |
| DNA | Dynamic Network Analysis |
| EOS | equation of state |
| EQ | equivalent |
| EUT | eutrophication |
| FG | fuel gas |
| FU | functional unit |
| GE | exported gas |
| GWP | global warming potential |
| INV | investment |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | life cycle assessment |
| LCI | life cycle inventory |
| MAETP | marine aquatic eco-toxicity |
| MILP | mixed integer linear programming |
| MINLP | mixed integer non linear programming |
| MOO | multi-objective optimisation |
| NG | natural gas |
| OE | exported oil |
| PART | partial |
| PR | Peng–Robinson |
| REF | reference |
| *Greek letters* | |
| $\delta$ | relative variation, % |
| $\eta$ | energy efficiency, % |
| $\rho$ | Pearson's correlation coefficient |
| $\sigma$ | energy intensity, % |
| *Superscripts* | |
| + | material-/energy-flow entering the system |
| – | material-/energy-flow leaving the system |

to possible system failures. However, this results in a lower efficiency of these engines, a larger fuel consumption and greater $CO_2$-emissions. The values of natural gas and of the $CO_2$-tax on the downstream petroleum sector have increased these last years [7–10]. Designing more efficient power generation systems and reducing the fuel consumption have thus gained interest [11,12].

These objectives can be achieved by (i) improving the performance of the processing plant or by (ii) increasing the efficiency of the utility plant. The first possibility has been investigated in a few works [13–15]. They revealed, based on detailed energy- and exergy analyses of the oil and gas processing system, several ways to decrease the total power consumption and exergy destruction. These works pinpointed the performance loss sources of such plants, especially in end-life conditions. The exergy destruction in the heat exchangers and the losses associated with the exhaust gases from the power turbines were two of the major sources of the thermodynamic irreversibilities taking place on an oil and gas platform.

The second route has been considered in works that suggested to integrate a bottoming cycle, either to the gas turbines [16–18] or to the processing plant [19]. The integration of steam cycles on oil and gas platforms in the North Sea region is not common, as it is believed that the additional investment costs related to the supplementary weight and space would outweigh the financial gains of exporting a higher amount of gas. However, it may be argued that (i) the steam cycle could replace one of the gas turbines present on-site, (ii) it could be placed on the top of the facility, (iii) new steam cycle technologies are more and more compact, and their weight has been brought down significantly these last years.

The engineering challenges of installing these power cycles are emphasised in Nord and Bolland [16,17], and a power-to-weight of about 10 tonnes per MW was estimated. For the case studies presented in the works of Kloster [11,12], the integration of a steam cycle was performed as a retrofit option on existing facilities, and the steam cycle was implemented on either one or two gas turbines. The economic benefits were emphasised, as the fuel and $CO_2$-tax costs decreased sharply, while the thermodynamic efficiencies of the retrofitted cycles were greatly enhanced.

Most works focus on possible layouts of the power cycles and on their behaviours at design and off-design conditions, while discussing shortly the heating and power requirements of the oil processing plant. The power cycles are generally regarded separately from the processing plant and are optimised individually, while their economic and environmental impacts are briefly assessed.

Besides focusing on the ways to design compact and low-weight steam cycles, it is critical to analyse the site-scale integration of such technologies. The various system configurations and the synergies between the gas turbines, the steam network, the cooling system and the processing plant should be identified and investigated systematically to improve the performance of the overall plant. The literature lacks the application of systematic energy and process integration approaches to such systems, and the objectives of the present work are therefore to:

- assess the thermoenvironomic (i.e. energetic, economic and environmental) performance of an existing oil and gas platform;
- evaluate the prospects and challenges associated with the integration of steam cycles at a site-scale level, by systematic process integration, rather than at the level of the combined cycle solely;
- estimate the total costs, local and life cycle $CO_2$-emissions and fuel savings simultaneously, as well as other environmental impacts, by considering the multi-period and multi-objective aspects of this optimisation problem.

## 2. Methodology

### 2.1. System description

#### 2.1.1. General overview

Oil and gas from the field reservoir, mixed with subsurface water, enter the production facility through several wells and via several pipelines. They are *always* extracted at high pressures (10–200 bar) but with temperatures either below ($\leqslant$10 °C) or above ($\geqslant$60 °C) the ambient ones, depending on the oilfield. The aim of an oil and gas facility is to *separate* the oil, gas and water phases on-site (Fig. 1): oil is sent to the shore for further treatment in refineries, gas is either exported or injected back to the reservoir to enhance oil production, and water is chemically treated and rejected to the sea. In some cases, the produced water is injected into the reservoir to maintain a high pressure [1].