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# Unit exergy cost and $CO_2$ emissions of offshore petroleum production

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ABSTRACT

The assessment of the exergy spent for production of oil and gas on offshore platforms is of primordial importance for evaluation of the environmental impact associated with petroleum derived substances. In this work the exergy cost for oil and gas produced on a Floating Production Storage and Offload (FPSO) ship is evaluated along the lifespan of the well taking off-design operation conditions of process plant and cogeneration plant into account. The impact of 3 different cogeneration plants and 2 different process plant operating modes was assessed. Distribution of exergy costs for the oil and gas was obtained using thermoeconomy to reduce the arbitrariness of cost partition criteria. Results reveal that the exergy cost of oil varies from 1.0 kJ/kJ to 3.2 kJ/kJ along the well lifespan depending on process plant operating mode and cogeneration plant configuration. The exergy cost of gas varies from 1.0 kJ/kJ to 2.4 kJ/kJ along the well lifespan depending on cogeneration plant configuration. The average emission of $CO_2$ for the natural gas ranges from 19.0 gCO2/MJ to 19.8 gCO2/MJ depending on the cogeneration plant configuration while for the oil it ranges from 19.4 gCO2/MJ to 26.8 gCO2/MJ and it also depends on process plant operating mode.



## 1. Introduction

The proper evaluation of products and processes become essential as awareness regarding environmental information increases. The quantity of goods and processes relying on petroleum derived substances is enormous and few papers are found in literature discussing the environmental costs related to oil and gas production. A Brazilian offshore platform was evaluated using exergy analysis in Ref. [1]; it was revealed that heating and compressing operations are the main exergy consumers of the plant. According to [2], 62%–65% of the total exergy destruction of an offshore platform is attributable to the power generation and waste heat recovery system. The exergy analysis of a production day of an oil and gas platform on North Sea was evaluated in Ref. [3]; it was showed that compressors are the main contributors for exergy destruction. An exergy analysis of an offshore end-life oilfield was performed in Ref. [4]; in this work authors state that focus should be set on processes including gas expansion and compression and that investigation on off-design operation of the platform processes plays an important role in the analysis of the plant. In Ref. [5], compression processes are indicated as the main exergy consumers while power generation is the main exergy destroyer on a FPSO for 3 different cases. A comprehensive work considering the off-design operation of compression trains is given in Ref. [6], it was highlighted that the CO2 compressors driven by gas turbines are important sources of irreversibility. The compression train was also evaluated for different petroleum compositions in Ref. [7]. Combined cycles were proposed as cogeneration plant for platforms in Ref. [8], the combined cycles provided a reduction in CO2 emissions ranging from 9.3% to 22.2% depending of the heat to power ratio demanded. The implementation of heat recovery, CO2 capture system and platform electrification can reduce CO2 emission by 15% as stated in Ref. [9]. The evaluation CO2 capture in an offshore platform was considered in Ref. [10] and it was concluded that a reduction of 77% of CO2 emissions causes a decrease of 2.8% in the exergy efficiency of the platform. Four different offshore platforms were compared in Ref. [11] and it was highlighted that exergy destruction was mainly related to gas compression systems and production manifold. In Ref. [12] it was highlighted the importance of a strong performance indicator for offshore platform performance evaluation. The use of an organic Rankine cycle (ORC) to improve the efficiency of FPSOs was proposed in Refs. [13] and [14], savings of about 15% based on fuel consumption were reported for

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the first and an ORC efficiency ranging from 23.7% to 27% depending on the working fluid was reported for the second. The unit exergy cost for both products of an offshore platform (oil and gas) was calculated for a single operating condition in Ref. [15] using gas turbines as cogeneration plants and thermoeconomy for cost allocation. The integration of the processes of an offshore platform was proposed in Ref. [16], the results indicate that (i) the system performance strongly depends on the level of mass integration within the platform, (ii) the oil and gas recoveries are markedly impacted by the number of separation stages and heat exchangers, and (iii) disregarding the inter-actions between the several plant sections lead to sub-optimum solutions.

The thermoeconomic methods [17–25], some of them compared in Ref. [26], are based on the generation of entropy (exergy destruction) along the production of a given product. A product resulting from a productive process that generates more entropy will be more penalized than a product originated from a productive process generating less entropy. This holds an environmental sense, as the generation of entropy is an absolute measurement of the reversibility of any process. As entropy generation is also inherent to any production process, thermoeconomic methods are general and suitable for the allocation of resources and waste in any process [27]. Auxiliary equations, exergy disaggregation and the treatment of dissipative components are the main differences found among thermoeconomic methods. Even though there are differences and a certain level of arbitrariness is expected, these methods of allocation provide a more rational approach than the methods usually found on literature [27].

The use of thermoeconomy to allocate cumulative environmental costs in processes related to the processing of petroleum and its products can be found in some researches: in Ref. [28] the unit exergy cost of the products of a petroleum refinery was calculated; in Ref. [29] the unit exergy cost of petroleum derived fuels was obtained; in Ref. [30] the unit exergy costs of petroleum and natural gas were used to calculated the average exergy cost of the electricity produced in Brazil; in Ref. [31] the unit exergy cost of transport fuels was assessed; in Ref. [32] exergy cost of vehicles end use was calculated; In Ref. [33] the unit exergy cost of ammonia was obtained. All these studies rely on the unit exergy cost for oil and natural gas provided by Ref. [15]. The initial steps for methodologies based on cumulative exergy consumption were given in Ref. [34].

In the present work the unit exergy cost of the gas and oil produced in a FPSO is calculated for all years of the well lifespan using thermoeconomy to rationally distribute the exergy spent to both products. The impact of 3 different cogeneration plants and 2 different operation modes are evaluated considering off-design operation condition for cogeneration and process plants. The specific emission of $CO_2$ for both products is also calculated using the same approach.

## 2. Methodology

The methodology used to calculate the unit exergy cost of the products of a FPSO considers the process plant configuration shown in Fig. 1 previously presented in Ref. [35]. In this plant the petroleum composed of water, gas, oil and sediments has its components separated by the density difference in the treatment and separation process. This process is usually composed of 3 or 4 separators in which the pressure is gradually decrease from 1500 kPa to atmospheric pressure while the temperature is increased from 40 °C to 85 °C. Desalinization and electrostatic treatment are also included in this process. Since it is a highly integrated process it is considered as a single component in this analysis. Then, the water is injected back into the well, the oil is pumped to an onshore basis and the gas is progressively dehydrated and compressed starting from the compression group A. After compression group A there are two possibilities for the gas: 1-) all the gas goes through compressors from group B1 and C and then it is injected back into the well at 55000 kPa; 2-) $CO_2$ is separated, compressed and injected back into the well (55000 kPa) using compressors from groups B2 and C and the natural gas (NG) free of $CO_2$ is exported at 25000 kPa using compressors from group B1. This output pressure strongly influences the exergy cost and CO2 emission of natural gas and it depends on the distance to the shore. The injection pressure (55000 kPa), on the other hand, depends on the geological characteristics of the costs of both products.

The steps of the employed methodology are described in Fig. 2. It starts from the production prediction that comes from existing prediction models (exponential, hyperbolic model, and harmonic models) as stated in Ref. [36]. This step is especially important to decide the design condition (process plant sizing) and to evaluate the increase in demand of energy due to off-design operation of equipment. Attention should be paid on the compression groups and their anti-surge control system (recirculation of the compressed gas when a minimum flow rate is achieved). For this application it is considered that compressors have an isentropic efficiency of 80%, the temperature after intercooling is 40 °C and minimum flow rate before starting the recirculation is 50% of design condition (maximum flow rate predicted). Heat is provided for the separation process by pressurized hot water at 135 °C which returns to the cogeneration plant at 100 °C. Therefore, by using the specific heat consumption given by more detailed models such as in Ref. [37] together with well production prediction and the considerations for compressors operation, it is possible to estimate the yearly power and heat demands for a given well. The specific heat consumption of the treatment and separation process varies with the well pressure, temperature and with the petroleum composition and has to be updated whenever significant variations are verified.

The selection of a proper cogeneration plant configuration to meet the process plant demands starts from calculation of the heat to power ratio demanded. This information is important to indicate whether supplementary firing is required or not; steam operation level (temperature and pressure) and type of steam turbine (backpressure and or condensation) when steam plants and combined cycles are assessed. Since the temperature of the water required by the process is relatively low (135 °C), it can be provided by all commonly used cogeneration technologies. Once the configuration of the cogeneration plant is decided, it has to be designed to meet the peak demands of heat and power which means that the cogeneration plant will operate in off-design conditions most of the time during the lifespan of the well. The equations used to model the cogeneration plant in off-design condition such as: variation of efficiency and exhaust gas condition for gas turbines and reciprocating engines as function of load and temperature; variation of overall heat exchange coefficients in heat exchangers as function of flow rate; and variation of steam turbine efficiency as function of flow rate come from Ref. [38] and from manufacturer data and are also presented in Ref. [35].

The best operation condition for each year of operation is obtained by using the off-design model together with an optimization algorithm. A solver using an Evolutionary algorithm, built-in as a Microsoft Excel add-in (population = 100, crossover = 7.5% and convergence = 0.001%) [39], was used for optimization [39] of load distribution among parallel equipment, supplementary fire, and bottoming and topping cycles in order to minimize fuel consumption.

The exergy consumed and the $CO_2$ emitted to produce each one of the products a FPSO (oil and NG) are calculated using optimized