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COMPARATIVE LIFE CYCLE ASSESSMENT OF DIFFERENT GAS TURBINE AXIAL COMPRESSOR WATER WASHING SYSTEMS

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ABSTRACT

Nowadays the climate change is widely recognized as a global threat by both public opinion and industries. Actions to mitigate its causes are gaining momentum within all industries. In the energy field, there is the necessity to reduce emissions and to improve technologies to preserve the environment. LCA analyses of products are fundamental in this context.

In the present work, a life cycle assessment has been carried out to calculate the carbon footprint of different water washing processes, as well as their effectiveness in recovering Gas Turbine efficiency losses. Field data have been collected and analyzed to make a comparison of the GT operating conditions before and after the introduction of an innovative high flow on-line water washing technique. The assessments have been performed using SimaPro software and cover the entire Gas Turbine and Water Washing skids operations, including the airborne emissions, skid pump, the water treatment and the heaters.

Keywords: Sustainability, Carbon Footprint, Gas Turbine, Axial Compressor, Water Washing, High Flow On-Line Water Washing, Life Cycle Assessment, SimaPro.

NOMENCLATURE

AP	Acidification Potential
AXCO	Axial Compressor
BH	Baker Hughes
CC	Combustion Chamber
CFP	Carbon Footprint
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
GHG	Greenhouse Gases
GT	Gas Turbine
GWP	Global Warming Potential
HFOLWW	High Flow On-Line Water Washing
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LHV	Lower Heating Value
NO_x	Nitrogen Oxides
OLWW	Off-Line Water Washing
PT	Power Turbine
Pt	Points
RMD	Remote Monitoring Diagnostics
WW	Water Washing

1. INTRODUCTION

Sustainability achievements are becoming an essential target of innovation and technology development in the turbomachinery scenario as Gas Turbines are one of the main contributors to CO_2 emissions. The increasing attention to the environmental protection and the need to follow a competitive market, allow to push in developing innovative technologies capable to improve GT efficiency and to avoid its losses. The main causes of GT performance losses can be identified in: axial compressor and turbine fouling, pressure losses in filters, blade erosion/corrosion, leakages. Gas turbine axial compressor fouling is known as the source of about 70 ~ 85 % of the performance degradation of the whole engine [1]. As a matter of fact, contaminants, ingested into the compressor, deposit in the flow path, alter the aerodynamic profile of blades and cause a reduction in the GT maximum output power and efficiency**.** To limit the effects of fouling, the compressor needs to be periodically cleaned. Two types of washing techniques are currently adopted: an on-line water washing and an off-line water washing. The two systems operate independently. For a better efficiency of cleaning it is recommended to periodically perform both on-line and off-line washes.

Recently, it has been demonstrated the effectiveness of a new High Flow On-line Water Wash [2]: by maintaining the GT axial compressors efficiency almost constant in time, HFOLWW permits to decrease the fuel consumption needed to balance the efficiency losses to get the required power, eventually reducing CO_2 emission [2-5].

1.1 Off-line water wash procedure

The most common approach to the gas turbine axial compressor cleaning is the so-called “off-line water wash”. Through this process, most of the fouling deposited on the compressor vanes is removed while the machine is running in crank. Although safe and effective, the process needs up to 24 hours of gas turbine downtime, with consequent production losses.

One off-line cleaning cycle requires a solution composed by 1/3 of cleaning solution and 2/3 of rinsing water. The cleaning solution is injected for a suitable time suggested by the manufacturer. After that period, the engine is rinsed to remove cleaning solution residues. It is generally suggested to wash and rinse the compressor twice. The temperature of the injected water is recommended to be from 38°C to 65°C [7]; if ambient temperature is lower than 10°C, an antifreeze solution is needed [7].

1.2 On-line water wash procedure

With respect to the off-line water wash, the on-line water wash is activated while machine is operating at base load with no needed to shut-off the engine. Two different options of on-line water washing are available: the standard “low flow” and the innovative “high flow” here proposed.

One on-line cleaning cycle requires a certain amount of water injected for a suitable period specified by manufactured. The temperature of the injected water is from 60°C to 65°C and even in this case, if the ambient temperature is lower than 10°C, an antifreeze solution is required [7].

The high flow on-line water washing system is a new methodology for axial compressor cleaning. It has been tested for offshore/marine applications, where the large part of fouling deposits consists of salt. It can be operated every day for a few minutes. Tests performed on GT engines show that by increasing the on-line water flow rate, the power recovered after fouling and cleaning the axial compressor is above 90% [7].

1.3 Effectiveness of the water washing procedures

Considering the RMD data of a medium size GT operated at base load, the load percentage over the fired hours is shown in red (Fig1). As shown in Figure1, after 2000 hours of operation, the compressor performance is strongly reduced, heavily affecting the overall GT performance. Performing the off-line washing, the % of load recovered (blue line) can reach up to ˜6% with a very small reduction with respect to the initial efficiency. However, between two successive off-line washings, the fuel consumption increases as well as the emissions.

To maintain the compressor efficiency as high as possible, aiming at following the green lines in Figure 1, the new high flow on-line water washing system is repeatedly activated daily. The green lines represent the efficiency curves that are expected by assuming an on-line water wash increasing effectiveness of 90%, 95%, 100%. The green continuous line (100%) indicates the no recoverable part of the losses due to other aging effects (e.g. erosion leading to profile losses). With an 100% effective high flow on-line washing, there would be no further benefit given by off-line washings.

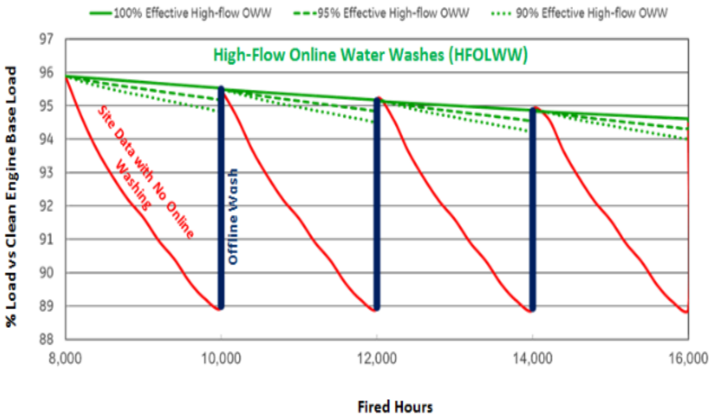


FIGURE 1: GT Degradation Curve. [7] *© 2020 Baker Hughes Company - All rights reserved.*

1.4 Description of the LCA Procedure

Target of the paper is the assessment of CO_2 emissions and environmental issues related to water washing procedures. To this end, it is needed to perform Life Cycle Assessment focusing on the two kind of water washing systems here considered: Off-line (OWW) and High Flow On-line (HFOLWW) Water Washing. Analysis refers to an offshore plant that can work in both configurations. Real data have been compared before and after the installation of the new HFOLWW skid, to evaluate the CO_2 emission due the type of water washing used.

The time frame ranges about 3 months, which is the period from two consecutive OWWs. In the first 3 months interval, only OWW process was available, while in the second interval both OWW and HFOLWW systems were carried out.

The LCA analysis was split up in two parts: the first refers to water washing systems operation and the second to gas turbine operation. In the first part of the study, the SimaPro software has been used to analyze the OWW and HFOLWW skids operation by evaluating the water and energy consumed in the given time frame. In the second part, in the same time frame, the gas turbine operation has been analyzed with reference to:

- Field data collection before and after the introduction of the HFOLWW system
- Data filtering and calculation of CO_2 emission by the evaluation of the amount of fuel used
- Data filtered refer to a specific GT operating condition to have data comparable

2 LIFE CYCLE ASSESSMENT

In recent years, sustainability issues are becoming a relevant part of the design of new products. Life Cycle Assessment is a quantitative tool widely used to determine the environmental benefits and potential impacts of a given product or technology. In 2012, Sloan reported a survey among of several managers declaring that 70% of them state that sustainability is an argument present in the agenda of their corporation [8]. Then sustainability is imposing itself as a resource for innovation and increase competitiveness rather than a tool for cost shrinking.

An LCA perspective considers the entire life cycle of a product, from raw material extraction and acquisition, to material processing and product manufacturing, distribution, use and end of life treatment. Through this global vision, a potential environmental load can be shift from one phase of the life cycle to another, or it can be shift from a process to another.

FIGURE 2: Life Cycle [10]

The steps of LCA include:

- Raw Material Extraction Phase: raw materials are extracted from their environment;
- Raw Material Processing Phase: extracted raw materials are processed into other used to produce products;
- Product Manufacturing Phase: products are manufactured and/or assembled;
- Distribution Phase: products are packaged and transported;
- Use Phase: products are used consuming other materials (paper, electricity, water, etc.);
- End of Life Phase: products are disposed (recycling, landfill, incineration, etc.).

The International Organization for Standardization (ISO), provides guidelines for conducting an LCA within the series ISO 14040 (Principles and Frameworks [9]) and 14044 (Requirements and Guidelines [10]).

The most important aspect of an ISO standard is the need for careful documentation to avoid interpretation problems. There is no single way to perform an LCA analysis, the important thing is to carefully document what you do.

The LCA procedure includes the following four steps:

- Definition of the goal and scope of the study;
- Inventory analysis, making a model of the process life cycle with all the necessary inputs and outputs;
- Impact assessment, understanding the environmental relevance of all the inputs and outputs;
- Analysis and interpretation of the study.

The LCA is based on process/technology modeling. A specific challenge of such activity is to be able to develop a model in close agreement with the reality.

3 METHODOLOGY

Scope of this work is the application of LCA methodology to the two above mentioned water washing axial compressor systems of an industrial gas turbine. GT are typically used for generator drive in industrial power generation and for mechanical drive for production units. Comparison of different water washing processes will be presented to draw conclusion. The impact of OWW will be compared with a new kind of water washing system (HFOLWW) in terms of process optimization and environmental impact assessment.

In SimaPro there are several impact assessment methods.

All the methods have the same structure:

1. Characterization: the substances that are part of an impact category are multiplied by a characterization

factor that expresses the relative contribution of the substance.

2. Damage assessment: all the impact category indicators are combined into a damage category. The impact category indicators with a common unit can be added. For example, all impact categories that refer to human health are expressed in DALY (disability adjusted life years). All the substances that could cause disability, are added into category Human Health.
3. Normalization: the impact category is divided by the reference. A kind of reference could be the average yearly environmental load in a country or continent, divided by the number of inhabitants. The choice of reference is free. It can be useful to communicate the results obtained to non-expert people of LCA. In SimaPro there are a set of references available. After normalization all the impact category indicators have the same unit, which makes it easier to compare them.
4. Weighting: not all the methods have this step. The results of the previous step are multiplied by the weighting factors and are added together to create single score. Also, in this case, in SimaPro there are a set of weighting factor available.

The inputs that have been considered in the present LCA analysis are:

- Amount of water
- Energy used for auxiliaries (e.g. pump drive)
- Energy consumption heaters, because the water must reach a temperature of 65°C [7]
- Detergent solution for Off-line water wash

Two method have been used: ReCiPe2016 and IPCC2013.

3.1 ReCiPe2016

In ReCiPe 2016 there are both midpoint (problem oriented) and endpoint (damage oriented) impact categories, available for three different perspectives (individualist (I), hierarchist (H), and egalitarian (E)). There are a sets of impact category with sets of characterization factors. At the midpoint level, 18 impact categories are addressed:

1. Climate change
2. Stratospheric ozone depletion
3. Ionizing radiation
4. Ozone formation, human health
5. Fine particulate matter formation
6. Ozone formation, terrestrial ecosystems
7. Terrestrial acidification
8. Freshwater eutrophication
9. Marine eutrophication
10. Terrestrial ecotoxicity
11. Freshwater ecotoxicity
12. Marine ecotoxicity
13. Human carcinogenic toxicity
14. Human non-carcinogenic toxicity
15. Land use
16. Mineral resource scarcity
17. Fossil resource scarcity
18. Water use

At the endpoint level, every of these impact categories are multiplied by a damage factor (specific for each categories) and added up in three endpoints:

- Human Health
- Ecosystems
- Resources scarcity

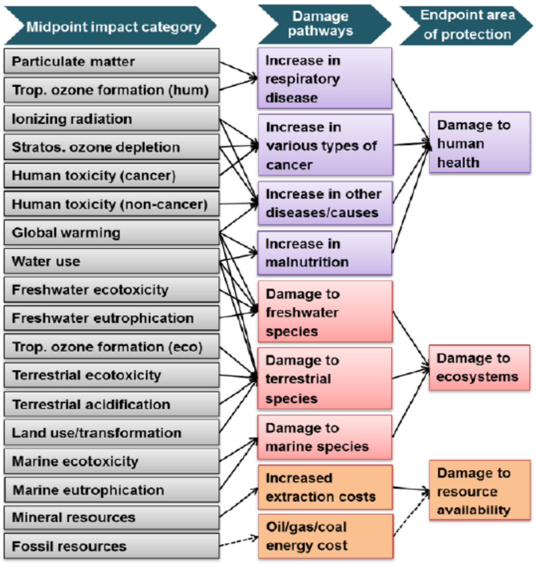


FIGURE 3: Relations Between the Impact Categories Midpoint and The Areas of Protection (Endpoint). [11]

These last categories are strictly linked to the three pillars of sustainability: environmental, economic and social pillars [12]. Environmental mechanisms and damage models have uncertainty, modeling has a certain level of incompleteness and uncertainty. In ReCiPe 2016 it was decided to group different sources of uncertainty and different (value) choices into a limited number of perspectives or scenarios, according to the "Cultural Theory" by Thompson 1990V [13].

There are three different perspective:

- Individualist (I): it is based on short-term interest and the most popular types of impact;
- Hierarchist (H): it is based on the most common political principles regarding timing and other issues.
- Egalitarian (E): is the most precautionary perspective, takes into consideration the longest time interval, types

of impact not yet fully established but with some indications.

These perspectives are used to group similar types of hypotheses and choices.

The endpoint characterization factors used in ReCiPe can be described as follows:

- Human Health: it is expressed as the number of year life lost and the number of years lived with disability. These years are added up in Disability Adjusted Life Years (DALYs). The unit is *years*.
- Ecosystems: expressed as the loss of species over a certain area, during a certain time. The unit is *species.yr*.
- Resources: expressed as the surplus costs of future resource production over an infinitive timeframe (assuming constant annual production), considering a 3% discount rate. The unit is *USD2013*. Mind that fossil resource scarcity does not have constant mid-to-endpoint factor but individual factors for each substance [11].

In the last step, all the values are summarized in the Single Score, that is the output of this method, a universal measure unit (Pt) that permit to compare different SimaPro practitioners' analyses.

3.2 Carbon footprint, IPCC2013

IPCC is another SimaPro methods, it is developed by the Intergovernmental Panel on Climate Change and permits to evaluate the airborne emission. It is related only to emissions of greenhouse gases to air and consider the global warming potential of each of it. The main GHG in atmosphere are listed below:

- Water vapor (H_2O)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Ozone (O_3)

The result of this kind of analysis is expressed in kilograms of carbon dioxide equivalent $kgCO_{2eq}$. Every GHG is compared to CO_2 emission, in one value we can found all the GHG air emission contribution [11]. Climate change can have negative effects on human health, the ecosystem and resources. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is at global scale.

IPCC 2013 is an update of the method IPCC 2007 developed by the International Panel on Climate Change. This method lists the climate change factors of IPCC with a timeframe of 20 and 100 years [11]

In the CO_{2eq} are added all the contribution of greenhouse gas, with some exceptions:

• excluding the formation of dinitrogen monoxide from nitrogen emissions.

• does not take into account the radiative forcing due to water, sulphate, NO_x, etc. in the lower stratosphere and upper troposphere.

• excluding the formation of CO_2 from CO emissions.

It is a widely used indicator for the evaluation of the carbon footprint.

4 OPERATION ANALYSIS

To quantify the benefits gained from the use of the high flow on-line water washing, data of water washing skids and GT operation have been analyzed before and after the introduction of the HFOLWW system.

A summary of the LCA drivers is reported below:

- Water washing system operation. Main parameters for the LCA are the utilities necessary to the water washing skids: the amount of demineralized water and detergent needed per washing cycle, as well as the energy needed to activate auxiliaries per washing cycle (i.e. pump and heaters). Analysis has been performed adopting ReCiPe2016 and IPCC2013 methods.
- Gas turbine operation. The main parameter for the LCA has been identified in GT fuel demand before and after the HFOLWW system introduction. To assess comparable gas turbine operating conditions, test data have been selected at the same GT power output, the same ambient conditions and the same PT speed.
  As the CO_2 emissions are directly linked to fuel demand, the IPCC is the most immediate method for the LCA.

All the assessments have been carried out in the period between two consecutive off-line washings, that approximately correspond to three months of engine operation, considering the same value of axial compressor efficiency as starting point.

In this time frame, 1 cycle of off-line water washing has been considered for the first assessment, 1 cycle of off-line wash + daily high flow on-line water wash has been considered for the second assessment.

Water Washing System Operation LCA		
Drivers	**Before HFOLWW**	**After HFOLWW**
Demi Water	800L	c.a. 20000L in 3 months
Detergent	200L	200L (only for off-line)
Energy	~ 50kWh per cycle	~ 50kWh per cycle
Frequency in 3 months	1 off-line cycle	1off-line cycle + 92 HF cycles
Gas Turbine Operation LCA		
Drivers	**Before HFOLWW**	**After HFOLWW**
Fuel Composition	Natural Gas	Natural Gas
Fuel Demand	Measured Data	Measured Data

TABLE 1: Drivers of Life Cycle Assessment*© 2020 Baker Hughes Company - All rights reserved.*

Two methods have been used for the system operation's life cycle assessment, the ReCiPe2016 and IPCC2013, while only the IPCC method has been used to analyze the environmental impact of a gas turbine operation.

As mentioned before (Fig.3), IPCC characterizes the climate change factor category by evaluating airborne emissions only. This category is one of the different midpoint characterization factors in the ReCiPe method.

When considering a carbon dioxide intensive system like a Gas turbine, the airborne emissions are dominant with respect to the other ReCiPe midpoints. For this reason, in this case the two methods show comparable results and thus only one can been selected.

4.1 Water Washing System Operation: ReCiPe2016

In the characterization phase, namely the first step of the ReCiPe analysis, the impact categories at the midpoint level are evaluated for both the off-line and the high flow on-line water washing processes.

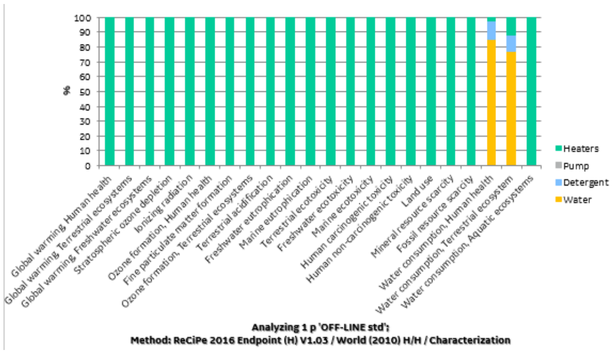


FIGURE 4: Midpoint Impact Category, OWW. *© 2020 Baker Hughes Company - All rights reserved.*

In Fig. 4 the result for the off-line water washing is shown. In most of the categories, the major impact on the environment is caused by the energy required to heat water tanks and to maintain water temperature. In addition, the impact of water heating is amplified as the source of energy is supplied by gas turbines and thus produced through fossil fuels. However, in two categories most of the effects are related to water and detergent consumption due to their impact on the human and ecosystems health.

Similar qualitative results are obtained when considering the HFOLWW process (Fig. 5). As in the previous analysis, also in this case heating has the highest impact on most of the categories. The main difference between the two washing approaches lies in the larger use of utilities (mainly washing water) observed for the HFOLWW. This result is expected since the HFOLWW is performed daily in the reference period (Paragraph 4). The relative impacts of the water consumption are increased by almost 10% with respect to the off-line case. It is worth to notice that with HFOLWW no detergent is needed.

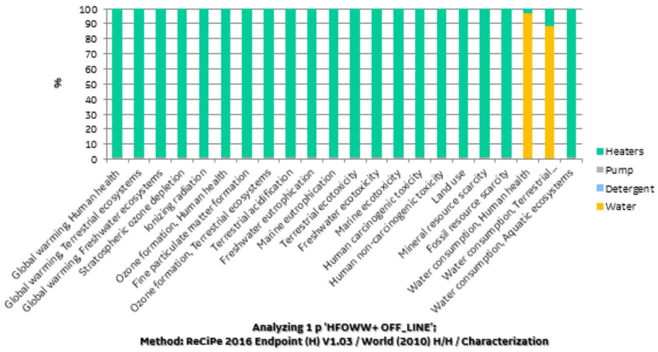


FIGURE 5: Midpoint Impact Category, HFOLWW Data. *© 2020 Baker Hughes Company - All rights reserved.*

After the characterization phase, the damage assessment is performed. In this analysis the midpoint categories are converted into endpoint factors. Data are normalized and weighed, transformed into SimaPro units and added to the Single Score.

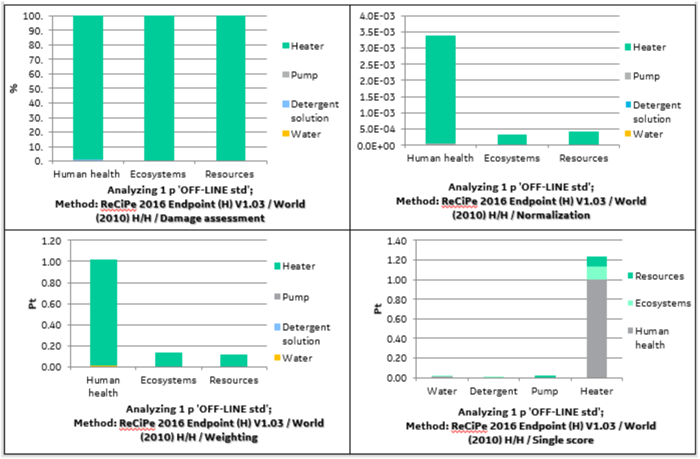


FIGURE 6: From Midpoint To Endpoint. Off-Line Water Washing Data *© 2020 Baker Hughes Company - All rights reserved.*

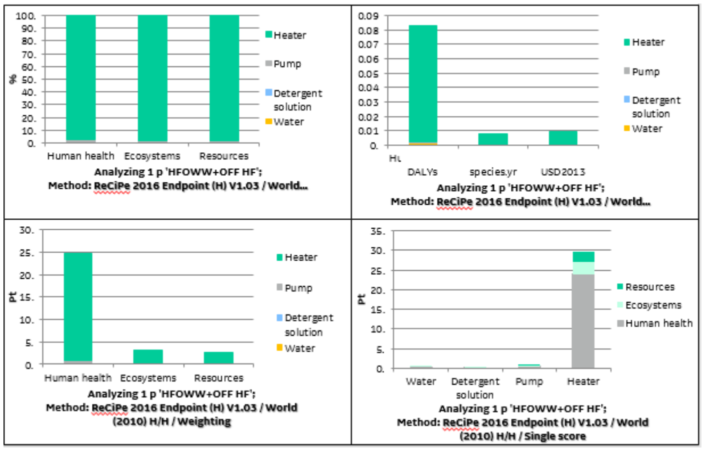


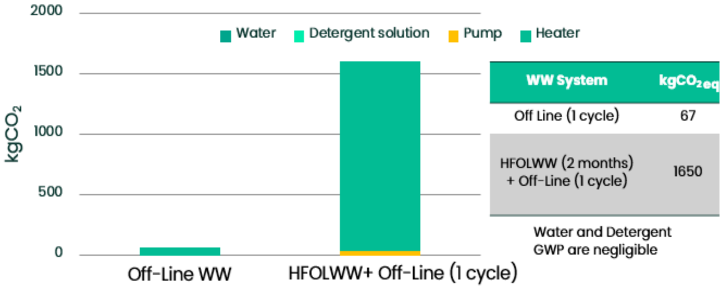
FIGURE 7: From Midpoint To Endpoint. HFOLWW Data. *© 2020 Baker Hughes Company - All rights reserved.*

FIGURE 8: **Single Score OFF-LINE VS HFOLWW.** *© 2020 Baker Hughes Company - All rights reserved.*

To assess the system operation in the reference period, the Single Scores of OWW and HFOLWW are compared. The environmental impact is roughly 10 times higher when using the HFOLWW with respect to the OWW due to the larger amount of energy used for the water heating. The impacts are mostly affecting the human health (24pts) with more contained effects on the resources (3pts) and ecosystems (3pts).

4.2 Water Washing Systems Operation: Carbon footprint IPCC

The carbon footprint related to the water washing systems operation is shown below:



WW System	$kgCO_{2eq}$
Off Line (1 cycle)	67
HFOLWW (2 months) + Off-Line (1 cycle)	1650

Water and Detergent GWP are negligible

FIGURE 9: **CO_2 Emissions Off-Line WW VS HFOLWW** *© 2020 Baker Hughes Company - All rights reserved.*

As expected, in the reference period, the CO_2 emissions of the daily HFOLWW operation are larger with respect to a single cycle of OWW. In particular, the two systems emitted 1650kg of equivalent CO_2 and ˜67kg of equivalent CO_2, respectively. In agreement with the results of the ReCiPe, also the IPCC shows that the heaters have the largest impact.

4.3 Gas Turbine Operation: Carbon footprint IPCC

The two water washing systems may have a different impact on the gas turbine operation. From the literature the fuel mass flow consumption for a gas turbine is given by:

$$\dot{m} = \frac{P}{LHV*\eta} \tag{1}$$

where:

$\dot{m}$ = fuel mass flow
P = shaft power
LHV = Lower Heating Value
η = global efficiency

From eq. (1), if the output power and fuel (LHV) are fixed, an increment of global efficiency yields to a reduction of fuel mass flow and a consequent reduction of the CO_2 emissions. For a given operating condition, the global efficiency of the gas turbine is strongly dependent on the axial compressor efficiency. Since the water washing acts by restoring the efficiency of a fouled axial compressor, its effects can be clearly measured through the reduction of fuel consumption (for a fixed output power).

To validate and compare the effectiveness of the two washing systems, the operation of a medium size gas turbine has been recorded for a period of 6months. In the first 3months the OWW has been tested then, in the following three months, the HFOLWW has been tested. Data have been filtered to have comparable operating condition before and after the introduction of the HFOLWW system. For the same machine, in the same application and same operating conditions (full speed full load), filters have been applied on shaft power, GT inlet temperature and on power turbine speed. About 450 samples have been considered to cover an operation period of 58days. The actual composition of the fuel gas burned in the GT has been considered in a combustion reaction model in order to determine the quantity of CO2 emitted by the machine. Any misleading data has been removed to ensure that the CO_2 emissions reduction are attribute to the different washing systems, only. In Fig. 10 the impact of the GT operation on CO_2 emissions is shown.

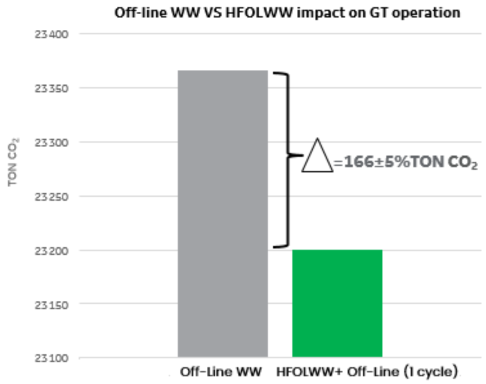


FIGURE 10: **Normalized CO_2 Gas Turbine Emissions**. *© 2020 Baker Hughes Company - All rights reserved.*

The reduction in fuel consumption yield to a reduction of about 166TON on CO_2 emissions in 58 when using the HFOLWW system. Based on the measured data, it is possible to identify also the economic benefit associated to the use of the HFOLWW. Considering countries where a carbon tax is applied, the reduction of greenhouse gas emissions yields to an economic return. In this case, the 166 TON of pure CO_2 saved in 58 days correspond to about 190 TON of equivalent CO_2 saved in the same period; extending to 1 year of GT operation this leads to 1050 TON of pure CO_2 and 1200 TON of equivalent CO_2 saved.

Considering an average carbon tax of 40€ for each TON of CO_2 emitted, the tax reduction associated to the emission reduction is evident. Moreover, the fuel saved becomes available for sale on market, bringing a double benefit.

5 CONCLUSIONS

An innovative HFOLWW methodology was proposed and compared with standard configuration trough LCA.

When the behavior of the whole gas turbine is analyzed by summing up all the contributions for the two processes, it is observed that the new washing system gives clear benefits in terms of CO_2 emissions, although in the analysis of the system operation the impact of the HFOLWW is higher (see e.g. Fig.10).

Giving a closer look to the results, we can observe that:

- As can also be seen from the results of the analysis of the washing system, LCA shows that the highest impact is always attributed to the heaters, because these are powered by electricity produced on the offshore platform by GT. Then, as the HFOLWW uses much more water, the environmental performance is much worse than OWW. As a matter of fact, Recipe and IPCC gave comparable results, in both HFOLWW has a greater impact. Furthermore, in the Recipe it is observed that this impact weighs more on human health.
- In the second part (the whole GT operation analyses) the data analysis shows that the introduction of the HFOLWW, led to a reduction in fuel consumption and consequently a reduction of CO_2 emission in atmosphere. The latest results show that HFOLWW permits to decrease airborne emission. The impact of CO_2 emissions reduction (in HFOLWW) is so high that system analysis is overshadowed. Therefore, the information obtained with IPCC can also be extended to the Recipe.

The comprehensive life cycle assessment of HFOLWW put in evidence the environmental and economic benefits of the procedure, allowing to quantify the impact in terms of costs and potential new incomes. This proves that LCA can be a proper tool for guiding the development of innovative design procedures and to support decision process in the management of the existing technologies.

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