A PRACTICAL APPROACH FOR MEASURING ENERGY AND CARBON PERFORMANCE OF TURBOMACHINERY IN OFFSHORE APPLICATIONS

Pedro Henrique de Almeida Barbosa
Principal Engineer - Rotating Equipment
Petrobras
Rio de Janeiro, RJ, Brasil

Leonardo Monteiro Barbosa Lima
Turbomachinery Advisor
Petrobras
Santos, SP, Brasil

André Varella Guedes
Turbomachinery Advisor
Petrobras
Rio de Janeiro, RJ, Brasil

Ronaldo Lucas Alkmin Freire
Rotating Equipment Advisor
Petrobras
São José dos Campos, SP, Brasil

Pedro Henrique de Almeida Barbosa is a Principal Engineer at Upstream Engineering Department of Petrobras in Rio de Janeiro, Brasil. He started his career in 1997 at Promon Engenharia and joined Petrobras in 2001. With over 20 years working on preparation and audit of turbomachinery specifications, technical proposal evaluation and vendor's drawings review, he has been assigned as rotating equipment job leader for several O&G projects. Mr. Barbosa is a member of the API Subcommittee on Mechanical Equipment (SOME), API 617 Task Force and TEXAS A&M Turbomachinery Advisory Committee for the Turbo & Pump Symposia. Mr. Barbosa received his BSME (1999) and MSME (2001) from Universidade Federal do Rio de Janeiro and his MBA (2010) from Universidade de São Paulo.

Leonardo Monteiro Barbosa Lima is currently a Turbomachinery Advisor working for Petrobras E&P Pre-Salt Santos Basin. With 12 years working on downstream and 6 years on upstream, he has accumulated experience in maintenance engineering, vibrations and performance monitoring, fault analysis and a wide range of turbomachinery operations. Mr. Lima received his Bachelor's degree in Mechanical Engineering (1999) from Federal University of Para and his Master's degree in Mechanical Engineering (2002) from Federal University of Santa Catarina.

Andre Varella Guedes is a Turbomachinery Advisor with Petrobras E&P Buzios Field Operations Unit. He has been working with turbomachinery in the upstream oil and gas business for 14 years. Mr. Varella has been involved in the design, acceptance tests, start-up, operation, and performance monitoring. His current duties involve technical support and troubleshooting with existing turbomachinery fleet in Petrobras upstream oil and gas services. Mr. Varella received his B.S. degree (Mechanical Engineering, 2005) and his M.S. degree (Mechanical Engineering, 2008) from Federal University of Rio de Janeiro. He has authored technical papers on turbomachinery thermodynamics and performance monitoring.

Ronaldo Lucas Alkmin Freire is a Rotating Equipment Advisor at PETROBRAS Research Center in Rio de Janeiro, Brazil. From 2009 to 2017, he provided technical assistance to the Engineering Department at PETROBRAS in various topics from conceptual design to final acceptance tests for new assets. Since 2017, his primary role is to lead R&D projects on turbomachinery and electric systems for E&P offshore. He holds a B.S. degree in Mechanical Engineering (2006) from Federal University of Itajubá and a M.Sc. in Aeronautical and Mechanical Engineering (2013) from Aeronautics Institute of Technology.

ABSTRACT

The purpose of this work is to present the first results of a practical approach developed for measuring the performance on energy and carbon of turbomachinery installed at offshore oil production plants, based on the methodology described in ISO 50006 (2014) and on the best practices from the oil and gas industry. Energy and carbon indicators are proposed at facility, system, and equipment levels to monitor the overall performance of the platform and to detect performance gaps related to a particular system or equipment of concern. Considerations are made on the open-source monitoring tool used for the assessment. Power demand profile and available data of the most energy intensive equipment from an existing Floating Production, Storage and Offloading (FPSO) are provided as a background for the proposed screening criteria for equipment and systems to be monitored.

A case study based on an existing Pre-Salt FPSO is presented to illustrate the results obtained with the proposed framework. Primary processing scheme and a turbomachinery arrangement highlight the characteristics of a typical FPSO operating in Brazilian Pre-Salt fields. Some discussions on the influence of operating modes on the FPSO energy and carbon performance show the challenges encountered in establishing an adequate baseline for the proposed indicators at the facility level, especially due to the gas treatment system for CO_2 removal. A statistical approach applied to some compressor efficiency datasets has led to practical conclusions on how efficient gas compression is at the equipment level, as time trend plots directly generated from the compressor efficiency datasets show high fluctuations due to the sensitivity of the calculated variable to the uncertainty of the instrument readings. Furthermore, the effect of optimizing the number of gas turbine generator sets in operation on the overall carbon emitted by the power generation system is presented to illustrate one possible action for raising the FPSO energy and carbon performance.

The proposed approach has proven useful for quickly detecting deviations and for tracking the effects of improvement actions on the FPSO energy and carbon performance. Indeed, by applying performance indicators at different levels of the facility, oil and gas companies should be able to identify bad actors in energy and carbon related to a particular equipment or system and to predict and compare the performance of new FPSO projects in relation to existing oil production plants. The results presented in this work show that the proposed approach is promising in driving turbomachinery energy performance and promoting decarbonization.

INTRODUCTION

Offshore production units are designed to deliver oil and gas within a specified reliability. Design choices made early in project life also dictate their lifecycle energy and carbon efficiency. Although production and reliability are closely controlled, for the majority of these units the energy and carbon performance are not monitored or even measured.

It should be a common understanding that oil production plants cannot be significantly more efficient in energy or carbon than they have been designed to. While it is quite difficult to achieve a more efficient way to operate these units under off-design conditions, it is possible to operate them in many less efficient manners than predicted without disturbing production. For instance, it is not unusual to find offshore production plants where the number of gas turbine generators in operation could be reduced without any loss in oil and gas production, or where compression and pumping systems operate with excessive recycling, especially when optimization requires manual intervention.

Although most of the existing offshore production units are not fitted with instruments primarily intended to measure energy and carbon performance, key performance indicators can be set and monitored by field instrumentation at different levels of the installation, thus, revealing potential causes that lead to a poor performance of a particular system or equipment.

To achieve this purpose, this work presents a practical approach based on ISO 50006 (2014) for using energy (and carbon) performance indicators at three different levels of assessment: installation, system, and equipment level. For the former level, an energy intensity indicator based on the relationship between the actual overall energy input and equivalent oil production is proposed to measure energy performance of the entire facility. As major rotating equipment typically found in offshore oil production plants, specific performance indicators for gas turbines, centrifugal compressors and centrifugal pumps are also proposed for monitoring turbomachinery energy and carbon performance at both system and equipment levels, including some possible ways to measure them with the existing instrumentation. On the other hand, a discussion on how to define proper baseline and reporting periods for each indicator is addressed in order to gather a representative and unbiased data set. Finally, attainable targets for each performance indicator should be established as a key part of an energy and carbon management system and the related improvement actions be close monitored and revised, if needed.

Practical considerations are made in this work for those cases where a lack of dedicated instrumentation at equipment level is found to be a problem in the field. Next steps for further enhancement of the proposed approach are also addressed. Trends and historical values for more than three years of accumulated recorded data from an existing FPSO are presented, showing that the proposed approach is promising.

ENERGY PERFORMANCE CONCEPTS AND DEFINITIONS

ISO 50006 (2014) standard provides general principles and guidance on how to establish, use and maintain energy performance indicators (EnPIs) and energy baselines (EnBs) to allow for measuring and managing the energy performance from an organization, in accordance with ISO 50001 (2018) requirements. According to ISO 50006 (2014), energy performance is a broad concept that encompasses energy consumption, energy use and energy efficiency. In this way, an Energy Performance Indicator (EnPI) is defined by ISO 50006 (2014) as "a value or measure that quantifies results related to energy efficiency, use and consumption in facilities, systems, processes and equipment". On the other hand, an energy baseline (EnB) is defined as a reference that characterizes and quantifies the energy performance of an organization for a certain period. Energy baselines (EnBs) allow companies to assess changes in energy performance behavior and they can be used to calculate energy savings, as a reference before and after undertaking improvement actions.

Organizations that have established an Energy Management System (EnMS) according to ISO 50001 (2018) set targets for their performance indicators on energy as part of planning process for this system. Figure 1 shows the relationship among EnPIs, EnBs and energy targets and how these concepts can be applied for the assessment of energy consumption.

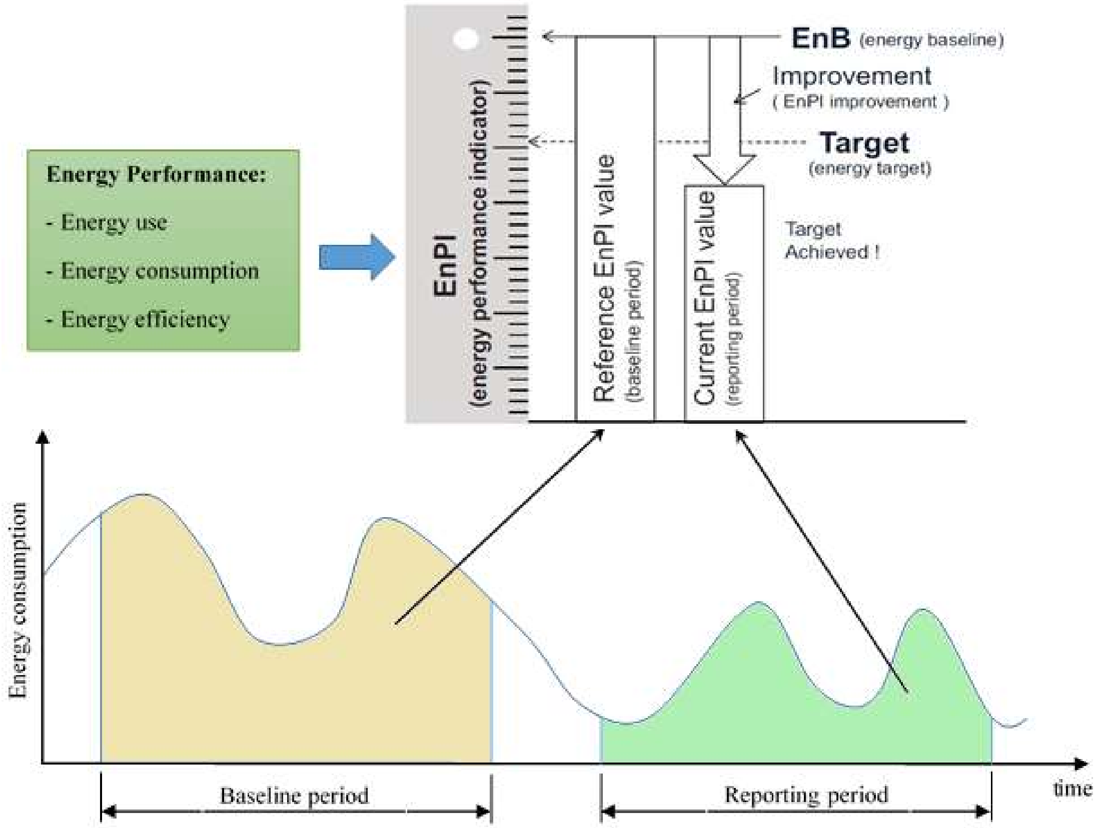


Figure 1. Energy Performance Concepts and Definitions. Modified from ISO-50006 (2014)

As shown in Figure 1, for each EnPI indicator there must be a baseline (EnB) and an associated target for the organization. Therefore, the periods for determining the energy baseline (EnB) and calculating the energy performance indicator (EnPI) should be long enough to cover the various forms of operation of the installation, system, process, or equipment. Typically, these periods are 12 months to capture the effects of seasonality on energy consumption and other relevant variables.

The methodology described in ISO 50006 (2014) allows the assessment at four different levels (installation, system, process, or equipment), or even for individual analysis of each action taken to increase energy performance. While installation-level monitoring provides users with general information on the performance on energy of the entire facility (which is useful for a first step of investigation), the other three levels of monitoring give specific energy performance information for a particular system, process, or equipment, being helpful for identifying bad actors and wasting spots inside the plant. However, it is up to the user to define which of these four levels will be used to establish the most adequate set of energy performance indicators, based on the applicable organization goals and site measurement constraints.

Energy Consumption, Energy Use and Energy Efficiency
According to ISO 50006 (2014), energy performance can be expressed in different ways, such as consumption units (GJ, MWh, etc.), specific consumption, peak power, percentage change in efficiency or dimensionless parameters, and its results in terms of energy consumption, energy use and energy efficiency are described as follows:

Energy Consumption
Quantifying the amount of energy applied to a facility, system, process, or equipment is crucial for measuring energy performance and its increments. When more than one form of energy is used (e.g., gas and electricity), it is important to convert them into a common unit of energy. In addition, energy consumption should represent the total energy consumed, including losses due to conversion processes.

Energy Use
Energy use is related to the kind of application of energy. Identifying the use of energy in the various systems of a facility (gas compression, compressed air, steam, hot water, etc.) facilitates its categorization and allows the organization's efforts to be focused on the most important uses.

Energy Efficiency
Energy efficiency is a metric typically used by organizations to measure energy performance and can be used as an EnPI indicator. As stated in ISO 50006 (2014), energy efficiency can be expressed in several ways: energy required/energy consumed; energy output/energy input; production output/energy input, etc. Another very common way to refer to energy efficiency is by means of energy intensity, when the energy performance is expressed by the energy input divided by the production output.

FPSO PROCESS DESCRIPTION AND SELECTION CRITERIA FOR EQUIPMENT MONITORING

A Floating Production and Storage Unit (FPSO) is an oil production and storage vessel typically used in deep and ultra-deep water depth offshore applications, such as those found in the pre-salt basins located offshore the Brazilian coast. Figure 2 shows a typical process plant scheme for a FPSO at the Brazilian pre-salt oil fields.

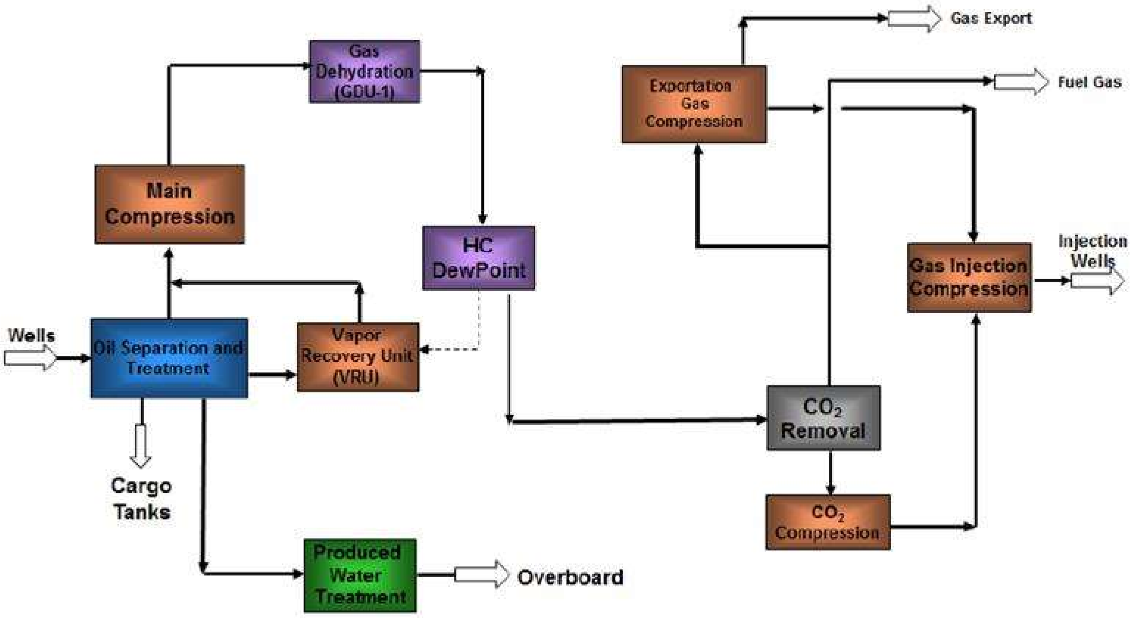


Figure 2. Typical Schematic of a Pre-Salt FPSO Oil Production Plant

As shown in Figure 2, the crude oil stream coming from the production wells flows into the Oil Separation and Treatment located at the entrance of FPSO topside processing plant. There, oil is separated from water and associated gas in the primary separator for further storage in cargo tanks, while water is sent to the Produced Water Treatment for further injection into the wells by injection pumps (or directed to overboard). In the Vapor Recovery Unit (VRU), a fixed-speed electric motor driven dry screw compressor recovers the remaining gas in the oil at lower pressures and routes it from the primary separator back to the main gas stream. After being compressed, the main gas stream is treated at the Dehydration and Dew Point Control units for further CO_2 removal. A small part of treated gas is used as fuel gas for gas turbines, while the remainder of the treated gas is either exported by the export compressors or mixed with the rich CO_2 gas stream coming from the CO_2 compressors, for further reinjection in the wells. It is important to notice that gas exportation demands reduced levels of CO_2 in the exported gas stream due to pipeline restrictions and to the absence of CO_2 removal units at onshore natural gas processing units to fit the product into market specifications.

On the existing pre-salt FPSOs over the Brazilian coast, the main compression, gas export and gas injection services are typically performed by electric motor driven centrifugal compressors fitted with variable speed hydraulic drives, while the CO_2 compression service is carried out by gas turbine driven centrifugal compressors. Regardless of the driver type, process gas compressors are by far the most important energy consumers in the entire platform, accounting for over 70% of its total energy demand.

Further details of the turbomachinery train arrangements and features found in the FPSO used for this assessment are described in the results section of this work.

Selection Criteria for Monitored Equipment

There are several systems and equipment with different sizes and required power in an offshore production unit. Generally, critical equipment are the ones with higher power demand and, hence, provided with more instrumentation, allowing energy (and carbon) performance monitoring.

To demonstrate the selection criterion proposed by the authors, Figure 3 presents the rated power demand required by each power consumer equipment from a typical FPSO operating at Brazilian pre-salt area. As can be seen, rotating equipment account for most of the total power consumption.

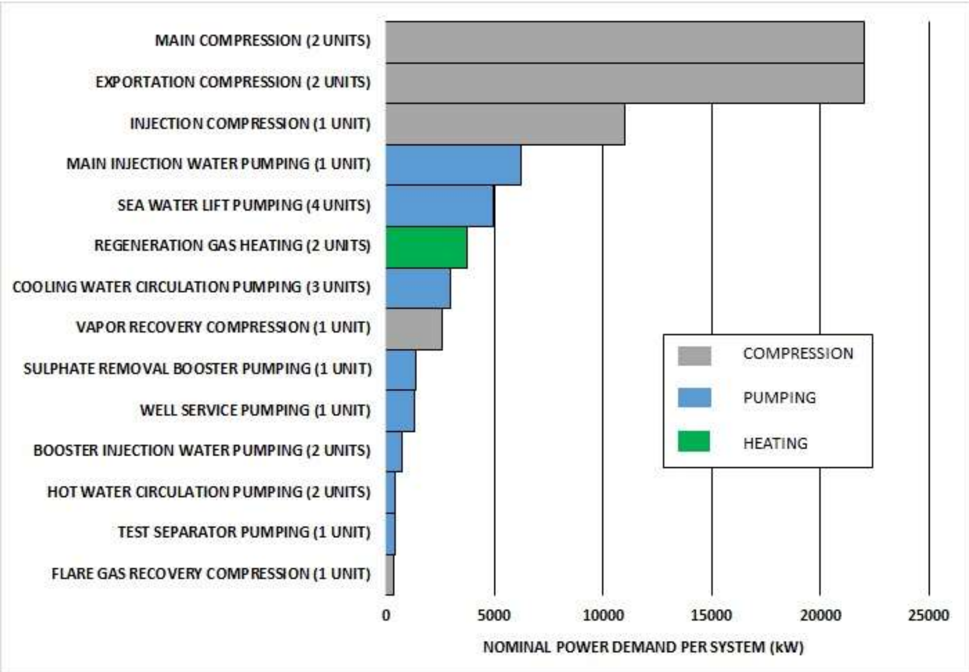


Figure 3. Typical Power Demand Profile for Process Equipment in a Pre-Salt FPSO Unit

The proposed criteria to select which equipment will be monitored takes into consideration power demand and available data to perform the analysis. In addition, the authors advocate that, if there is not a particular need to measure energy and carbon performance of equipment that are not subjected to continuous operation, equipment under such a type of service can be exempted from the assessment.

For smaller equipment or for that equipment subjected to intermittent operation, energy and carbon performance monitoring is optional, since the individual gains are not representative for the overall performance of the installation. For instance, equipment such as the Flare Gas Recovery Compressor, the Cooling Water Circulation Pump and the High-Pressure Water Pump shown in Figure 3, due to their modest power size, could be exempted from monitoring without causing a major impact in the energy performance management of this platform. Similarly, the Well Service Pump and Test Separator Pump could also be exempted from monitoring due to their intermittent operation. On the other hand, there are situations where the measurement becomes challenging or even impractical due to the lack of field instrumentation. For the example shown in Figure 3, equipment with lower power demand than the VRU compressor do not present enough instrumentation to allow for continuous monitoring of their energy and carbon performance. With that said, for the equipment listed in Figure 3, the authors have decided to monitor energy and carbon performance only of the greatest power demanding ones, up to the VRU Compressor. This evaluation should consider specific scenarios for each offshore units aiming to monitor the majority of equipment. For the selected case, although only half of the equipment listed in Figure 3 was selected, they account for 95% of the power demand.

When the only available instrumentation for a group of equipment operating in parallel is located at suction and discharge piping manifolds, an alternative way to include them in the monitoring would consist in applying performance indicators at a broader level of assessment, thus measuring the overall performance of the system (or service) they belong. For some of the energy intensive turbomachinery found in older offshore production units, the assessment at system level may be the only available choice. Fortunately, this situation is unusual in a typical FPSO nowadays.

More than just an alternative to capture the energy and carbon performance of pumps or compression systems with no dedicated instrumentation at equipment level, this approach is particularly interesting for those cases where relevant information on the overall system performance should be added to the assessment at equipment level. For example, centrifugal compressors arranged in parallel can simultaneously operate close to or at their best individual energy performance (in accordance with their EnPIs at equipment level), while the compression system they belong to is experiencing excessive gas recirculation and, therefore, the overall system performance is not energy or carbon efficient.

PROPOSED APPROACH FOR MEASURING TURBOMACHINERY ENERGY PERFORMANCE

Based on the methodology described in ISO 50006 (2014), the proposed approach lies on the establishment of a set of key EnPIs at three different levels of assessment (installation, system, and equipment levels) that can be used either to anticipate the energy performance of new FPSO projects or to measure the performance of existing FPSO units, as detailed below:

Energy Performance Monitoring at Installation (or Facility) Level

In order to quantify the overall turbomachinery energy efficiency of the platform by an energy intensity index, an EnPI applicable to the entire FPSO is proposed, according to Equation (1).

$$EII = \frac{EnIn_{FPSO}}{NEP_{FPSO}} \tag{1}$$

Where:

EII = *the Energy Intensity Index, Btu/boe (MJ/boe)*
$EnIn_{FPSO}$ = *the overall energy input to the platform, Btu (MJ)*
NEP_{FPSO} = *the FPSO net export production, boe*

To determine the overall energy input to the platform ($EnIn_{FPSO}$), it is necessary to measure the overall FPSO fuel gas (or diesel) consumption and the lower heating value of the fuel (LHV) during the reporting period.

Care should be taken when using the proposed *EII* for benchmarking, as this parameter alone may not be sufficient to compare energy performance between platforms of different complexity or different operating modes (e.g., pre-salt vs. post-salt platforms; gas export vs. gas reinjection, etc.). A possible way to meet this purpose could be achieved by segregating the assessment at the installation level in clusters of platforms with the same complexity, or even by developing a normalization procedure, that takes such differences out of the equation. However, it is important to notice that the methodology described in ISO 50006 (2014) is primarily intended to be used as a timeline comparison tool for each particular installation, instead of a benchmarking assessment for different facilities.

Energy Performance Monitoring at System Level

Due to their power demand, some process plant systems play a major role in the overall energy performance of an oil production plant. Notably, power generation and gas compression are the main energy consumer systems of a platform, thus demanding a further evaluation on their performance, as discussed below. However, other continuous duty energy intensive systems found in a typical FPSO unit, such as water injection, seawater lift and cooling water pump systems might also be energy monitored. In this case, specific energy performance indicators in accordance with ISO 14414 (2019) can be established and used for the assessment of each of these pump systems.

Power Generation System

The adoption of an EnPI to measure the overall performance of the power generation system is recommended due to the following reasons:

- Power generation systems typically operate with an association of gas turbine generator sets in parallel, which makes it desirable to monitor the overall energy performance of this system.
- Some platforms are not fitted with dedicated flow instruments for individual measurement of the gas fuel consumption, making the measurement of energy performance at equipment level impractical.
- By using a proper EnPI, it can be useful to undertake a benchmarking on the overall energy performance of power generation

systems installed at different assets, since there is great similarity of this system between different FPSOs.

One possible EnPI for this system can be derived from the heat rate definition for gas turbines, according to Equation (2).

$$HR_{GenSys} = \frac{\dot{m}_{f\_GenSys} \cdot LHV}{NOP_{GenSys}} \quad (2)$$

Where:

HR_{GenSys} = *the overall power generation system heat rate, Btu/kWh (kJ/kWh)*
$\dot{m}_{f\_GenSys}$ = *the total mass flow of the fuel to the system, lb/h (kg/h)*
LHV = *the lower heating value of the fuel, Btu/lb (kJ/kg)*
NOP_{GenSys} = *the overall net output power delivered by the power generation system, kW*

Heat Rate is a classical term normally used by the industry to indicate the energy performance of a gas turbine as the amount of fuel required to generate one unit of delivered power. However, the use of heat rate as an energy performance indicator can be expanded to the power generation system, especially when more than one gas turbine driven generator sets operate in parallel.

Another possible EnPI for this system is proposed in Equation (3) as the overall power generation system efficiency (η_{GenSys}), which is the inverse of the proposed overall power generation system heat rate (HR_{GenSys}) presented in the Equation (2) above. Indeed, authors have decided to use the overall power generation system efficiency in the examples presented in this paper, considering that efficiency is a more intuitive energy concept.

$$\eta_{GenSys} = A \cdot \frac{NOP_{GenSys}}{\dot{m}_{f\_GenSys} \cdot LHV} \quad (3)$$

Where:

η_{GenSys} = *the overall power generation system efficiency*
A = *energy conversion factor,* $3412.14 \cdot \frac{kWh}{BTU} \left(3600 \cdot \frac{kWh}{kJ}\right)$
NOP_{GenSys} = *the overall net output power delivered by the power generation system, kW*
$\dot{m}_{f\_GenSys}$ = *the total mass flow of the fuel to the system, lb/h (kg/h)*
LHV = *the lower heating value of the fuel, Btu/lb (kJ/kg)*

It is important to note that the overall power generation system efficiency (η_{GenSys}) is a dimensionless number, thus requiring both heat input and electrical power output with same units in the calculations. Constant factor A was added to this equation to conciliate these units.

Gas Compression Systems

An evaluation of the overall performance in energy of each FPSO gas compression system (VRU, main, export, CO_2, and injection) allows for the identification of performance gaps not related to the compressors themselves, such as unnecessary gas recycling, non-optimized load balance between compressors operating in parallel, abnormal pressure drops in the piping system, etc. To achieve this purpose, the proposed approach consists of evaluating only the portion of the gas absorbed power related to the net gas flow delivered by the compression system, instead of the total gas flow through compressor casings.

Ideally, the proposed EnPI is given by the ratio between the net gas flow delivered by the compression system to the plant and total power required to drive the compression system, as defined in Equation (4).

$$\eta_{CompSys} = \frac{\sum \dot{m}_{Comp} \cdot \Delta h_{Comp}}{\sum P_{Comp}} \quad (4)$$

Where:

$\eta_{CompSys}$ = *the overall efficiency of the gas compression system*
$\dot{m}_{Comp}$ = *the net gas mass flow delivered by each compressor train to the gas processing plant, lb/s (kg/s)*
Δh_{Comp} = *the total enthalpy added to the gas by all sections of each compressor train, Btu/lb (kJ/kg)*
P_{Comp} = *the total power required to drive each compressor train, HP (kW)*

However, for those cases where no dedicated process flow instruments are available in the field for measuring the net gas mass flow delivered by each compressor train to the gas processing plant ($\dot{m}_{Comp}$), one possible alternative is to use the Equation (5) as follows:

$$\eta_{CompSys} = \frac{\dot{m}_{CompSys} \cdot \Delta h_{CompSys}}{P_{CompSys}} \quad (5)$$

Where:

$\eta_{CompSys}$ = *the overall efficiency of the gas compression system*
$\dot{m}_{CompSys}$ = *the net gas mass flow delivered by the compression system to the gas processing plant, lb/s (kg/s)*
$\Delta h_{CompSys}$ = *the total enthalpy added to the gas by all compressor sections, averaged across machinery trains, Btu/lb (kJ/kg)*
$P_{CompSys}$ = *the total power required to drive the compressors in the system, HP (kW)*

Actually, the results presented in this paper for this EnPI were calculated using Equation (5) in lieu of Equation (4), due to the lack of dedicated instrumentation for measuring the net gas flow delivered by each compressor.

If the compressors are driven by gas turbines, then the total power required to drive the compression system can be evaluated by means of the heat input delivered by fuel gas, which is the product of the total fuel mass flow and its lower heating value (LHV). In this case, the overall power to drive the system ($P_{CompSys}$) shall include the turbomachinery train efficiencies. This methodology also applies to gas turbine driven pumps.

Energy Performance Monitoring at Equipment level

Deviations on the performance of gas turbines, gas compressors and large pumps heavily affect the overall efficiency of an offshore production platform, so they need to be monitored by specific indexes.

For the assessment at equipment level, a comparison of the proposed EnPIs with as tested or as designed turbomachinery performance data can be added to the methodology proposed by ISO 50006 (2014), as a further reference for the monitoring.

Gas Turbines

As discussed above, one of the most used parameters to evaluate gas turbine energy performance is the Heat Rate, as presented in Equation (6).

$$HR = \frac{\dot{m}_f.LHV}{NOP} \tag{6}$$

Where:

HR = *the gas turbine heat rate, Btu/kWh (kJ/kWh)*
$\dot{m}_f$ = *the mass flow of the fuel, lb/h (kg/h)*
LHV = *the lower heating value of the fuel, Btu/lb (kJ/kg)*
NOP = *the gas turbine net output power, kW*

For power generator applications, the gas turbine net output power (*NOP*) can be determined from the electric power delivered by the generator set to the FPSO electrical grid, considering the mechanical and electrical losses associated to the gear unit and generator. For mechanical drive applications, the gas turbine net power output may be either directly measured by means of a torquemeter installed at the gas turbine output shaft or calculated considering process data measurements related to the driven equipment such as flow, suction and discharge conditions.

Another possible EnPI for gas turbines is the adiabatic thermal efficiency, as proposed in Equation (7). Although heat rate is a very common energy performance indicator for gas turbines, authors have decided to use the adiabatic thermal efficiency in the examples presented in this paper, due to the same reasons efficiency was used above for the power generation system.

$$\eta = A \cdot \frac{NOP}{\dot{m}_f.LHV} \tag{7}$$

Where:

η = *the gas turbine efficiency*
A = *energy conversion factor,* $3412.14 \cdot \frac{kWh}{BTU} \left(3600 \cdot \frac{kW}{kJ}\right)$
NOP = *the gas turbine net output power, kW*
$\dot{m}_f$ = *the mass flow of the fuel, lb/h (kg/h)*
LHV = *the lower heating value of the fuel, Btu/lb (kJ/kg)*

Compressors

Polytropic efficiency (η_p) is the most used parameter to measure centrifugal compressor energy performance. It can be determined by many ways, from simple thermodynamic equations derived from the ideal gas laws to more sophisticated calculation procedures. Usually, the choice among them largely depends on the gas conditions handled by the compressor and on computational resources, as these factors dictate the accuracy of the calculation. For instance, relations based on the enthalpies and entropies of the gas at compressor suction and discharge render better results for gas conditions far from the ideality. However, if that is not the case, a practical way to determine the polytropic efficiency for the purposes of this assessment is to use simplified calculations as per Equations (8) and (9).

$$T_2 = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} . T_1 \tag{8}$$

$$\frac{n-1}{n} = \frac{k-1}{k.\eta_p} \tag{9}$$

Where:

η_p	= *the compressor polytropic efficiency*
T_1	= *the absolute suction temperature, K*
T_2	= *the absolute discharge temperature, K*
p_1	= *the absolute suction pressure, kPa*
p_2	= *the absolute discharge pressure, kPa*
k	= *the gas specific heat ratio*
n	= *the polytropic exponent*

On the other hand, many times the gas handled by the compressor does not behave as a perfect gas and a more accurate way to determine the compressor polytropic efficiency should be carried out. Indeed, for most cases, the authors recommend the use of more rigorous calculation procedures, such as the one defined in ASME PTC 10.

Using the polytropic efficiency as EnPI for compressors allows for comparing this parameter with the performance data delivered by the supplier in the performance curves and data sheets. However, the polytropic efficiency of a compressor may vary with flow, handled gas and compressor speed. Therefore, such effects shall be considered during the assessment to allow proper comparison with reference values.

Centrifugal Pumps

A similar approach used for centrifugal compressors can also be applied for centrifugal pumps. In this case, the pump efficiency is determined by measuring head, flow and absorbed power, in accordance with Equation (10).

$$\eta = \frac{\Delta P.\dot{Q}}{P_{abs}} \tag{10}$$

Where:

η	= *the pump efficiency*
Δp	= *the differential pressure provided by the pump, kPa*
$\dot{Q}$	= *the volumetric flow of the pumped fluid,* m^3/s
P_{abs}	= *the power absorbed by the pump, kW*

Using the pump efficiency as EnPI for centrifugal pumps allows for comparing this parameter with the performance data delivered by the pump supplier (performance curves, data sheets, etc.). In this case, the power absorbed by the pump may be directly measured if the equipment is electric motor driven (deduced by the driver mechanical efficiency). The pump efficiency can be calculated by measuring suction and discharge pressures and flow.

PROPOSED APPROACH FOR MEASURING TURBOMACHINERY CARBON PERFORMANCE

The authors' proposal for measuring turbomachinery carbon performance is based on an extrapolation of ISO 50006 (2014) methodology. By setting key carbon performance indicators at three different levels of assessment (installation, system, and equipment level), evaluation of the main sources of greenhouse gases (GHG) emissions in an FPSO unit can be done as detailed below:

Carbon Performance Monitoring at Installation (or Facility) Level

The overall FPSO carbon efficiency can be measured by a carbon intensity index according to Equation (11).

$$GHGII = \frac{CarbonOut_{FPSO}}{NEP_{FPSO}} \tag{11}$$

Where:

$GHGII$	= *the Greenhouse Gases Intensity Index, kg* CO_2e*/boe*
$CarbonOut_{FPSO}$	= *the total carbon dioxide equivalent emitted by the FPSO, kg* CO_2e
NEP_{FPSO}	= *the net FPSO export production, boe*

The portion of the proposed $CarbonOut_{FPSO}$ associated with combustion in gas turbines can be determined either by direct measurements of gas turbine emissions or by stoichiometric calculation protocols.

Carbon Performance Monitoring at System and Equipment Levels

In addition to GHGII, a set of turbomachinery carbon indicators is also proposed, both at system and equipment levels, to evaluate the carbon performance of the main sources of greenhouse gases (GHG) emissions in an offshore oil production plant.

Carbon Monitoring at System Level

The carbon performance associated to the power generation system can be measured by means of a carbon intensity index (CII_{GenSys}), as described in Equation (12).

$$CII_{GenSys} = \frac{CarbonOut_{GenSys}}{NOP_{GenSys}} \tag{12}$$

Where:

CII_{GenSys} = *the Carbon Intensity Index for the power generation system, kg* CO_2e/MWh
$CarbonOut_{GenSys}$ = *the overall carbon dioxide equivalent mass flow emitted by the power generation system, kg* CO_2e/h
NOP_{GenSys} = *the net output power delivered by the power generation system, MW*

The net output power delivered by the power generation system (NOP_{GenSys}) can be direct measured from the overall electric power delivered by the system to the FPSO electrical grid.

Similarly, the carbon performance associated to a particular gas turbine driven compression system can be measured by means of a carbon intensity index ($CII_{CompSys}$), as described in Equation (13).

$$CII_{CompSys} = \frac{CarbonOut_{CompSys}}{NOP_{CompSys}} \tag{13}$$

Where:

$CII_{CompSys}$ = *the Carbon Intensity Index for the gas turbine driven compression system, kg* CO_2e/MWh
$CarbonOut_{CompSys}$= *the overall carbon dioxide equivalent mass flow emitted by the compression system, kg* CO_2e/h
$NOP_{CompSys}$ = *the net output power delivered by the gas turbine driven compression system, MW*

The net output power delivered by the gas turbine driven compression system ($NOP_{CompSys}$) can be determined from the product of the net gas mass flow delivered by the compression system to the plant and the total enthalpy added to the gas by all compressor sections.

The overall carbon dioxide equivalent emitted by the power generation system ($CarbonOut_{GenSys}$) or by the gas turbine driven compression system ($CarbonOut_{CompSys}$) can be estimated by simplified equations, as those presented by Maia and Neves (2010), where the LHV of the fuel and gas turbine expected efficiency may be customized for each application.

Carbon Monitoring at Equipment Level

The carbon performance associated to a particular gas turbine driven generator, compressor or pump can be measured by means of a carbon intensity index (CII), as described in Equation (14).

$$CII = \frac{CarbonOut}{NOP} \tag{14}$$

Where:

CII = *the Carbon Intensity Index for the gas turbine driven equipment, kg* CO_2e/MWh
CarbonOut = *the carbon dioxide equivalent mass flow emitted by the gas turbine driven equipment, kg* CO_2e/h
NOP = *the gas turbine net output power, kW*

For power generator applications, the gas turbine net output power (NOP) can be determined from the electric power delivered by the generator set to the FPSO electrical grid, considering the mechanical and electrical losses associated to the gear unit and generator. For mechanical drive applications, the gas turbine net power output may be either directly measured by means of a torquemeter installed at the gas turbine output shaft or calculated considering process data measurements related to the driven equipment such as flow, suction and discharge conditions.

CONSIDERATIONS ON THE MONITORING TOOL USED FOR THE ASSESSMENT

Online performance monitoring is an ongoing industry effort over the last decades. However, some real breakthroughs have only been achieved in the last five years. First, by means of commercially available solutions to convey monitoring data from historian databases to C# applications and Python scripts. Then, by means of Internet of Things (IoT) programming tools to wire together data flows and Python scripts, allowing users to develop their own online performance monitoring dashboards.

The software tool used by the authors to monitor energy and carbon performance is a web browser flow-based programming environment. Since early beginnings, the environment proved to be stable, flexible, and user-friendly, allowing any amateur-in-programming engineer to develop turbomachinery performance dashboards. It has since evolved into a platform for analytics as well as a machine learning (mostly anomaly detection) intranet platform.

It is important to note that the dashboards presented in this section of the work are not intended to show specific details of a particular machine performance assessment, but rather provide a general view on the monitoring tool used for the assessment, showing the types of analysis being performed at equipment level.

Having said that, Figure 4 brings an overview of the dashboard developed for monitoring gas turbines. On the left, the first tab presented contains the temperature spreads in the combustion chamber, pressure and temperature profiles along the gas flow path, a bar plot for efficiency monitoring and a performance data table. On the right, the next two tabs show historical data, x-y and time trend plots and a dew point analysis of the fuel gas.

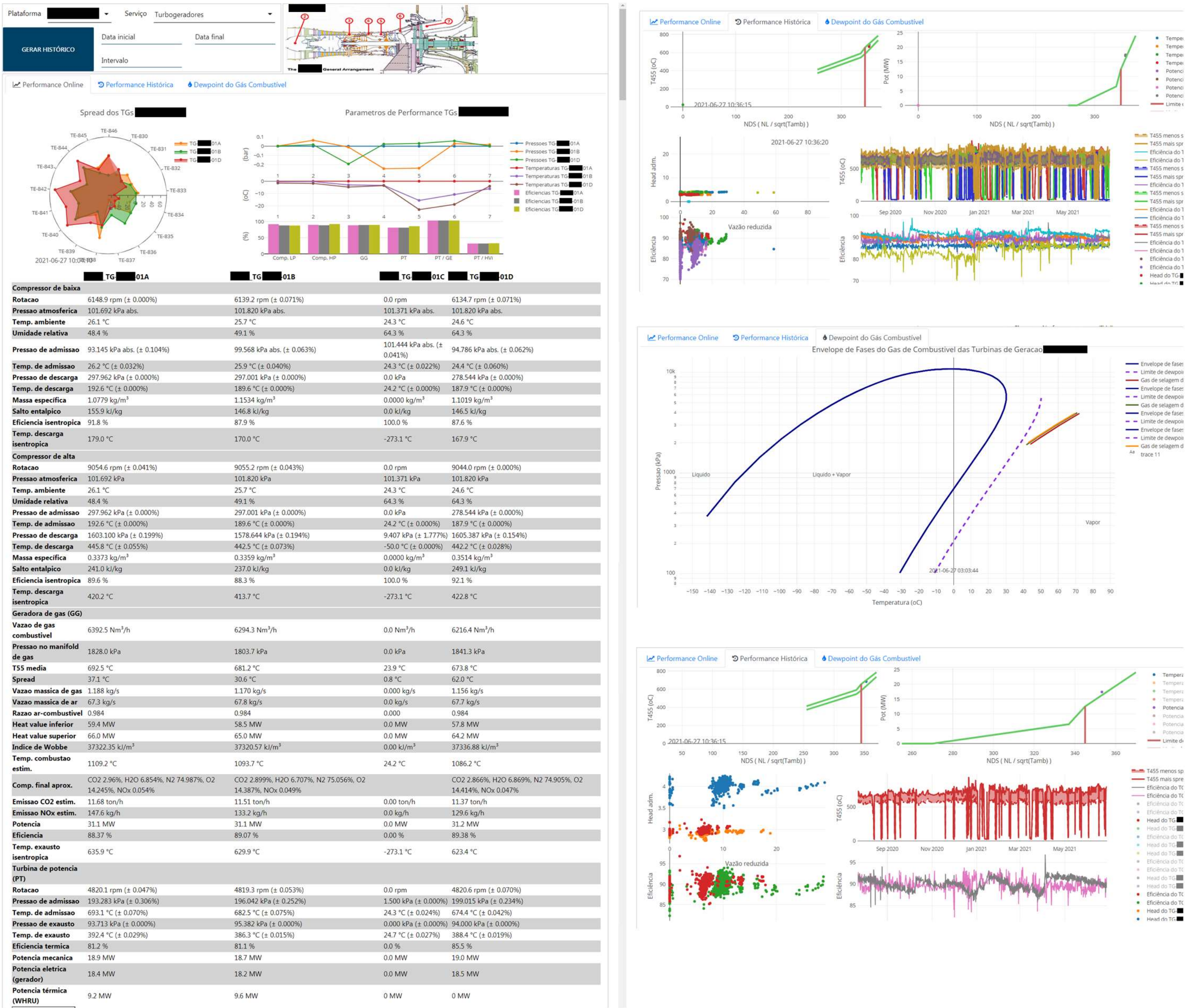
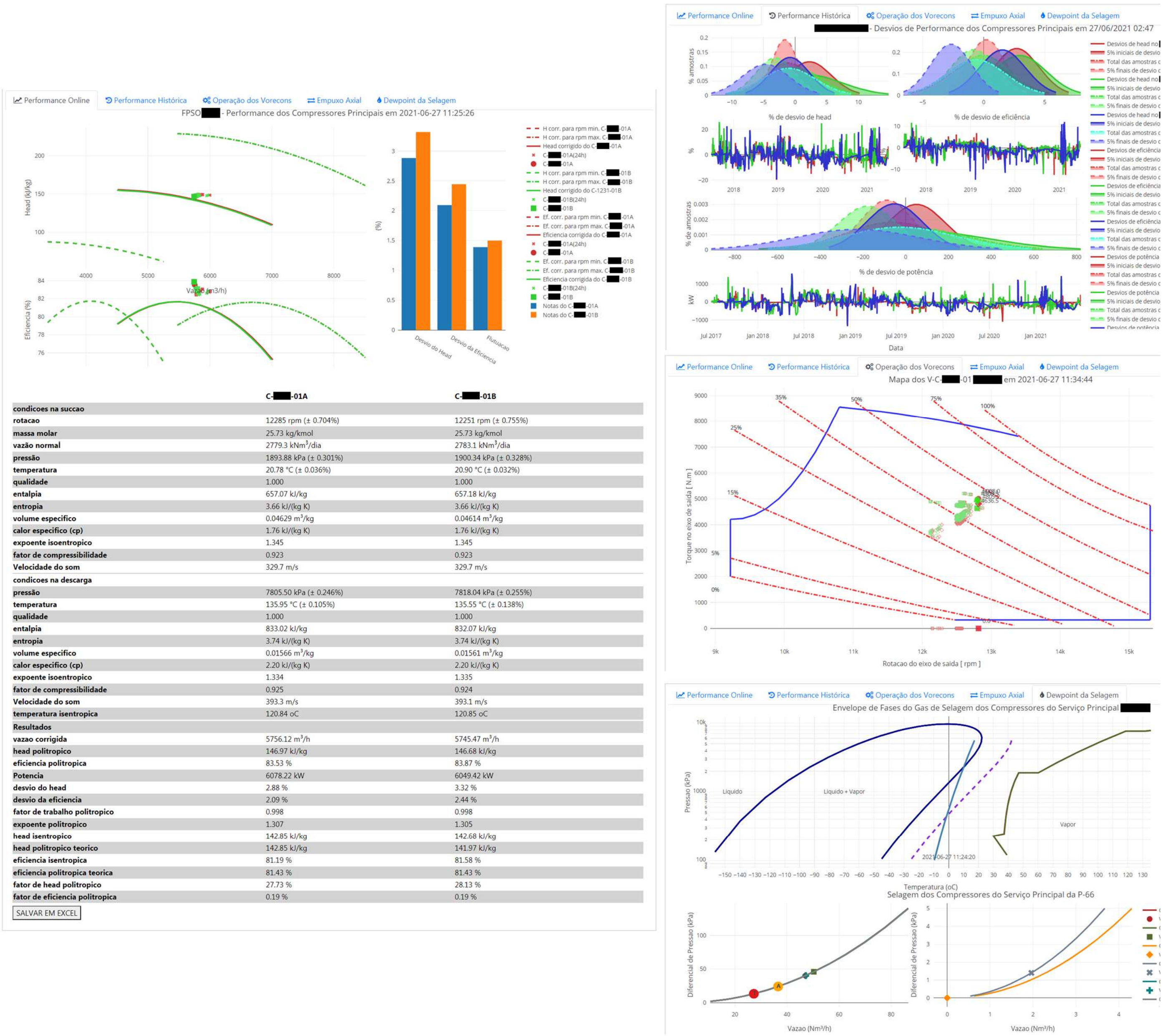


Figure 4. Online Performance Monitoring Dashboard for Gas Turbines

Some additional considerations regarding this dashboard:

- The table contains not only energy performance data but also the estimated CO_2 and NOx emissions, which can further be used to compute other key performance indicators, if needed.
- One of the main concerns while operating gas turbines is that the fuel gas is properly conditioned. Temperature drops bringing the gas fuel close to or below the dew point can cause damage to the burners, especially when a direct measurement of the fuel gas manifold temperature is not available. By using thermodynamics packages, it becomes possible to estimate the temperature drop from fuel gas header to the gas turbine manifold and set up an alarm to operations.
- Pens can be turned on and off, as shown in the plots presented on the right bottom corner of Figure 4. In this case, the use of this feature revealed that temperature spread in the combustion chamber has been increasing over time (red filled trend) and that air compressor efficiency range was at least 5% wide (after outliers' removal – grey and pink pens). That is quite significant, since the air compressor absorbed power is about 50% higher than the output power delivered by the gas turbine to the electric generator. This example illustrates an additional investigation derived from the proposed approach at equipment level that should play an important role in energy performance, as it can be used to tune maintenance scheduled wash intervals to minimize gas turbine performance degradation.

Figure 5 brings an overview of the dashboard developed for monitoring compressors, as well as related gear units and auxiliary systems (such as dry gas sealing systems). Data are presented is a similar way to the gas turbine dashboard, creating an intuitive user interface.



	C-[redacted]-01A	C-[redacted]-01B
condicoes na succao		
rotacao	12285 rpm (± 0.704%)	12251 rpm (± 0.755%)
massa molar	25.73 kg/kmol	25.73 kg/kmol
vazão normal	2779.3 kNm³/dia	2783.1 kNm³/dia
pressão	1893.88 kPa (± 0.301%)	1900.34 kPa (± 0.328%)
temperatura	20.78 °C (± 0.036%)	20.90 °C (± 0.032%)
qualidade	1.000	1.000
entalpia	657.07 kJ/kg	657.18 kJ/kg
entropia	3.66 kJ/(kg K)	3.66 kJ/(kg K)
volume especifico	0.04629 m³/kg	0.04614 m³/kg
calor especifico (cp)	1.76 kJ/(kg K)	1.76 kJ/(kg K)
expoente isoentropico	1.345	1.345
fator de compressibilidade	0.923	0.923
Velocidade do som	329.7 m/s	329.7 m/s
condicoes na descarga		
pressão	7805.50 kPa (± 0.246%)	7818.04 kPa (± 0.255%)
temperatura	135.95 °C (± 0.105%)	135.55 °C (± 0.138%)
qualidade	1.000	1.000
entalpia	833.02 kJ/kg	832.07 kJ/kg
entropia	3.74 kJ/(kg K)	3.74 kJ/(kg K)
volume especifico	0.01566 m³/kg	0.01561 m³/kg
calor especifico (cp)	2.20 kJ/(kg K)	2.20 kJ/(kg K)
expoente isoentropico	1.334	1.335
fator de compressibilidade	0.925	0.924
Velocidade do som	393.3 m/s	393.1 m/s
temperatura isentropica	120.84 oC	120.85 oC
Resultados		
vazao corrigida	5756.12 m³/h	5745.47 m³/h
head politropico	146.97 kJ/kg	146.68 kJ/kg
eficiencia politropica	83.53 %	83.87 %
Potencia	6078.22 kW	6049.42 kW
desvio do head	2.88 %	3.32 %
desvio da eficiencia	2.09 %	2.44 %
fator de trabalho politropico	0.998	0.998
expoente politropico	1.307	1.305
head isentropico	142.85 kJ/kg	142.68 kJ/kg
head politropico teorico	142.85 kJ/kg	141.97 kJ/kg
eficiencia isentropica	81.19 %	81.58 %
eficiencia politropica teorica	81.43 %	81.43 %
fator de head politropico	27.73 %	28.13 %
fator de eficiencia politropica	0.19 %	0.19 %

SALVAR EM EXCEL

Figure 5. Online Performance Monitoring Dashboard for Compressors

Although online data are used for this dashboard, they are not strictly real time because ‘as designed’ curves need to be corrected for the actual speed, suction conditions, and gas composition at a considerably high computational cost. Currently, there are over 300 compressor sections being monitored under a 50-minute time cycle by the software tool developed by the authors. Moreover, due to the lack of online chromatography for most of the monitored plants, most of the time gas composition needs to be updated manually based on offline chromatographic analysis.

RESULTS OF THE PROPOSED METHODOLOGY

Main Features of the FPSO Used for the Assessment

The FPSO where the proposed methodology was applied is located at the pre-salt fields of Santos Basin in Brazil. This unit is designed to process up to 150 kbpd of oil, 120,000 bpd of produced water, 180,000 bpd of seawater for injection, and 6,000,000 Sm^3/d of associated gas, according to the simplified processing scheme shown in Figure 2. The oil processing plant consists of a single train with three-stages of separation at 2,000 kPaa and 40°C, 770 kPaa and 90°C, and 220 kPaa and 85°C, respectively. Produced water plant is not as energy demanding as other processes, because water is disposed overboard. However, a significant water flow needs to be treated and pressurized to 25,000 kPa for injection into the reservoir. The process gas plant comprises the Gas Dehydration Unit with a molecular sieve system, a hydrocarbon Dew Point Control Unit with a Joule-Thomson valve, and a CO_2 Removal Unit with membranes, designed to specify the gas to be exported and the fuel gas to be used in the gas turbines with CO_2 concentrations less than 3% vol/vol.

The main power generation system consists of four dual-fuel gas turbine driven generator sets arranged in a 3 x 33% configuration (i.e., with one spare set), with an individual power supply capacity of 25 MW at site conditions. Therefore, the nominal generation capacity is 75 MW for an installed capacity of 100 MW.

Besides the gas turbine-driven power generators, the other major turbomachinery trains in the FPSO are related to the gas processing plant. In the Vapor Recovery Unit (VRU), a dry screw compressor (1 x 100%) is arranged in a single motor-driven train with two compression stages. The first stage collects gas from the 2^{nd} stage electrostatic treater at 220 kPaa, whereas the second stage pressurizes the gas streams coming from the first stage of compression and from the 3^{rd} stage electrostatic treater at 770 kPaa, delivering gas at 2,000 kPaa. The main compression system, comprised of three (3x50%) motor-driven centrifugal compressors of one compression section each, collects gas from the free water separator and from the VRU compression system at 1,950 kPaa and pressurizes it up to 8,200 kPaa. Process gas is then delivered to the Gas Dehydration Unit.

Similarly, the exportation compression system, comprised of three (3x50%) electric motor-driven centrifugal compressors of two compression sections each, collects gas coming from the CO_2 Removal Unit at 5,100 kPaa, and pressurizes it up to 25,100 kPaa for gas exportation and/or gas lift. The injection compression system, comprised of two (2x100%) motor-driven centrifugal compressors of one compression section each, collects gas either from the CO_2 membrane system or from the exportation compression system at 25,000 kPaa, and pressurizes it up to 55,000 kPaa for injection into the reservoir.

Finally, the CO_2 compression system, comprised of two (2x100%), double-casing, turbine-driven centrifugal compressors of four compression sections each, collects permeated gas from the CO_2 Removal Unit at 400 kPaa and pressurizes it up to 25,100 kPaa. Compressed gas is then delivered to the injection compression system. It is noteworthy that main, exportation and injection compressors have fixed speed motors fitted with hydraulic variable speed drives.

Energy and Carbon Performance Measurements at Installation Level

The assessment of carbon and energy performance at installation level begins with the analysis of certain aspects and data related to the FPSO operation, such as modes of operation of the plant, equivalent barrels of oil produced, water and gas injection and carbon emissions flowrate.

Figure 6 shows FPSO operation from the beginning of production ramp up. As new wells were lined up, production has gradually been increased up to a flat reached in April 2018, when the production plateau was achieved. The FPSO remained in the production plateau with full reinjection of all produced gas until September 2019, with exception of gas used for internal consumption and losses. During this period, gas pipeline was not available, and the CO_2 compressor has remained not commissioned. Actually, commissioning of the CO_2 Removal Unit and CO_2 compression systems usually takes place only at the FPSO final location, due to the absence of gaseous hydrocarbons in the integrator shipyards. As of September 2019, with the pipeline available and the CO_2 separation and reinjection systems properly commissioned, exportation of associated gas started and should predominate throughout the remaining FPSO lifetime.

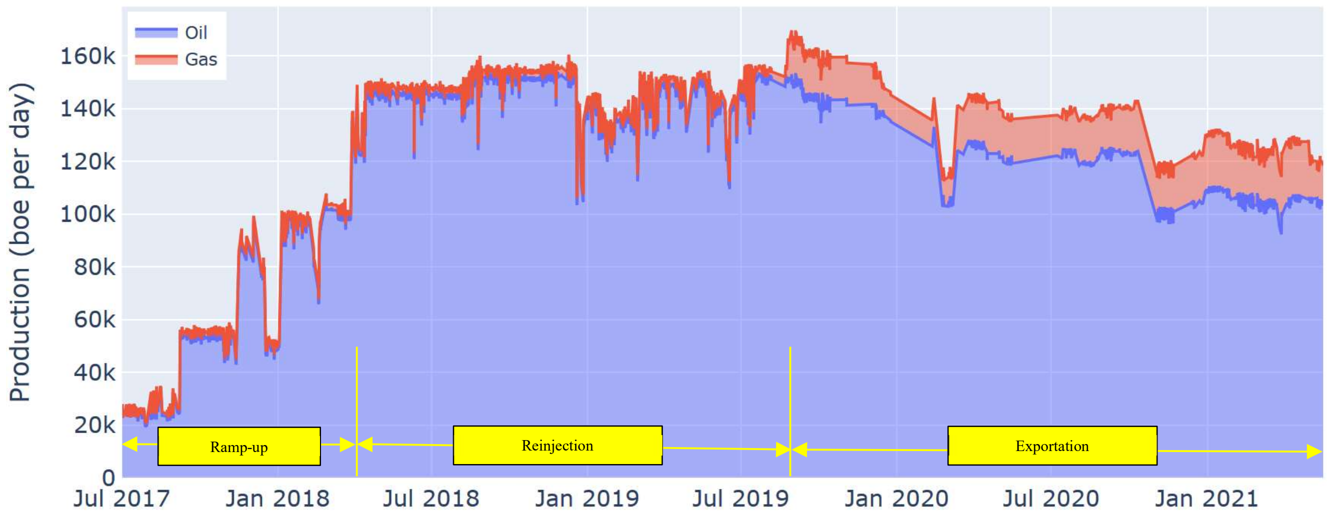


Figure 6. FPSO Net Production in Barrels of Oil Equivalent per Day since Start-up

From the point of view of energy and carbon performance, the main difference between total reinjection and gas exportation is that in the first one only the motor-driven compressors are in operation (i.e., VRU, Main, Export and Injection compression services). However, in gas exportation operating mode, a slight reduction in power demand from the Export and Injection compressors is expected, as the rich-hydrocarbon portion of gas flow (retained) at the CO_2 membrane system is compressed only up to the export pressure, which is considerably lower than the injection pressure. On the other hand, during gas exportation, the portion of the gas flow rich in CO_2 (permeate) is compressed up to the injection compressor inlet pressure by the gas turbine-driven CO_2 compressor. Trends shown in Figure 7 clearly identify the changeover in operating modes, when gas exportation becomes the predominant mode of operation. Finally, Figure 7 also shows that the CO_2 removal process is more energy than carbon intensive, since both the power generators and the gas turbine-driven CO_2 compressor will run on a lower CO_2 content fuel gas during the gas exportation.

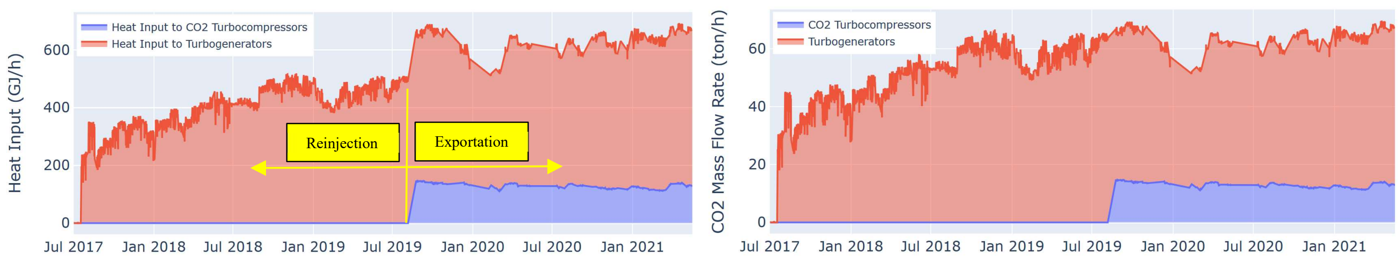


Figure 7. FPSO Heat Input and CO_2 Emissions

It is noteworthy that a moving average filter was applied in all trend plots to remove major outliers and facilitate technical analysis, without compromising the overall medium- and long-term behavior of such metrics. Moreover, one should consider that, after March 2020, the Covid-19 pandemic might have influenced somehow the production curve and other defined indices in certain periods, due to a momentary adjustment between supply and demand.

The proposed energy and carbon performance indicators at installation level are derived from overall parameters of net hydrocarbon production, energy input in the form of fuel gas and the related direct CO_2 emissions from combustion in turbines. Both graphs in Figure 8 convey essentially the same information, although in different ways, since emissions in this case are directly associated with the stoichiometry combustion. During the ramp-up phase, the energy and carbon performance indicators are in an unfavorable situation. At this stage, some compressor recycling may be needed, auxiliary systems whose electrical demand does not vary with the production of hydrocarbons are in operation, turbomachinery in general are far away from their best efficiency point and, obviously, the FPSO is not operating at its full capacity. Specific energy consumption and specific CO_2 emissions will stabilize at the end of the ramp-up phase as soon as the last oil well is opened and the FPSO reaches its nominal capacity. After some period in this condition, the energy and carbon performance indicators start to deteriorate gradually. The sudden change in these installation level indicators (especially in the EII indicator), in September 2019, is due to the change in the operating mode to gas exportation. Anyway, after changing the operating mode, gradual deterioration of the overall FPSO energy and carbon performance has remained.

Figure 8. Energy and Carbon Performance Indicators at Installation Level

Energy and Carbon Performance Measurements at System Level

Figure 9 shows the electrical power demand profile of the FPSO main power generation system. In general, there is a certain stability in the demand profile in the period analyzed, and after the start of operation of the CO_2 separation membrane, a small reduction in electrical demand was observed, although it recovered almost entirely throughout 2021. It is worth mentioning that despite of a small decline in the FPSO production, electrical demand relies predominantly on large turbomachinery associated to gas production and water injection into the reservoir. In the period evaluated, the associated gas flow remained close to the installation's nominal capacity and the injection water flow increased after starting the second main water injection pump.

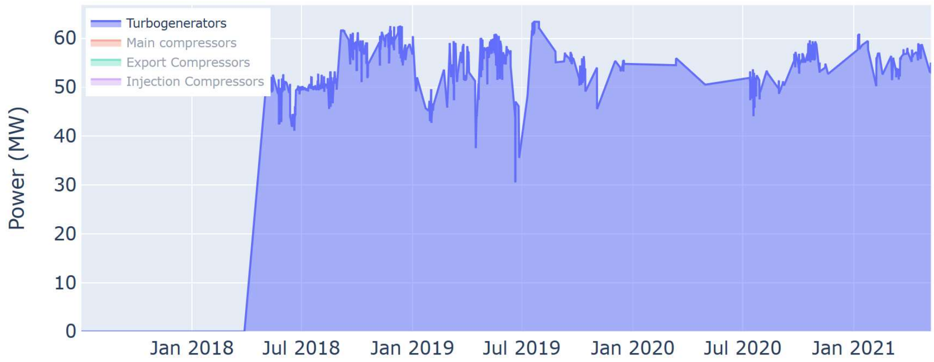


Figure 9. Electric Power Demand Profile of the FPSO Main Power Generation System

Table 1 presents the fuel gas composition. One can note that the system operates during ramp-up until the commissioning of the CO_2 separation membrane system with a fuel gas which has a smaller lower heating value (LHV) and larger CO_2 contents, until the CO_2 separation membrane starts operating. The evaluated FPSO does not have an online gas chromatograph, that is, the energy and carbon performance monitoring consider the result of periodic chemical lab analyzes.

Table 1. Fuel Gas Composition at Different Operating Modes (% mol/mol)

Chemical element	Before CO_2 membrane commissioning	After CO_2 membrane commissioning
Methane	68.03	71.05
Ethane	8.49	10.84
Propane	4.00	6.27
Isobutane	0.53	0.89
N-butane	0.91	1.54
Isopentane	0.22	0.29
N-pentane	0.31	0.35
Hexane	0.35	0.18
Heptane	0.54	0.15
Nitrogen	0.73	0.83
Carbon dioxide	15.99	7.61
LHV @15°C (kJ/kg)	34,350	41,090

Based on the fuel gas compositions presented in Table 1, for the same levels of power demand and efficiency, carbon emissions associated to the power generation system should be higher before the CO_2 Removal unit starts operating. In practice, however, there is a marked change in the overall power generation system efficiency (see Figure 10), which can be mainly attributed to the way the system is operated, since no relevant signs of gas turbine performance degradation were observed and, ultimately, the influence of the fuel gas composition on the turbine efficiency is also very small.

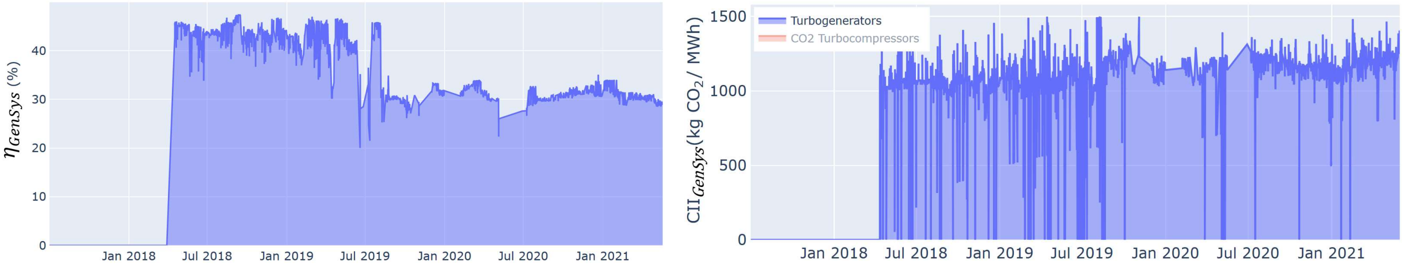


Figure 10. Overall Efficiency and Carbon Intensity Index Associated to the Main Power Generation System

A similar approach can be applied to monitor energy and carbon performance of compression systems. For instance, Figure 11 shows the gas absorbed power profile of the CO_2 compression system. Using gas power instead of shaft power is particularly useful when direct torque measurement or indirect shaft power calculation is unavailable or impractical, as illustrated in this example. The possible use of analytical models to calculate shaft power of gas turbine drivers as a function of heat input and ambient conditions were not investigated in this work, as there are concerns regarding model calibration and gas turbine performance degradation over time.

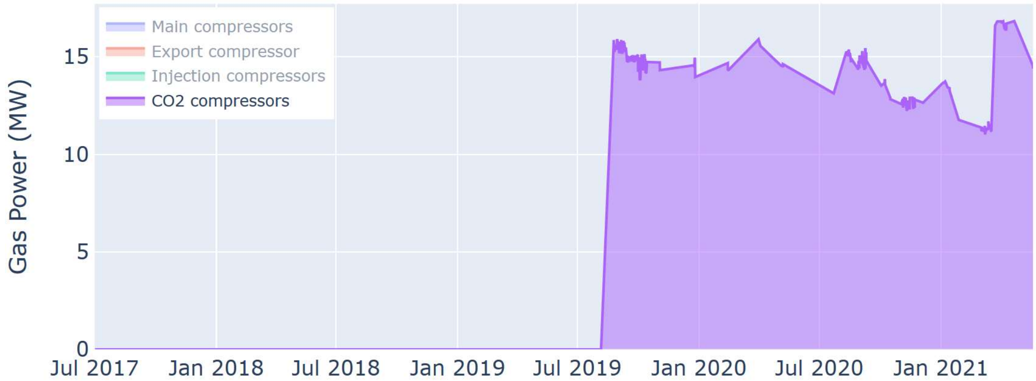


Figure 11. Gas Power Demand Profile for the CO_2 Compression System

The results of the energy and carbon performance evaluation of the CO_2 compression system are shown in Figure 12. In general, one can note from Figures 11 and 12 is a direct correlation between the gas power demand and efficiency of this system and an inverse correlation between gas power demand and the Carbon Intensity Index. Indeed, as of March 2021, when an increase in gas power demand occurred, the efficiency of the system also increased and, consequently, specific carbon emissions decreased. This observation corroborates the fact that the gas turbine efficiency increases significantly as the operating point approaches to the rated power.

Figure 12. Efficiency and Carbon Intensity Indexes for the CO_2 Compression System

This approach is useful not only to monitor the relationship between the system load and energy efficiency or carbon emissions, but also for troubleshooting possible sources of performance degradation in the compression system (gas recirculation, pressure drops, etc.), most of them located out of the compressor package limits and therefore, not captured by the assessment at equipment level. Obviously, it also requires a deeper investigation on the energy and carbon performance of each compressor individually (including its compression sections), for the completeness of evaluation.

Energy and Carbon Performance at the Equipment Level

Energy and carbon performance indicators at equipment level can be used for additional investigations derived from the performance assessment of the entire facility or from the system the equipment belongs to, even though sometimes it is difficult to get immediate practical results from this bottom-level assessment. For example, Figure 13 shows performance data for the Main Compressor "C" of the analyzed FPSO. As shown on the right-side time trend plot of Figure 13, there are some peaks in the calculated polytropic efficiency with quite accentuated deviations (about ± 10%) in relation to the polytropic efficiency predicted in the supplier's performance data for the same operating conditions. Similar fluctuations are also observed in head and shaft power.

As time trends are quite noisy, even after removing outliers and high-frequency noise, a statistical approach was adopted. Normal distributions were fitted to the first 5% of the time trend samples, the entire dataset, and the last 5% of the time trend samples. For each fitting, the Kolmogorov-Smirnov (ks) importance index was calculated to indicate statistically meaningful changes between samples. For the 5% sampling, the index reflects dissimilarity to the whole dataset distribution, being ever more dissimilar as it approaches an index of 100%. The whole dataset presents the most telling Kolmogorov-Smirnov index: the one resulting from comparing the two 5% data subsets.

In this example, performance trends point to somewhat 'good confidence' (K-S statistic close to 70%) reductions in both compressor head and gas power, and even a better confidence for the efficiency reduction (K-S statistic around 90%). Considering that the FPSO main compression service is less prone to changes in gas composition during operation, the energy assessment at equipment level has revealed a decrease in polytropic efficiency since the platform startup, which might be costing as much as 200 kW just for this compressor.

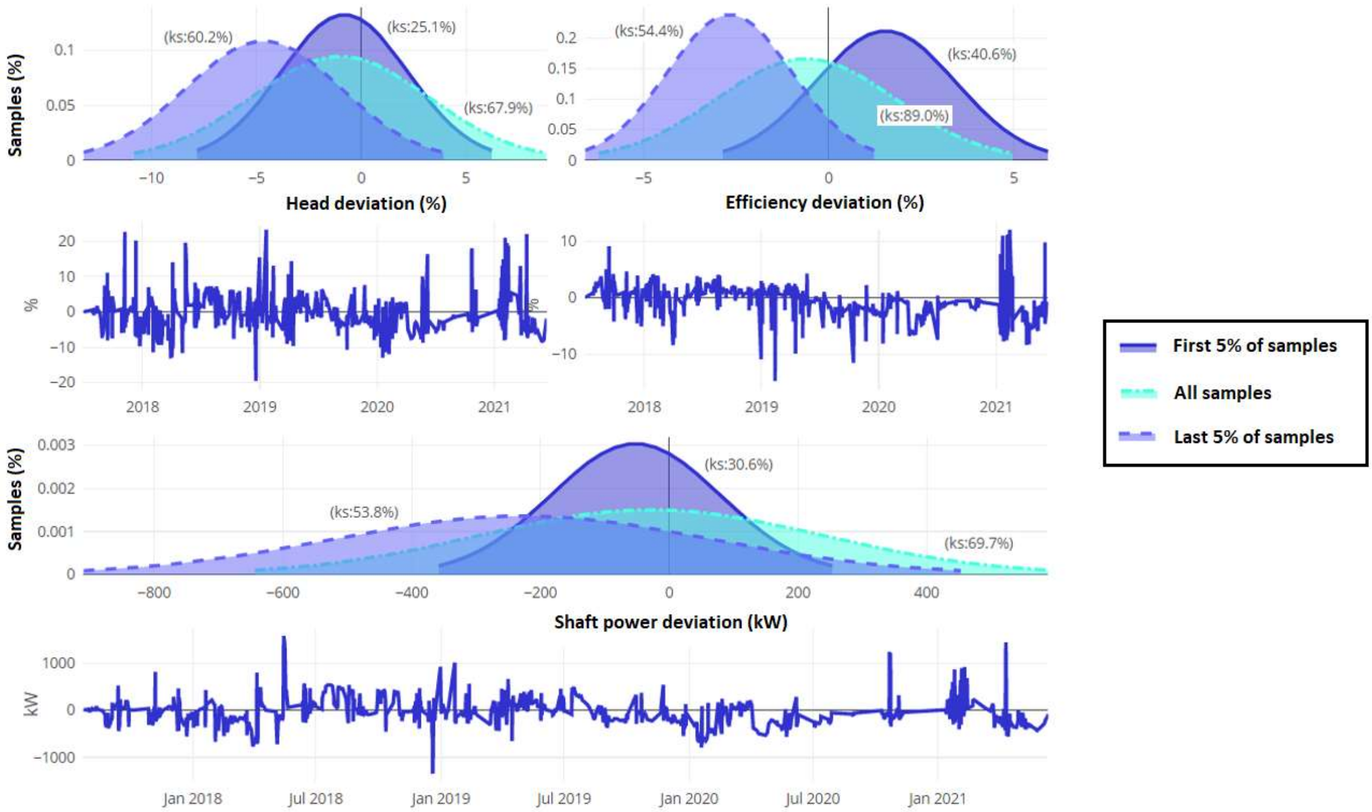


Figure 13. Performance Data (Historical Deviations and Normal Distributions) for the FPSO Main Compressor "C"

A typical polytropic efficiency for the main compressors is around 80%. Even considering the large deviations in the efficiency time trend shown in Figure 13 (± 10% deviations are to be expected), the overall efficiency of the FPSO main compression system should not remain for long periods at, or below, 60%, as it was further observed. The same is applicable to all other compression systems, especially export compression. The key argument here is that individual compressor efficiencies cannot cause large periodic fluctuations in the overall system efficiency. This leads to a conclusion that other energy loss mechanisms have come into play. Usually, for compression systems, major energy losses are caused by recirculation and throttle valves, whilst controlling capacity or preventing compressor surge.

There is still much uncertainty involved in these calculations, especially for those FPSO compression services subjected to significant changes in gas composition, such as export and injection compressors. For these machines, caution should be taken during the assessment to render reliable (and useful) information for the decision-making process.

Example of an Improvement Action for Raising Energy and Carbon Performance

Driving energy and carbon performance in existing facilities might be challenging because, most of the time, improvement actions are related to interventions in the field. However, there are simple improvement actions that can lead to significant results. For instance, Figure 14 shows the influence of the number of gas turbine generator sets in operation on the carbon emissions, for the rich CO_2 fuel gas composition scenario presented in Table 1. As can be seen in this example, by shutting down one gas turbine generator set, for any given power demand on the chart it is possible to considerably reduce the overall carbon emissions from this system, as the efficiency at both equipment and system level goes up. Below 45 MW, the outliers presented in this figure for three power generator sets operating in parallel seem to be associated to the opening of gas turbine bleed valves to avoid surge in the air compressor. Otherwise, the influence of any transient conditions or faults in the instrumentation readings cannot be discarded.

Of course, the decision for shutting down a power generator set like the one presented in this example depends on other factors, such as the expected time and frequency that all machines will be required to operate together due to transient power demands, safety constrains and a reliability analysis to ensure that production will not be compromised.

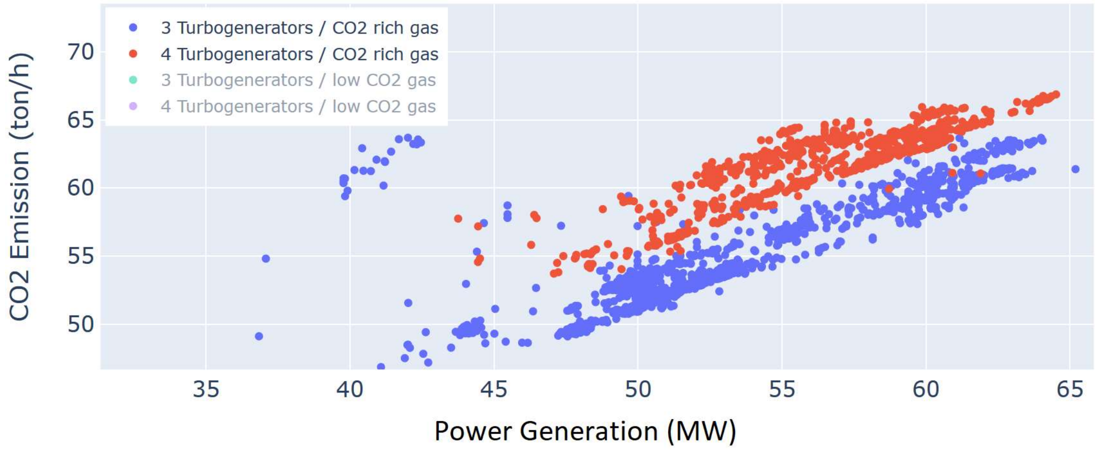


Figure 14. The Influence of the Number of Generators in Operation on the Carbon Emissions

CONCLUSIONS

The approach presented in this paper is as an important step towards building a practical (but effective) energy and carbon management system for the upstream segment, especially for those oil and gas companies where energy and carbon performance assessments of their offshore production assets have not been implemented yet. By applying the proposed performance indicators at different levels of the facility, end users should be able to monitor deviations in the overall performance of their oil production plants, as well as to identify bad actors in energy and carbon related to a particular equipment or system. Moreover, the approach proposed by the authors can also be used to predict and compare the energy and carbon performance of new FPSO projects in relation to existing units, helping engineers to select the most appropriate design solution.

Questions such: has the FPSO been designed to be energy and carbon efficient? Is the FPSO itself (and its systems) being operated in an efficient manner? Are the turbomachinery trains performing as expected or have their performance been deteriorated due to a lack of proper maintenance? Hopefully, this work can start to answer these questions from a practical standpoint.

For the latter question raised above, perhaps the key point of discussion is to decide when a turbomachinery maintenance program should be considered inappropriate. In many cases, that is not an easy problem to address, as it combines inherent assessment difficulties and operation personnel resistance while production remains unaffected by performance degradations. Indeed, such decision will largely depend on the analysis of operational expenditure associated with energy and environmental issues against maintenance costs and the imminent risk of production losses due to turbomachinery downtime.

In that sense, even though process gas compressors are probably the most energy intensive consumers in an offshore oil production plant, they are also the most difficult rotating equipment to evaluate in the field. Unfortunately, typical issues found in most of existing FPSO gas processing plants such as: unknown process gas compositions, poor instrumentation, operation in off-design conditions and presence of liquids in the gas stream, make the accuracy of the assessment in energy and carbon at equipment level still challenging for this type of equipment. To avoid these limitations, new FPSO projects should be designed with a proper set of dedicated instrumentation at equipment level to allow for direct measurement of real-time process gas compositions and gas turbine-driven compressor power.

Finally, the results presented in this work show that the proposed approach is promising and seems to be a valuable source of information for optimizing turbomachinery energy performance and promoting decarbonization.

REFERENCES

ASME PTC-10, 2014, "Performance Test Code on Compressors and Exhausters", American Society of Mechanical Engineers, New York, NY.

ISO/ASME 14414, 2019, "Pump system energy assessment", Second Edition, International Organization for Standardization, Geneva, Switzerland.

ISO 50001, 2018, "Energy management systems – Requirements with guidance for use", Second Edition, International Organization for Standardization, Geneva, Switzerland.

ISO 50006, 2014, "Energy management systems – Measuring energy performance using energy baselines (EnB) and energy performance indicators (EnPI) – General principles and guidance", First Edition, International Organization for Standardization, Geneva, Switzerland.

Maia, J. L., Neves, M. V., 2010, "Method of Equivalent CO_2 Emissions Sources Identification and Quantification of Offshore Petroleum Product Units", SPE Paper Number 126699, SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Rio de Janeiro, Brazil.