UNIVERSIDAD SAN FRANCISCO DE QUITO

Colegio de Ciencias e Ingeniería

Assessment of efficient energy use of power generation systems in the oil industry.

A case study: The GE LM2500 turbine, Repsol Ecuador

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Tesis de grado presentada como requisito para la obtención del título de Ingeniero Mecánico

Quito, diciembre de 2014

Universidad San Francisco de Quito
Colegio de Ciencias e Ingeniería

HOJA DE APROBACIÓN DE TESIS

Assessment of efficient energy use of power generation systems in the oil industry.
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Quito, diciembre de 2014

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AGRADECIMIENTOS

La gratitud eleva nuestra mirada, nos quita los ojos de las cosas que nos faltan para que podamos ver las bendiciones que poseemos.

Max Lucado

A mi amoroso buen Padre DIOS por alentar mi espíritu diariamente con su Palabra y por haber forjado mi carácter para soportar las vicisitudes del camino.

A Carlos y Clarita por ser un ejemplo de perseverancia. Les agradezco por su amor, preocupación y apoyo brindado tanto en la prosperidad como en la dificultad.

A Darío por su apoyo, su amor y toda su entrega desinteresada durante estos tres años que hemos compartido juntos.

A Danilo un amigo verdadero que siempre confió en mi y me supo brindar su apoyo en toda adversidad que he enfrentado en mi vida.

A Jeison y Andrés colegas cuyo amplio conocimiento de ingeniería me sirvió como referente para mejorar mis capacidades y sentirme segura de expresarlas.

A Jesús quien me brindo la apertura para desarrollar mi proyecto de tesis y darme las directrices para tener éxito en el proceso.

A Edgar y Luis quienes me supieron guiar y responder mis preguntas en todo momento.

DEDICATORIA

Porque de él, y por él, y para él, son todas las cosas. A él sea la gloria por los siglos. Amén

Romanos 11:36

A DIOS quien me ha impulsado a alcanzar mis logros, y ha sacado lo mejor de mi permitiéndome observar en el difuso panorama una luz que me ha conducido al éxito y la autorrealización, a mi madre que me ha brindado su amor y atención en todo momento de mi vida, a mi tío Carlos que ha sabido ver en mi un gran potencial de superación y fortaleza, a Darío que ha sido siempre mi apoyo y compañía, a mis amigos, colegas y profesores que han sido mi ayuda y me han abierto las puertas de su confianza para desarrollarme como persona y como profesional.

Resumen

En el siguiente trabajo se presenta un estudio de la turbina de generación eléctrica serie GE LM2500 de 20MW de capacidad nominal, la misma que se encuentra ubicada en el campo de producción petrolera NPF operado por Repsol. Se busca relacionar las variables termodinámicas del ciclo de la turbina con la eficiencia de la misma.

La industria petrolera requiere una gran cantidad de energía para extraer, procesar y transportar los recursos petroleros. Las redes eléctricas cercanas a los campos petroleros son débiles o inexistentes, por lo tanto, es imperativo para las empresas de extracción de petróleo generar su propia energía. Además, los campos de petróleo están generalmente ubicados en lugares apartados y ambientalmente sensibles, por lo que temas como la contaminación por la quema de combustibles, las emisiones de gases de efecto invernadero y los costos de transporte de combustible, deben ser considerados. Como respuesta a esta problemática, existe gran énfasis en el desarrollo de políticas que promuevan sistemas de gestión de la eficiencia energética, concluyendo que implementar uno de estos sistemas en una industria asegura el mejoramiento de los recursos energéticos disponibles, trayendo beneficios económicos y medio ambientales.

Este trabajo detalla el análisis estadístico de los datos de la turbina GE LM2500 obtenidos durante 39 meses en el campo petrolero NPF. Sin embargo, no se contó con las variables necesarias para realizar un análisis total del ciclo de la turbina. Por lo tanto, la metodología se adaptó a la disponibilidad de los datos definiendo una técnica de relaciones empíricas entre variables utilizando gráficos estadísticos. El objetivo fue identificar patrones y determinar la influencia de las variables en el desempeño de la turbina para posteriormente buscar estrategias que mejoren su eficiencia tomando en cuenta las prácticas de operación en el campo petrolero. Luego del análisis correspondiente se puede concluir que en general, los valores de eficiencia son aceptables, los mismos se encuentran cercanos a los valores nominales. La relación entre la eficiencia y la potencia muestra una fuerte dependencia, esto quiere decir que si las condiciones de operación son a alta carga, la eficiencia se incrementará. Se determinó además que se pueden obtener valores altos de eficiencia utilizando poco flujo de combustible y esto probablemente se asocia con una buena calidad de la combustión. Así también, al realizar el análisis de eficiencia de la Segunda ley se pudo observar que en el segundo semestre del 2012 existe un cambio favorable en el desempeño de la turbina, este pudo ser ocasionado por un buen mantenimiento, un cambio en la calidad del combustible o un cambio en la operación de la misma.

Abstract

This work presents the assessment of the power generation turbine series GE LM2500, rated at 20MW, particularly looking at the relation between its efficiency and thermodynamic variables. The study case is a turbine commissioned at the North Production Facility (NPF) in *Bloque 16*, Orellana province of Ecuador, and operated by Repsol.

The oil industry requires significant amounts of energy to extract, process and transport oil resources. Electrical grids nearby oilfields are weak or inexistent, therefore it is imperative for oil extraction companies to generate their own power. In addition, oilfields are usually located in remote or environmentally sensible places, so issues such as fuel burning contamination, greenhouse gas emissions, and fuel transportation, costs inevitably come out. As a response, large emphasis exists on developing policies that promote energy efficiency management system (EnMS). Implementing an EnMS policy ensures a better usage of global energy resources, improvement in efficiency, and economical and ecological benefits.

This work details the statistical analysis of data, for the GE LM2500 turbine, collected in the oilfield (North Production Facility) for 39 months. Since not all the values required for a complete thermodynamic analysis were available, a different methodology based on statistical plots was used to empirically relate the variables with the available data. The main objective was to identify patterns and determine the influence of the different thermodynamic variables in the turbine performance. Later on, strategies that enhance the turbine efficiency based on working conditions were proposed. The main conclusion of this analysis was that the machine efficiency is higher when it is working close to the its nominal rating. The analysis showed that the efficiency and power output have a strong linear dependence. This means that if the operating conditions are with high load, the efficiency will increase accordingly. It was further determined that high values of efficiency can be obtained using low fuel mass flow, and this is probably associated with an optimal combustion condition. Last but not least, it was observed in the Second-law analysis that there was a favourable enhancement of the turbine performance during the second half of 2012. The reasons for this different behaviour of the turbine performance may be maintenance, different fuel quality or a component replacement in the turbine.

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Nomenclature

T_1 : Inlet Compressor Temperature
T_2 : Outlet Compressor Temperature
T_3 : Inlet Turbine Temperature
T_4 : Outlet Turbine Temperature
P_1 : Inlet Compressor Pressure
P_2 : Outlet Compressor Pressure
P_3 : Inlet Turbine Pressure
P_4 : Outlet Turbine Pressure
P_{r-} : Relative pressure
r_p : Pressure ratio
$\dot{m}_a$: Air mass flow
$\dot{m}_f$: Fuel mass flow
$\dot{v_f}$: Fuel volume flow rate
ρ_f : Fuel density
q_{in} : Heat input
q_{out} : Heat output
w_{in} : Work input
w_{out}: Work output
h_-: Enthalpy
$\dot{W}_e$: Power output
$\dot{Q}_{in}$: Heat Input
η_{th} : Thermal efficiency
η_I : First-law efficiency
η_{II} : Second-law efficiency
$\eta_{th,rev}$: Carnot efficiency

1 Introduction

The serious need to save energy and reduce greenhouse gas emissions worldwide brings energy management systems (EnMS) to the spotlight. A large emphasis exists on developing policies that promote energy efficiency. Implementing an (EnMS) methodology is the most economic, proven and readily available way to ensure a better use of global energy resources.(International Energy Agency, 2014)

In this respect, it is known that the oil and gas industry is the cornerstone of the global energy market supplying most of the energy used by the society. Nevertheless, it also requires significant amounts of energy to extract and process the resources until they get to the end users (Accenture, 2012). That energy is generated mainly by gas or diesel turbines due to the shortage of strong electrical grids nearby production fields. In this particular context, a methodology or protocol to perform efficiently the operation of a gas turbine would be a key player to achieve energy efficiency targeted in policies and normative.

Another reason to take into discussion is the fact that energy demand is increasing steadily due to population growth and the improvement of living standards around the world. Obviously more fossil fuels need to be burned to match the demand, but the downside is the significant increment of concentration of carbon dioxide and greenhouse gasses provoking global warming and changes in the weather patterns with all associated problems. Consequently, different solutions have been proposed to reduce the usage of fossil fuels and tackle the aforementioned environmental issues. Among those proposed solutions, renewable energy sources such as solar, wind, hydroelectricity, wave or biomass are active research fields that have been successfully implemented. However, even in the best-case scenario, fossil fuels will still be required. This later condition raises the claim for more efficient energy conversion procedures, particularly looking at fossil fuels because they must be complementary to renewables resources.

As stated before, energy efficiency will be a key player to reduce fuels consumption and greenhouse gas emissions related to burning them. Energy efficiency for fossil fuels is obviously a widely open research field that includes different stages such as extraction, transportation, distribution, storage, management, power conversion, among others. Clearly most of those topics are beyond the scope of this project. This project will be concentrated on the efficiency of the power generation by a gas turbine required to operate the equipment in an oilfield. The analysis will be carried out from a thermodynamical point of view. The electrical side of the conversion system will not be considered. Due to the available data and facilities provided by Repsol, the study case will be a GE LM2500 turbine located in Ecuador's *Bloque 16* operated by the same company, Repsol. However, it is expected to come out with methodologies and procedures that could be applied in other similar turbines, not only restricted to this particular device in its particular operating location.

1.1 Power generation systems in the oil industry

Oil industry requires large quantity of electrical energy to operate heavy equipment that performs processes such as extraction, pumping, drilling among others. The required electrical energy must flow continuously since the oil extraction is ideally scheduled in a 24 hours, 365 days operating period. The production cannot be interrupted because that would represent significant economical losses for the company. Thus, oil industry is not only a massive energy producer, but also an important consumer. In addition, oil production fields are located in harsh places (offshore, rainforest, desserts) where weak or even non existing electrical grids are common factors. For the reasons mentioned before, it is imperative for oil extraction fields to generate their own power to ensure the continuous energy flow and even more important, the right match between demand and generation.

Energy efficiency is a main player in the oil industry due to the large amount of energy involved in all its operating processes. However, roughly speaking, the performance of those processes is not optimal and there are important energy looses in the associated power conversion scheme. From the electrical side, modern generators can easily achieve efficiencies above 80% and it is a well known fact that the low efficiency is tightly related to the combustion engines. Nevertheless, the energy conversion train must be seen as an integrated system and optimised in that sense. One straightforwardly way to improve the performance of the entire system could be by setting optimal working conditions (input and output relations) according the operational requirements. An approach using real data is usually possible and the entire analysis can be carried out based on field working conditions rather than simulations or approximations. At the end, optimal working conditions and boosted performance is expected to lead to energy efficiency of the process and reduced fuel consumption. The later condition will bring multiple benefits, such as enhancing the sustainability of the energy system, increasing life span of the machine, reducing the required power rating and associated costs, supporting strategic objectives for economic and social development, reaching the goals and targets imposed by government and regulation policies, promoting environmental goals (commonly regulated by policies) and increasing prosperity.

1.2 Repsol facilities and location

Repsol is a Spanish energy company that performs activities in Upstream (Exploration and Production of hydrocarbons) and Downstream (Refining), with operations in 50 countries around the world. It is also dedicated to the merchandising of oil and petroleum products. Repsol is committed to technological innovation to build a more efficient, secure, competitive and sustainable energy business model (Repsol, 2014).

Particularly, Repsol has been in Ecuador since 2000 for developing Upstream activities of crude oil and LPG (liquid petroleum gas). Its operations have been developed in *Bloque 16* and *Tivacuno* in the province of Orellana. Fig 1 shows a sketch of the location. The crude oil extracted from *Bloque 16* is transported through 120 kilometers of pipeline until it reaches the *Sushufindi* station(Repsol, 2014).This oilfield occupies almost 139000 hectares of the Waorani Ethnic Reserve (where the Waorani etnicity dwells) and the Yasuni National Park. For that reason, it is important for Repsol to have social responsibility with the neighbouring communities and a strong commitment with the environment.

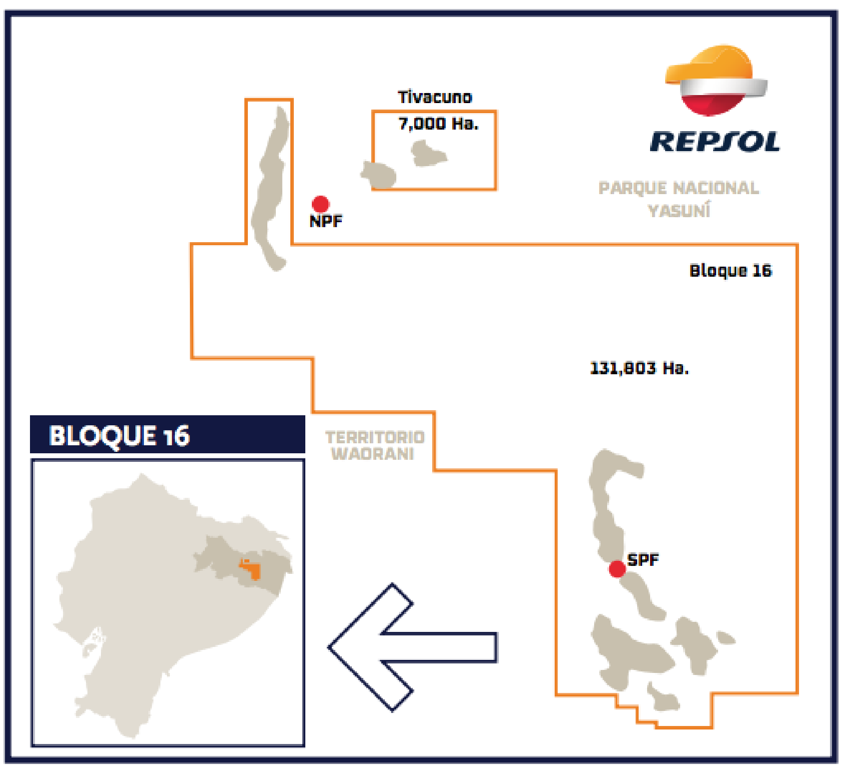

Figure 1: *Bloque 16* location (Repsol, 2014).

As mentioned in Section 1.1, oil industries usually are independent power producer utilities. Repsol is not an exception, since the oilfield operation needs approximately 100 MW to carry out all processes. (Delgado, 2014). This amount of power cannot be supplied by the Ecuadorian electrical grid (*Sistema Nacional Interconectado*). Thus, as it is shown in Fig 1, *Bloque 16* has two energy generation facilities. The North Production Facility (NPF) produces 37.15 MW and the South Production Facility (SPF) produces 59.15 MW (Fig 2). Table 1 gives a description of the power generation units in each facility with their respective power capacity in MW.

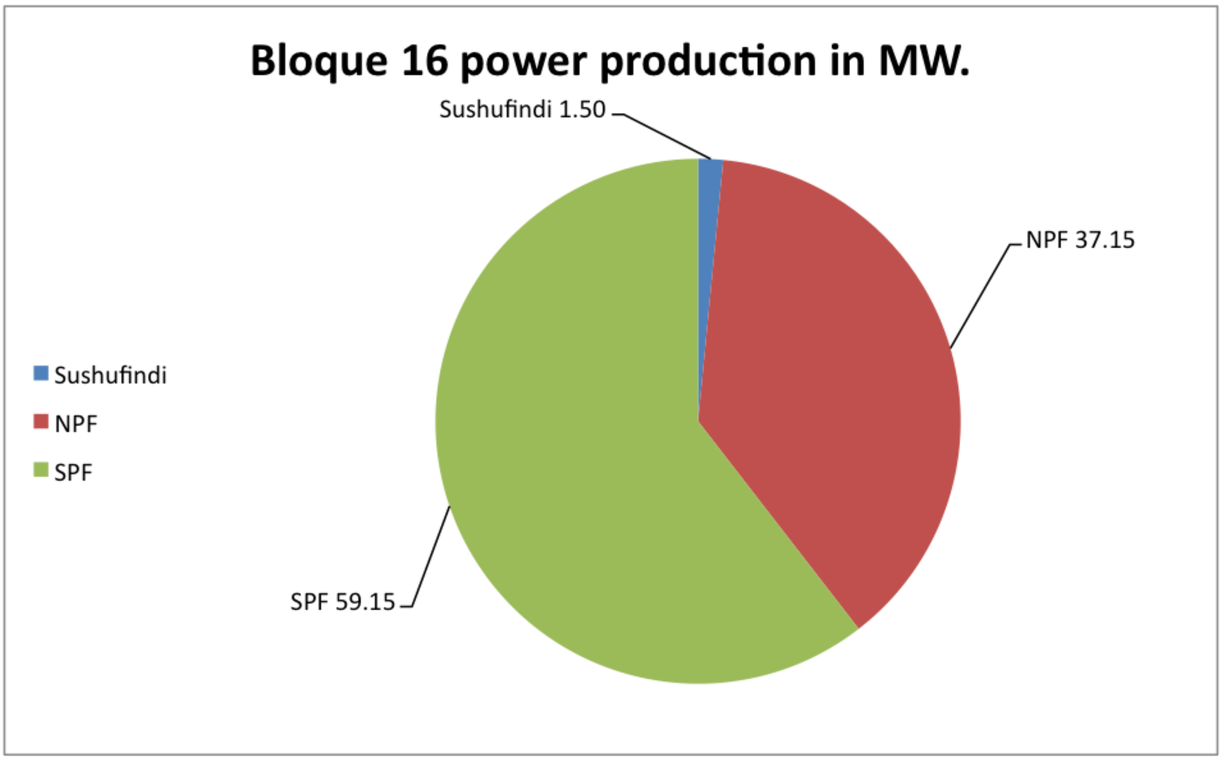

Figure 2: *Bloque 16* power production

Table 1: *Bloque 16* Power Production and Installed Capacity of the Machines.

Facility	Units	Machine	Type of fuel used	Nominal capacity per unit in MW	Installed capacity per unit in MW	Total installed capacity in MW	Total Production in MW
Sushufindi	2	Solar Centaur Turbine	Diesel	4.57	3.00	6.00	1.50
Sushufindi	1	Engine Caterpillar	Diesel	-	1.60	1.60	-
NPF	2	GE LM 2500 Gas Turbine	Diesel	20.00	17.00	34.00	31.20
NPF	7	Waukesha Engine	Gas	1.10	1.00	7.00	5.95
SPF	1	GE LM 2500 Dual Turbine	Gas-Diesel	24.00	20.00	20.00	17.00
SPF	14	Waukesha Engine	Gas	1.10	1.00	14.00	2.25
SPF	7	Wartsila Engine	Crude oil	6.125	6.00	42.00	39.90
SPF	1	Mustang Caterpillar Engine	Diesel	-	1.80	1.80	-
TOTAL							97.80

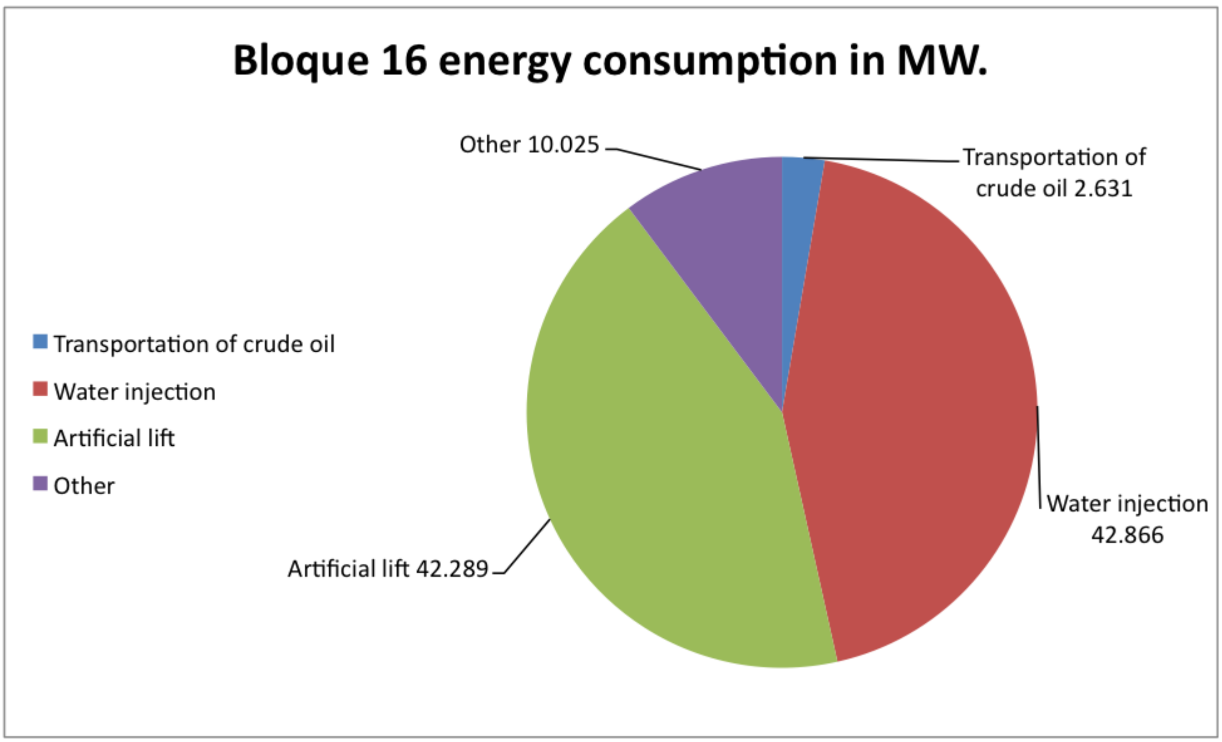

Figure 3: *Bloque 16* energy consumption

Complementary, Fig 3 shows the power consumption per machine (in MW) in the field operated by Repsol. It is clear that the largest amount of energy is consumed by the electrical machines associated with artificial lift and water injection (both pumping processes).

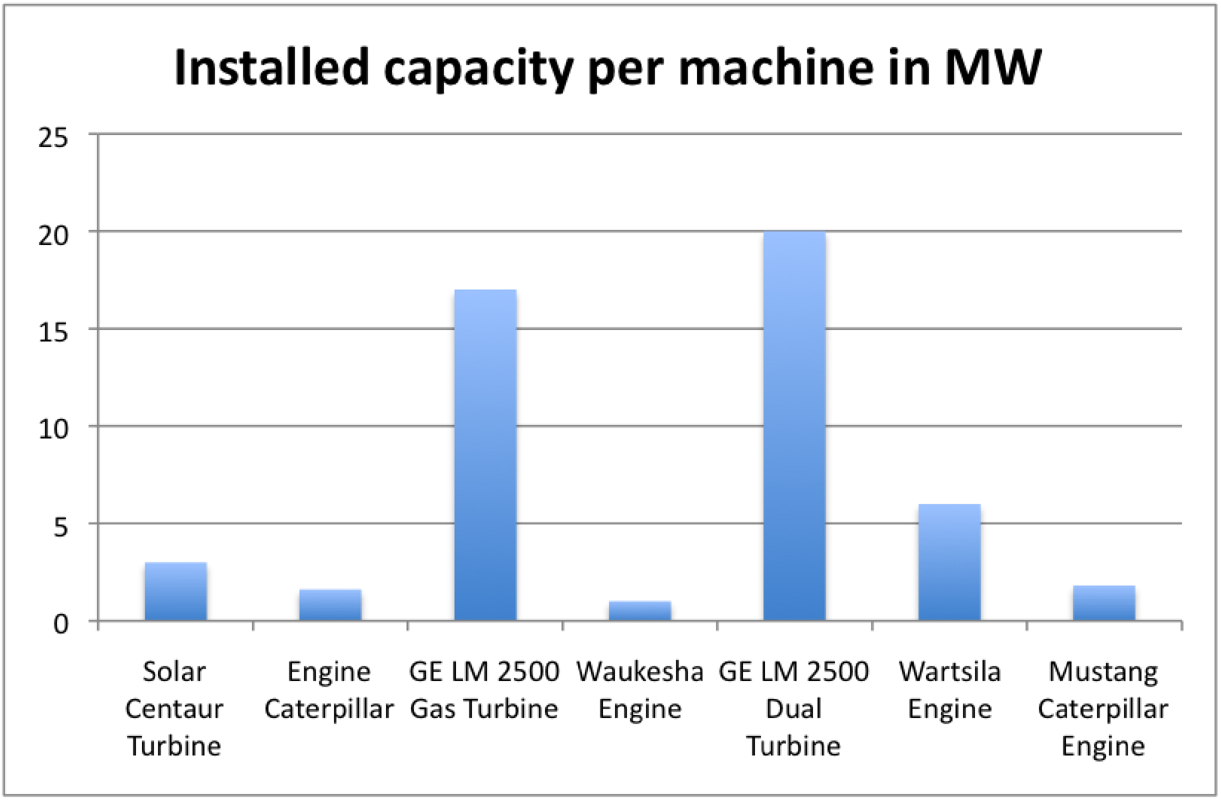

Figure 4: Installed capacity per machine

As seen in Fig 4, GE turbines are the machines with the highest power production per unit. The chosen turbine for this study was the GE LM 2500 from NPF, it was commissioned in 1993. Therefore it has a bigger quantity of data available for this statistical study. The idea is to develop a methodology that can be applied and proved in this turbine and afterwards apply it on different machines.

1.3 The ISO 50001 standard.

Energy costs have increased steadily over the years. This fact drives the attention of the energy organizations regarding their power performance and have motivated reconsiderations of their energy policy. Some standards have been established to guide organizations to accomplish a better execution of their energy conversion processes. For instance, the ISO 50001 Energy Management System (EnMS) which aims to enable organizations to establish systems and necessary processes to improve energy performance, while reducing greenhouse gasses emissions (ISO, 2011). This standard does not specify energy performance criteria. It describes a general-purpose system to provide strategies to increase energy performance and to promote better practices within the organizations. Before developing an Energy Management System (EnMS), the organization needs to define the scope, boundaries and activities that the company itself needs to address as to its management system. Also, it is necessary for the organization to have data records and documentation about the energy production and consumption. Those guidelines are important to build an energy baseline that allows monitoring and identifying performance indicators and to support an effective improvement in organization energy performance. (The Hong Kong Electronic Industries Association, 2013)

Particularly in Ecuador, Repsol has implemented an EnMS to improve the performance of its practices by reducing the consumption of energy in the oil extraction process. Repsol defined an scope and created an EnMS procedure back in 2012, and since then the company has been working towards its objectives. In January 2014, after an audit done by Lloyd's Register Quality Assurance, Repsol was certified with the ISO 50001.(LADS magazine, 2014)

1.4 Relevance and aims of this study

As was mentioned before, oil and gas industry requires huge amounts of energy for its operation. Most of that energy is generated by gas turbines operating sometimes at low efficiency levels that imply environmental, social, and economical issues that need to be addressed immediately. One solution could be switching the current machinery to state of the art equipment, but it will required large investment, production breaks and training time that cannot be allowed in a full time operating industry such as oil extraction. A more feasible approach would be improving the efficiency of the current turbines chiefly by identifying the key stages and variables in the energy conversion process to set optimal working points. This research will be looking at highlighting the different parameters and variables that can effectively affect the efficiency of a diesel turbine.

This study is expected to establish the basic guidelines and a base line for a technical approach to achieve a more efficient operation of gas turbines for power generation. The proposed analysis will be focused on understanding the working cycle of the turbine, particularly addressing the identification of parameters and variables that are strongly related with the efficiency of the device. In this context, the first steps will be calculating the machine efficiency and underlining its relationship with power generation variables such as temperature and pressure at different stages of the generation chain. The main idea is to carry out a statistical analysis to assess how tightly related is the efficiency of the turbine with different variables involved in the power conversion process. Once the main relationships are identified, the efficiency can be empirically written as a function of the process variables and then it will be possible to propose improvements in the current operation conditions by setting optimal working points.

The outcomes of this empirical approach based on real operation data could be considered milestones in this field since the suggested ideas could be straightforwardly implemented in the current equipment with a minimum extra cost and without further physical modifications. Two key deliverables of this study will be a practical methodology and an operation guide proposal that include the efficiency of the turbine and its related parameters. Since it is expected to establish mathematical relationships between variables, those associations can be easily plotted or summarized in tables to be read and set by an automatic controller to drive the turbine in a more efficiency way. At the end, this study and its results will be supporting guidelines in order to accomplish the ISO50001 normative in the oil industry. Also, it is anticipated that the methodology used in this research to analyze the data available for this particular turbine could be applied in similar devices.

2 Theoretical framework

2.1 The Brayton cycle

Gas turbines usually operate in the Brayton cycle. A schematic representation of the cycle is displayed in Fig 5. The first state (1) starts with the inlet air in the compressor, increasing air's pressure and temperature. Then, in the combustion state (2), fuel is added through fuel nozzles and combustion occurs. The thermal energy of the combustor runs the high pressure turbine (HPT) which drives the compressor (3). The exhaust gasses from this turbine pass to the low pressure turbine that provides the work required to drive the shaft of the generator (4) and finally the exhaust gases go to the atmosphere (5). The combination of the compressor, combustor, and high pressure turbine are often called gas generator set and the entire arrangement is shown in Fig 6.

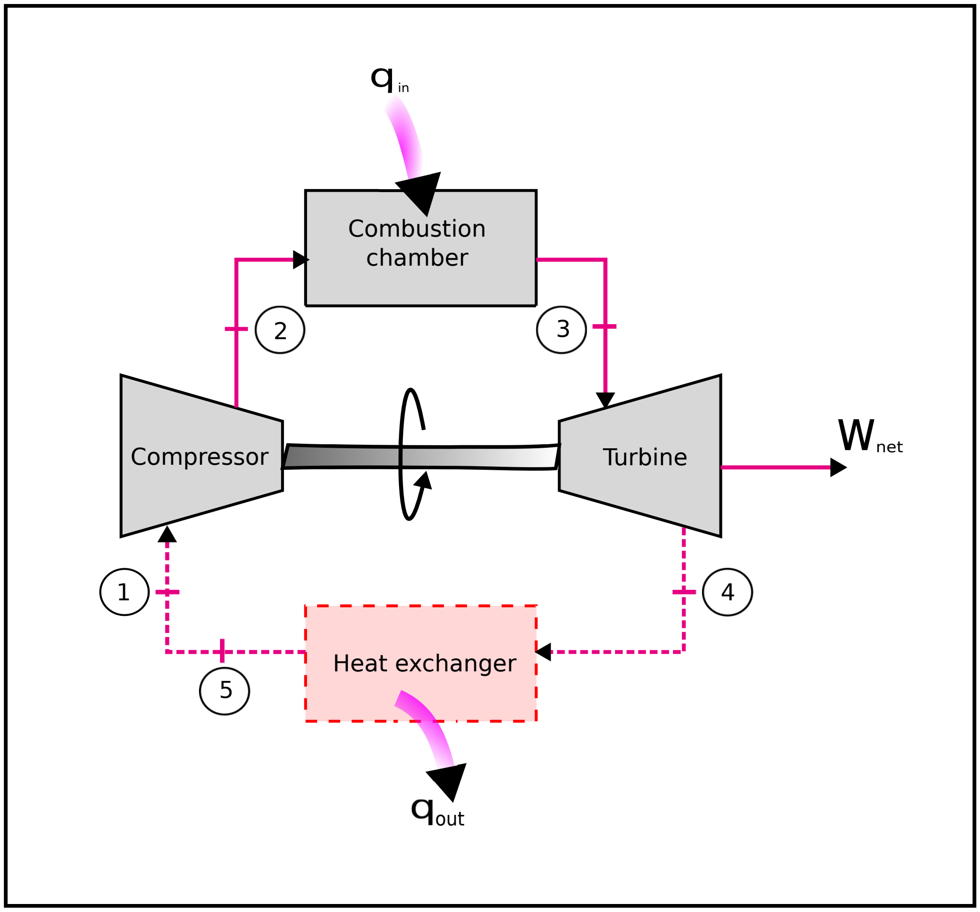

Figure 5: Schematic of the closed cycle gas turbine engine

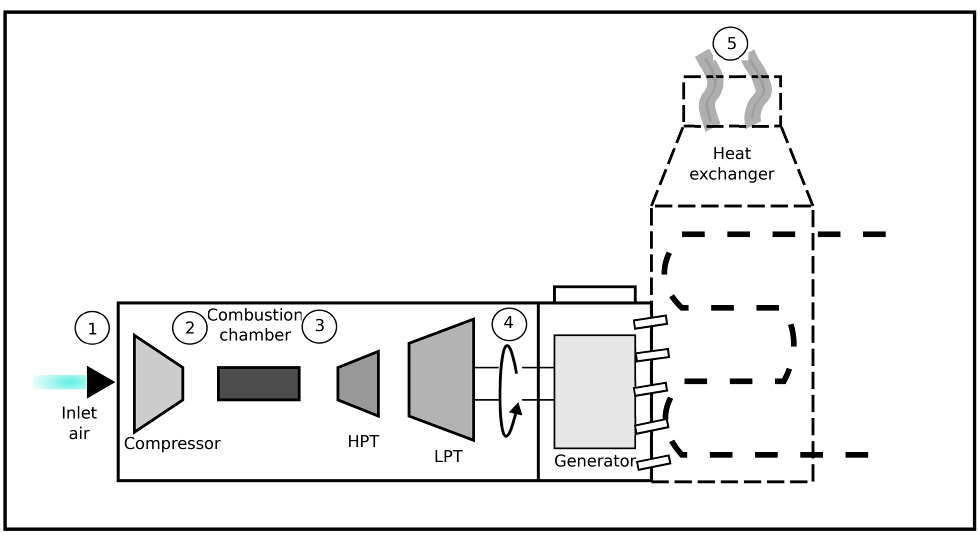

Figure 6: Layout of a generator set

To make an appropriate study of the cycle, it is needed to manage the complexities using some approximations. For the present study, the cycle is considered an air-standard cycle because air-standard assumptions are being applied. The working fluid composition changes from air and fuel to combustion products after the course of the cycle. Nevertheless, considering that no chemical reaction in the combustion chamber happened because air is predominantly nitrogen, the working fluid closely resembles air at all times (Cengel Y., Boles M., 2006). Using the air-standard assumptions, the combustion process is replaced by a heat addition process and the exhaust process is replaced by a heat rejection process. Consequently, the ideal Brayton cycle comprises of four internally reversible processes that are listed below and are identified in Fig 7:

1-2 Isentropic compression in the compressor

2-3 Heat addition at constant pressure

3-4 Isentropic expansion in the turbines

4-1 Heat rejection at constant pressure

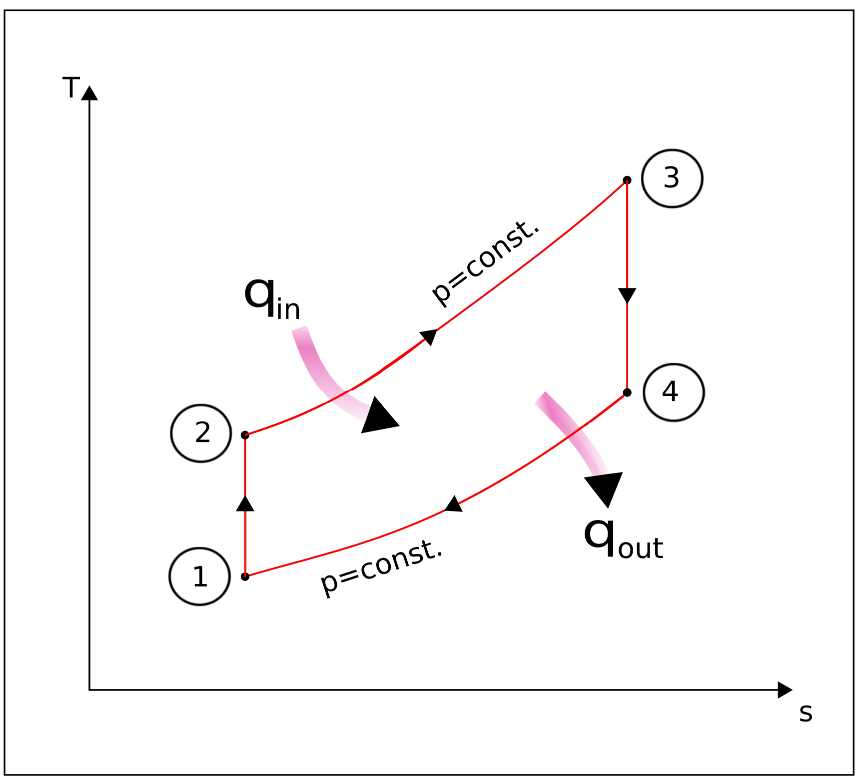

Figure 7: Temperature-Entropy (T-s) diagram of an ideal Brayton cycle

From Fig 7 processes **2-3** and **4-1** are isobaric. Thus, $P_2 = P_3$ and $P_1 = P_4$.
Then the pressure ratio can be expressed as:

$$r_p = \frac{P_2}{P_1} \tag{2.1}$$

Also, from Fig 7 processes **1-2** and **3-4** are isentropic. Thus, the following equations can be used:

Compression of an ideal gas:

$$\left(\frac{P_2}{P_1}\right)_{s=const} = \left(\frac{P_{r2}}{P_{r1}}\right) \tag{2.2}$$

Expansion of an ideal gas:

$$\left(\frac{P_4}{P_3}\right)_{s=const} = \left(\frac{P_{r4}}{P_{r3}}\right) \tag{2.3}$$

Cengel Y., Boles M. (2006) present Equation 2.4 noticing that "the four processes of the Brayton cycle are performed in steady- flow devices, they should be analyzed as steady-flow processes. When the changes in kinetic and potential energies are neglected, the energy balance for a steady-flow process can be expressed, on a unit–mass basis, as":

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet} \tag{2.4}$$

Therefore,

Heat addition to the combustion chamber:

$$q_{in} = h_3 - h_2 \quad \left[\frac{kJ}{kg}\right] \tag{2.5}$$

Heat rejection to the atmosphere:

$$q_{out} = h_4 - h_1 \quad \left[\frac{kJ}{kg}\right] \tag{2.6}$$

Work input to the compressor:

$$w_{comp,in} = h_2 - h_1 \quad \left[\frac{kJ}{kg}\right] \tag{2.7}$$

Work output of the turbine:

$$w_{turb,out} = h_3 - h_4 \quad \left[\frac{kJ}{kg}\right] \tag{2.8}$$

Thermal efficiency:

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} \tag{2.9}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} \tag{2.10}$$

2.2 Turbine GE LM2500.

The General Electric (GE) LM2500 is a gas turbine intended for industrial or marine applications, with a simple-cycle and a high-performance engine (Badeer,G., 2005). It can be used in the industry as a power generator when it is coupled with an electric generator, or as a marine propeller for shipping. The LM2500 turbine is comprised of: a 16-stages, 18:1 pressure ratio compressor; a fully annular combustor with externally mounted fuel nozzles; a two-stage, air-cooled high-pressure turbine which drives the compressor and the gearbox; and a six-stage, low-pressure power turbine (GE Aviation, 2014). In the report of GE 2014, the average performance of the turbine LM2500 is 24 050 kW with a thermal efficiency of 36%. In order to achieve its nominal efficiency, the turbine must work at the following standard conditions: 60 Hz, 3 600 rpm, 59°F, sea level atmospheric pressure, 60% relative humidity, 4 inches water inlet loss and 6 inches water exhaust loss. Fig 8. shows a cross-section scheme of the turbine.

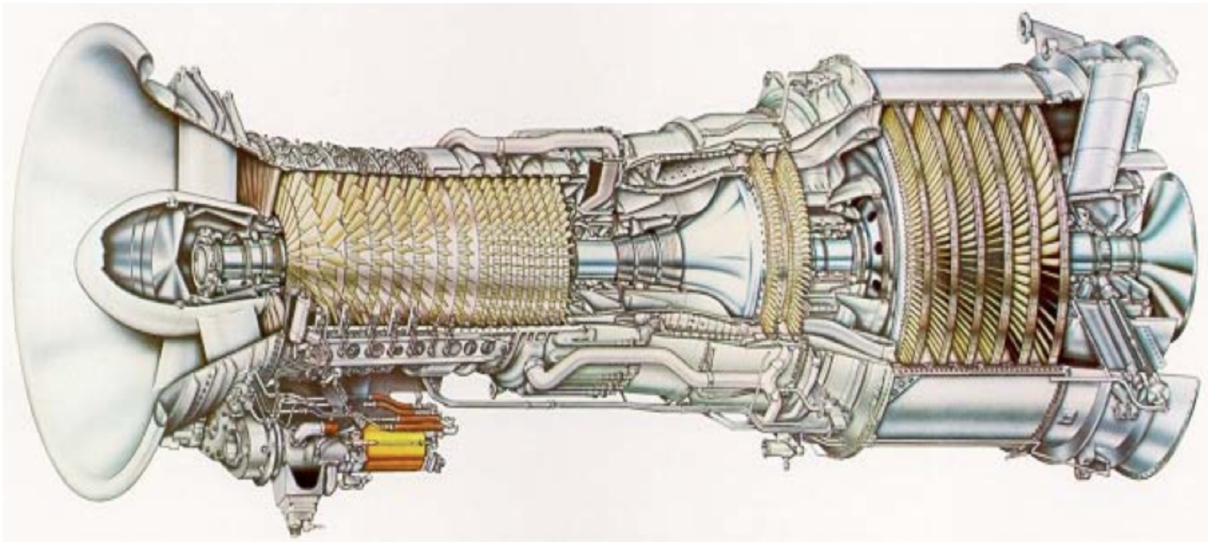

Figure 8: GE LM 2500 Turbine scheme (GE Energy, 2014)

General Electric, the manufacturer of this type of turbines, sells services mainly to the US Navy. The unique feature of this type of engines is that they can be removed from a ship to be repaired in a relatively short period of time. Another application field for the LM2500 marine gas turbine is the thermoelectric power generation when the turbine is coupled to an electrical generator to become a genset (turbine-generator set) as shown in Fig 9 (GE Aviation, 2014).

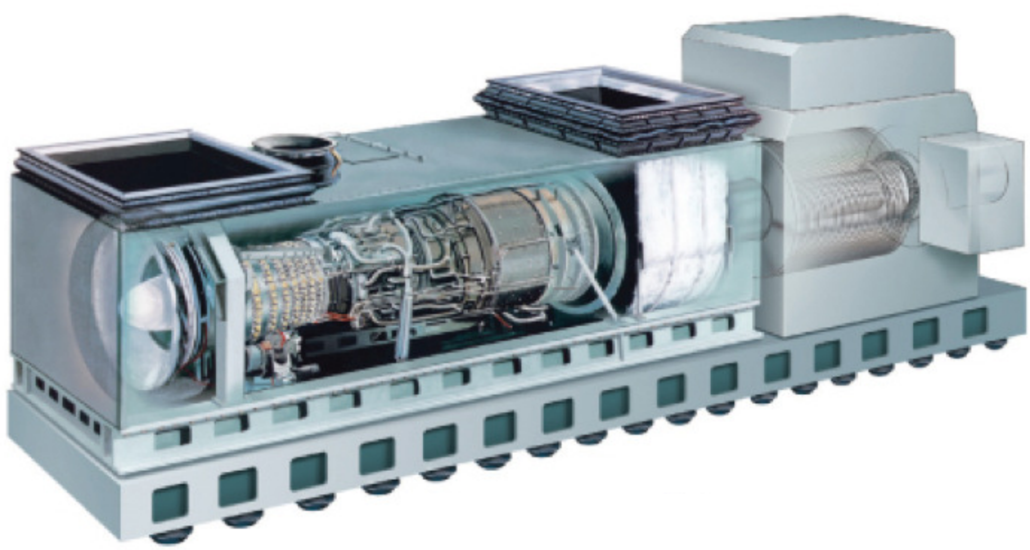

Figure 9: GE LM 2500 Generator Set (GE Aviation, 2014)

3 Methods

3.1 Data collection

The present analysis was based on the operating data of the GE LM 2500 Gas Turbine operated by Repsol. The data was acquired from a daily log sheet of 39 months since January of 2010 until March of 2013 and it was collected every day from 2am until 10pm every four hours. It gives a total number of 7140 points of data for each variable . The meaningful variables for this study are the listed below:

- T_1 : Inlet compressor temperature.
- P_2 : Outlet compressor pressure.
- T_3 : Inlet turbine pressure.
- $\dot{v}$: Fuel volume flow rate.
- $\dot{W}_e$: Power output.

3.2 Brayton cycle calculations

The turbine variables mentioned in the previous section are shown in red in Fig 10. The variables in blue were not provided, so the present analysis needs to consider the cycle as ideal. All the variables (red and blue) are necessary to carry out a complete theoretical analysis of the cycle, but due to the shortage of some of them, a methodology of empirical relations between variables is proposed in Section 3.4 to deal with this data limitation. Also, it has to be emphasized that in this analysis the heat exchanger of the genset was not considered.

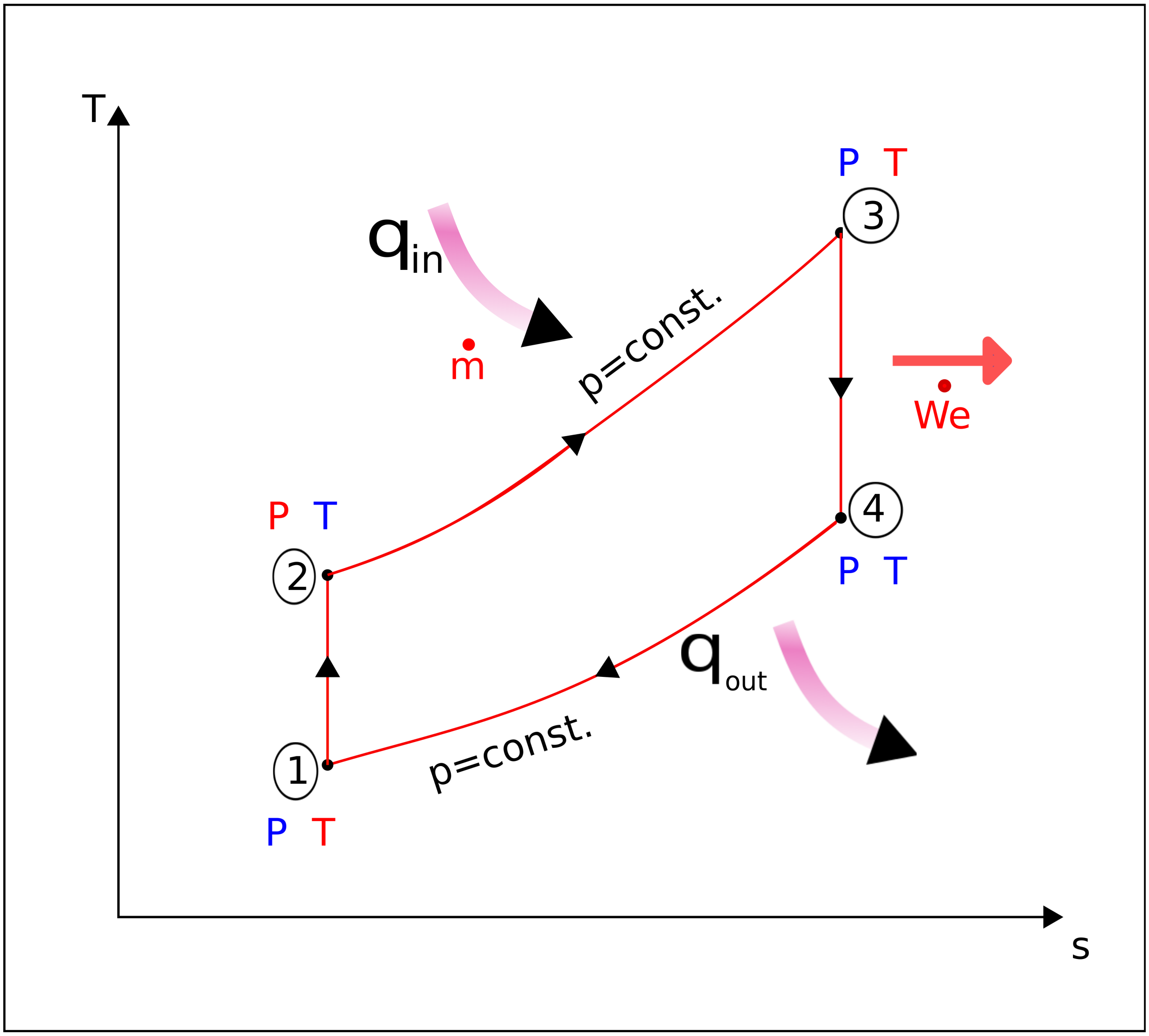

Figure 10: Temperature-Entropy (T-s) diagram with the variables needed for calculations of the Brayton cycle

Prior to start the calculations it is convenient to display together all the formulas and values that will be used throughout this study.

The pressure ratio is $r_p = 18$ (presented in the report of GE 2014).

Fuel density:

$$\rho_f = SG_f \times \rho_{water} \quad \left[\frac{kg}{m^3}\right] \tag{3.1}$$

Where $SG_f = 0.8403$ is the specific gravity of the fuel. Its value was obtained from the report presented in Appendix A, and $\rho_{water} = 1000\frac{kg}{m^3}$

Fuel mass flow:

$$\dot{m_f} = \rho \dot{v_f} \quad \left[\frac{kg}{s}\right] \tag{3.2}$$

Heat input:

$$\dot{Q_{in}} = \dot{m_f} LHV \quad [MW] \tag{3.3}$$

Where $LHV = 4.2533 \times 10^4 \left[\frac{kJ}{kg}\right]$ is the lower heating value of the fuel. It was obtained from the report presented in Appendix A.

First-law efficiency:

$$\eta = \frac{\dot{W_e}}{\dot{Q_{in}}} \tag{3.4}$$

Reversible efficiency (Carnot efficiency) :

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} \tag{3.5}$$

Second-Law Efficiency:

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \tag{3.6}$$

Table 2 presents a summary of the calculations for the first set of data available:

Table 2: Calculation summary

Variable	Units	Example value*	Obtained from
r_e	-	18	Eq 2.1
P_1	KPa	101.3	Atmospheric pressure
T_1	^0C	24.6	Data set
P_2	KPa	1282.4	Data set
h_1	$\frac{KJ}{kg}$	297.77	Thermodynamic property tables using T_1
Pr_1	-	1.3479	Thermodynamic property tables using h_1
Pr_2	-	24.262	Eq 2.2
T_2	^0C	395.5	Thermodynamic property tables using Pr_2
h_2	$\frac{KJ}{kg}$	679.55	Thermodynamic property tables using T_2
$w_{in,comp}$	$\frac{KJ}{kg}$	381.77	Eq 2.7
T_3	^0C	719.6	Data set
P_3	KPa	1282.4	Equal to P_2
h_3	$\frac{KJ}{kg}$	1037.6	Thermodynamic property tables using T_3
Pr_3	-	110.74	Thermodynamic property tables using h_3
q_{in}	$\frac{KJ}{kg}$	358.05	Eq 2.5
$\dot{m}_f$	$\frac{kg}{s}$	1.146	Data set
$\dot{Q}_{in}$	MW	48.74	Eq 3.3
W_e	MW	12.6	Data set
η_{th}	%	25.85	Eq 3.4
*The example value is the calculation corresponding to the first data set of the time series			

3.3 Quality control

The data quality control was done as follows:

- Eliminating data that contains zeros and alphabetical characters before doing any calculations.

- Eliminating outliers that visually are not coherent with the normal operating range of the turbine.

The operational range of each variable in the turbine is displayed in Table 3 to detail what was the criteria for eliminating data points from the data set.

Table 3: Operational range of some variables of the Brayton cycle in the LM2500

Variable	Symbol	Units	Minimum	Maximum
Inlet temperature of the compressor	T_1	$°C$	22	37
Outlet pressure of the compressor	P_2	KPa	1000	1570
Inlet temperature of the turbine	T_3	$°C$	677	827
Efficiency	η	%	25	40
Output power	$\dot{W}e$	MW	8	18
Diesel mass flow	$\dot{m}_f$	$\frac{kg}{s}$	0.7	1.3
Heat input per unit mass	q_{in}	$\frac{KJ}{kg}$	310	480
Heat input	$\dot{Q}_{in}$	MW	30	55

3.4 Bi-variate plots

Bi-variate plots were used to determinate the empirical relations between variables associated with the energy conversion process. Roughly explained, this technique follows the next steps:

- Find trends in the available data and get the time series where the data points intersect each other.
- Establish the influence of different process variables on the turbine efficiency based on bi-variate plots.
- Observe the probabilistic occurrence in the data.

3.5 Relationship between variables

The following relations were obtained from the formulas mentioned in Section 2.1 and the assumption of ideal gas:

$$h_1 = f(T_1)\ from\ the\ ideal\ gas\ properties \tag{3.7}$$

$Pr_1 = f(T_1)$ from the ideal gas properties.

$Pr_2 = f(T_1)$ obtained from equation 2.2.

$T_2 = f(Pr_2) = f(T_1)$ obtained from equation 2.2 and ideal gas properties.

$h_2 = f(T_2) = f(T_1)$ obtained from ideal gas properties.

Since $w_{comp,in} = h_2 - h_1$. Thus, $w_{comp,in} = f(T_1)$.

$h_3 = f(T_3)$ from the ideal gas properties.

$Pr_3 = f(T_3)$ obtained from equation 2.3.

Since $q_{in} = h_3 - h_2$. Thus, $q_{in} = f(T_3)$ and $f(T_1)$.

4 Results

After the data quality control, it was required to find an empirical distribution function, $n = n(x, y)$, between the two variables of interest (x and y) and the number of occurrences n. To get $n(x, y)$, each variable had to be discretized with an arbitrary resolution but restricted to obtain a smooth distribution surface. For example, to obtain this kind of surface the reader should refer to Fig 11 where x axis indicates W_e : Output Power and y axis is η_I : First-law Efficiency. This plot will introduce the graphic method since it displays the relation between two variables in a probabilistic context. The relation between two variables where it is possible to observe the three-dimensional distribution is called bi-variate plots throughout this work.

As seen below, the range of data for η_I is approximately 0.28 to 0.38 and for W_e is 8 to 18 MW. These ranges were used to fix the resolution of the graphic as it was mentioned before. Also, it can be seen that the data have a relatively low dispersion and present a strong linear relationship (the corresponding linear regression was calculated). Using this the linear relationship the system behaviour can be described.

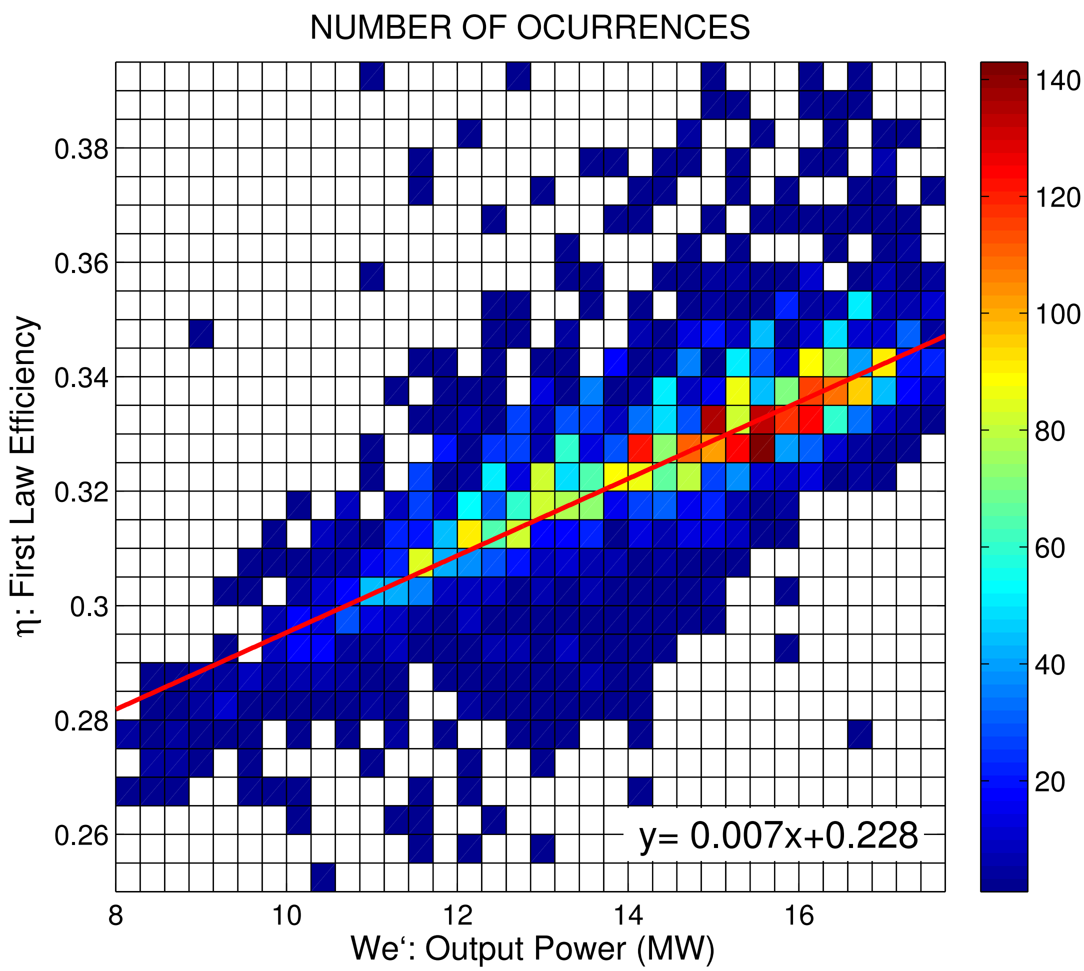

Figure 11: Relation between Output Power and First-law efficiency

Relation of $\dot{W}e$ with η_I and η_{II}

This section shows the analysis of efficiency and power production. The analysis of the First-law efficiency allows us to know the net work produced relative to the heat supplied. A bi-variate plot (Fig 11) was used to establish the relation between the η_I : First-law Efficiency and the $\dot{W}_e$: Output Power. It can be seen that the plotted data follow a positive linear relation with low dispersion. From the previous results it is clear that the $\dot{W}_e$ and η_I are tightly related and the behavior of the turbine can be predicted in terms of the load.

The First-law efficiency results were promising but literature in this topic states that "The first-law efficiency makes no reference to the best possible performance, and thus the first-law efficiency alone is not a realistic measure of performance. To overcome this deficiency, it is defined the second-law efficiency as a measure of actual performance relative to the best possible performance under the same conditions" (Cengel Y., Boles M., 2006). Thus, the best possible performance is defined by the Carnot cycle efficiency (Equation 3.5). Cengel and Boles described the Carnot cycle as the most efficient cycle operating between two specified temperature limits, even though it cannot be achieved in reality, the efficiency of an actual cycle can be improved by attempting to approximate the Carnot cycle more closely (Cengel Y., Boles M., 2006). Consequently, a Second-law efficiency analysis was carried out to confirm the previous results from the First-law efficiency study.

Fig 12 supports the results of the analysis displayed in Fig 11. A strong positive linear relation with low dispersion is evidenced in both plots, $\dot{W}_e$ with η_I and η_{II}, most of the data points fall on the regression line. It is seen that greater values of $\dot{W}_e$ generate higher values of both efficiency definitions.

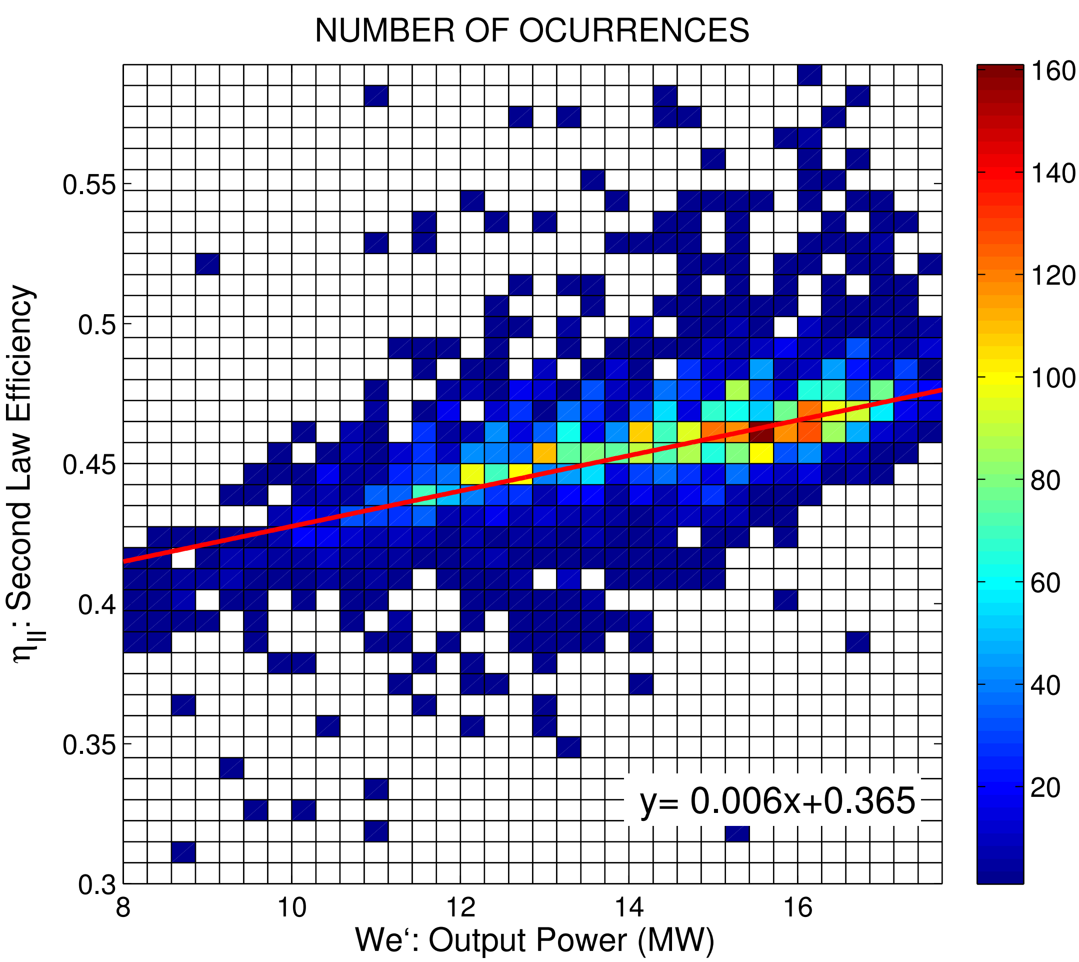

Figure 12: Relation between Output Power and Second-law efficiency

Power production costs at different efficiency levels

The following cost study allows us to understand in a better way the economical implications of reducing the working load at producing power. The linear regressions presented in Fig 11 and 15, make possible to quantify the efficiency of the turbine in economical terms.

The energy reference is set by the effective installed load of $17MW$, and is evaluated in the range from $17MW$ to $9MW$ for an operation period of one day. Table 4 summarizes an assessment of different scenarios for daily power production and their respective costs and efficiency. The production cost was calculated based on the linear regressions previously presented and a referential price for the diesel fuel is taken as \$0.85 per liter (Energy Information Administration, 2012). Further details of this evaluation can be found in Appendix C.

Table 4: Results of a case study about the power production

Production load (MW per day)	η_I (%)	Barrels per day $(\frac{bbl}{day})$	Day cost $(\frac{\$}{day})$	Production cost $(\frac{\$}{MW\ per\ day})$	Production cost $(\frac{\$}{kWh})$
17	34.7	765.13	103476.1	6086.83	0.25
15	33.3	691.17	93473.57	6231.57	0.26
13	32	617.20	83471.05	6420.85	0.27
11	30.5	543.25	73468.53	6678.95	0.28
9	29	469.28	63466.00	7051.78	0.29

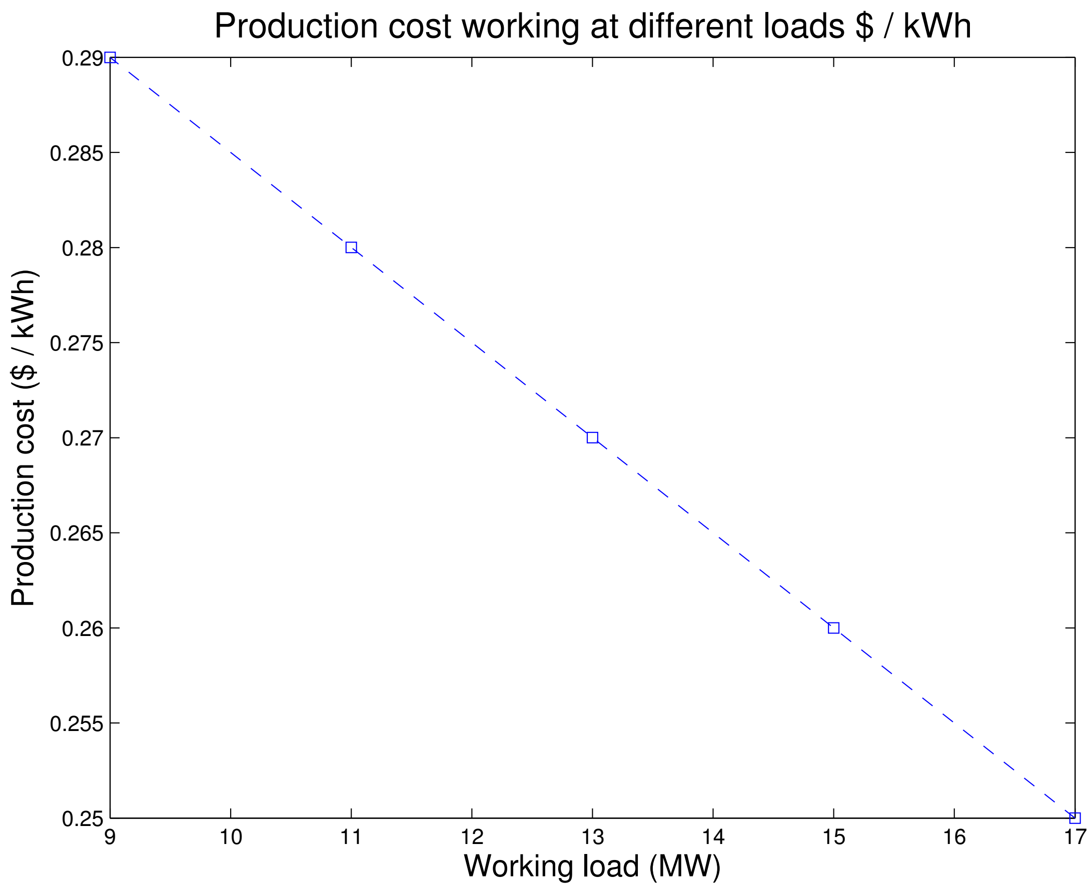

Figure 13: Production cost working at different loads

From Table 4, looking at the production cost of 6086.83 ($\frac{\$}{MW\ per\ day}$) corresponding to 17MW per day and the 7051.78 ($\frac{\$}{MW\ per\ day}$) corresponding to 9MW per day. It can be seen that it is possible to save up to \$1000 per MW per day in fuel costs by operating close to operational load (17 MW) instead of low load (9MW), chiefly due to the important increase in efficiency (6%). At this stage, just from the economical point of view it is recommendable to operate close to nominal load, however, additional factors such as power requirements, power flow control (generation and demand), and safety operation of equipment in the oilfield, must limit this possibility. Extra factors, particularly electrical considerations, are beyond the scope of this work, but it is recommended a further study to integrate them and identify all potential constrains in the turbine operation range. In conclusion, operating at low power implies lower efficiency and causes more economical expenses than working close to the nominal power.

One of the reasons for the decline in efficiency in the turbine when it works at low power is the necessity of a base load. A further study is worth to quantify this minimum power and evaluate its impact on the efficiency of the entire working range of the machine.

Minimum turbine base load

It is a well known fact that there are looses associated with irreversibilities of the thermodynamical cycle such as friction, heat transfer, among others. Therefore, even with an unloaded turbine some input power will be required to overcome those looses and allow the turbine to keep rotating. The following relation between Q_{in} : Heat Input and $\dot{W}_e$: Output Power (Fig 14) describes in a better way the implications that the base load has with the turbine behavior.

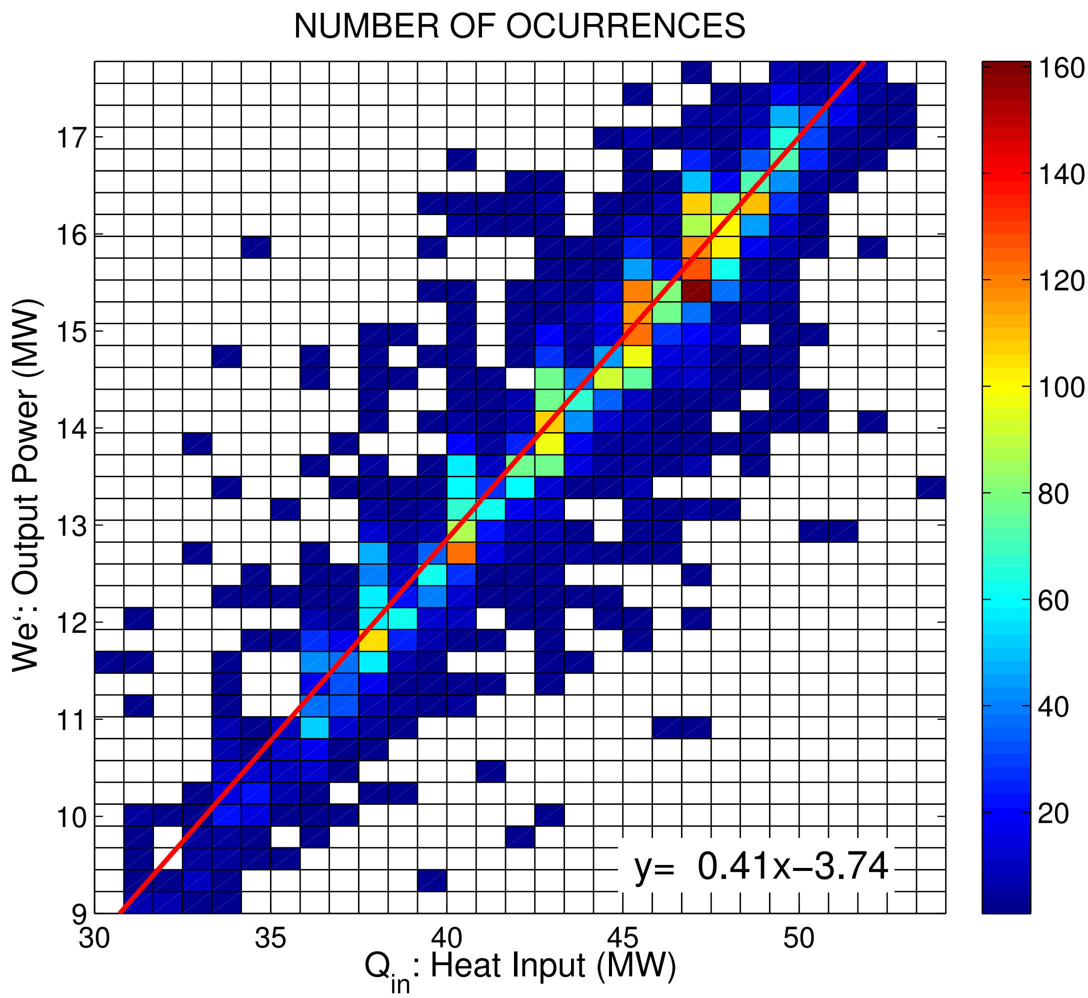

Figure 14: Relation between Heat Input and Output Power

Looking at Fig 14, the data has a strong linear relation between Q_{in} and $\dot{W}_e$ with very low dispersion. However, regarding the linear regression it can be seen that the y-intercept represents a base heat input when the turbine is unloaded. Therefore, the efficiency $\left(\eta = 0.41 - \frac{3.74}{Q_{in}}\right)$ cannot be calculated in a straightforward way due to its dependence with Q_{in}.

In order to quantify the base heat input, the analysis will consider that the turbine is unloaded. The linear regression of Fig 14 will be used to find the value of the minimum heat input (base load) to keep it rotating even when it is not producing any output power. This base energy is necessary for any load quantity and it will be present every time the turbine is turned on. Fig 16 displays the calculation results. The red point depicts the initial base load value ($Q_{in}(0) = 9.01MW$) with an unloaded turbine ($\dot{W}_e = 0MW$), and then $Q_{in}(0)$ is evaluated in the linear regression of Fig 15 to obtain the initial fuel mass flow ($m(0) = 0.72\frac{kg}{s}$).

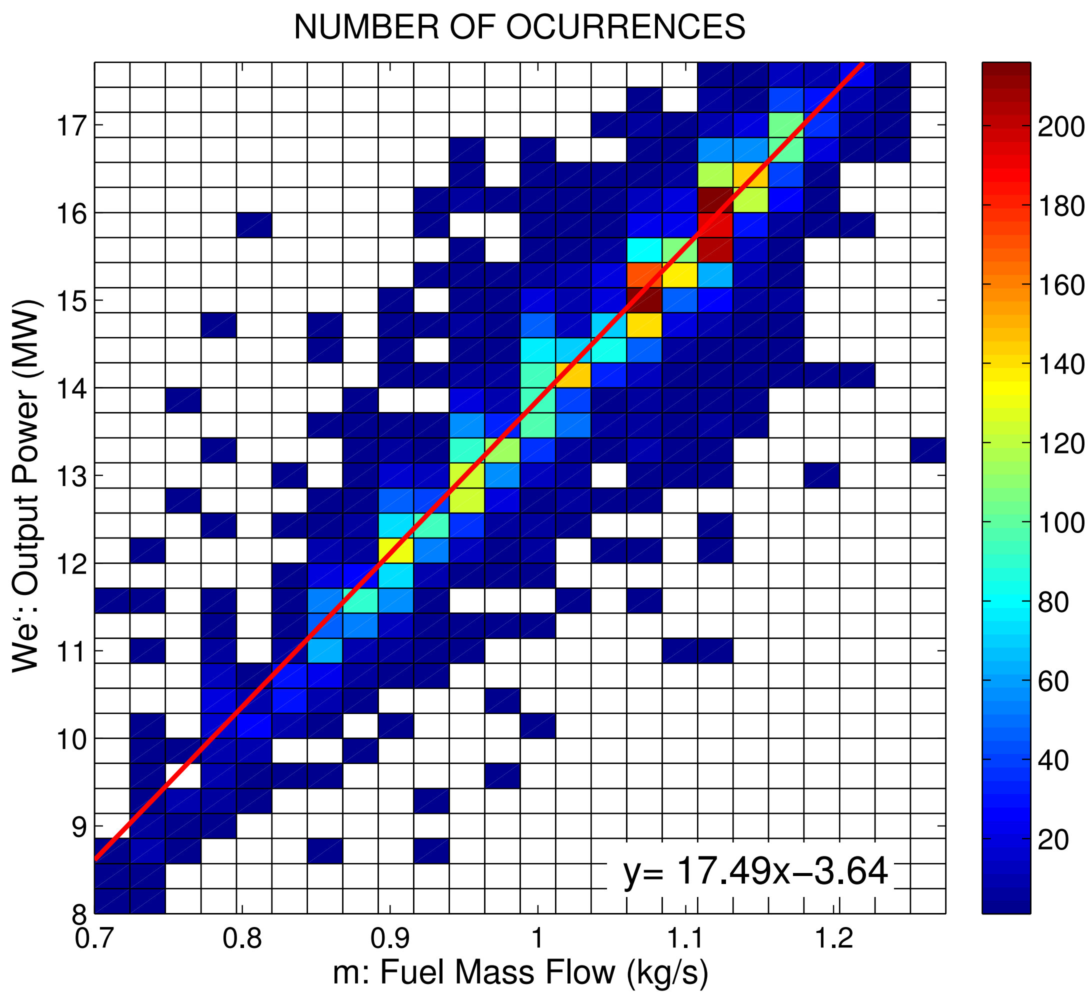

Figure 15: Relation between Fuel Mass Flow and Output Power

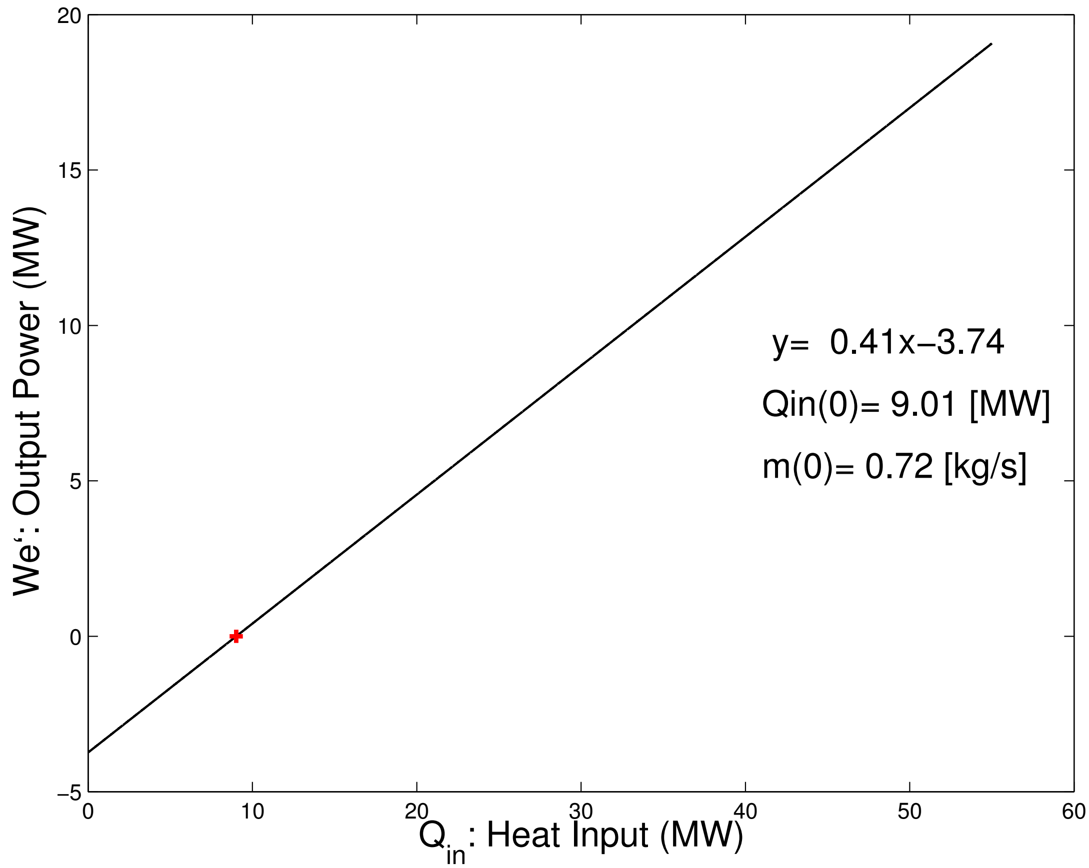

Figure 16: Initial fuel mass flow

This study led to prove that when the machine is working at low load, the minimum power necessary to initialize the machine will be more representative in comparison to the power output, so that the efficiency will be lower since that minimum base load will not do useful work.

Second-law efficiency analysis

As it was mentioned before, the Second-law efficiency is a tool to evaluate the performance of an engine in a better way. Thus, it was decided to find further relations between both efficiency types to identify features about the performance of the machine. Observing carefully at the data distribution of Fig 17, two different trends are identified, one with greater slope that the other. The data points that have greater slope are of interest since it means that higher values of Second-law efficiency can be achieved with the same value of First-law efficiency. It is important to identify the points that meet the aforementioned condition in the time series and search for factors that can cause this favourable behaviour.

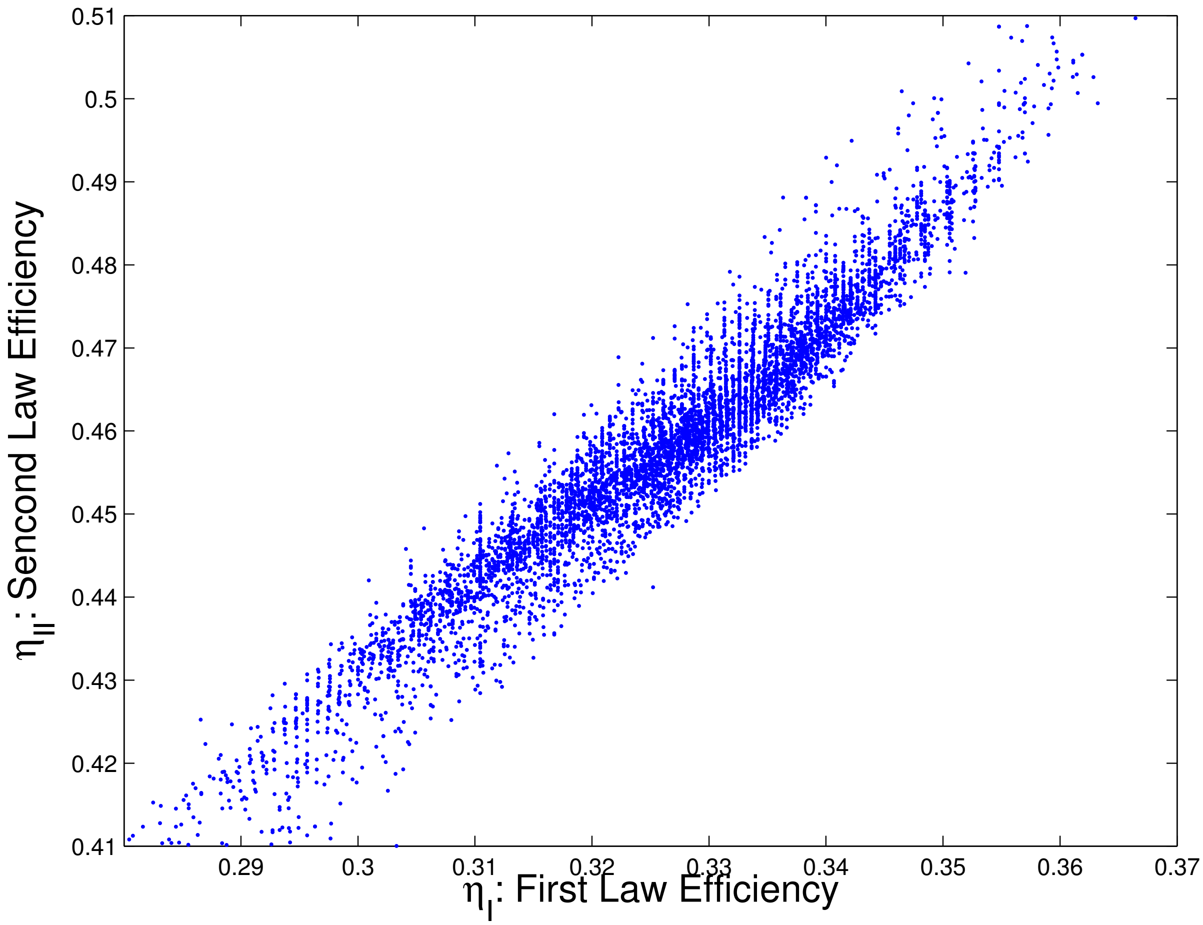

Figure 17: Linear regression to identify two trends in the data

The data points that have a greater slope were identified using the method explained next. Firstly, two linear regressions were calculated to classify the two data trends. After this, it was required to assign each point to one of the linear regressions presented in Fig 18. For this, the vertical distance between each point and both regression lines were found and then each point was assigned to the line with the least distance.

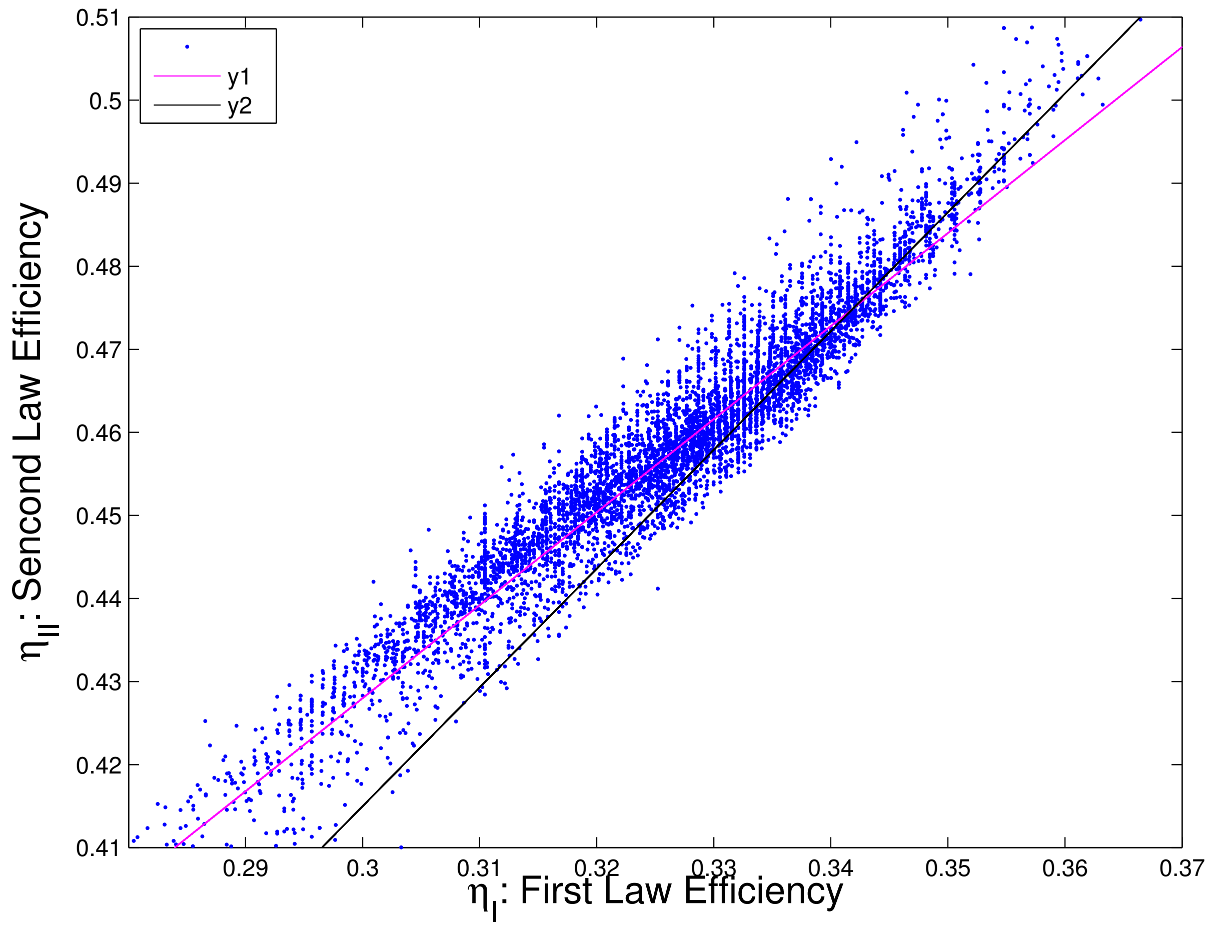

Figure 18: Linear regression to identify two trends in the data

The points with a greater slope (remarkable for this study) are presented in red in Figures 19 and 20. From both figures, it can be seen that the data is randomly scattered, but at the end of the time series it is evident that the points are gathered together closer to the second half of year 2012. This brings out a recommendation of taking into account the factors of the turbine that have changed since 2012. These factors may be maintenance, a change in the fuel's quality or a change in the turbine components.

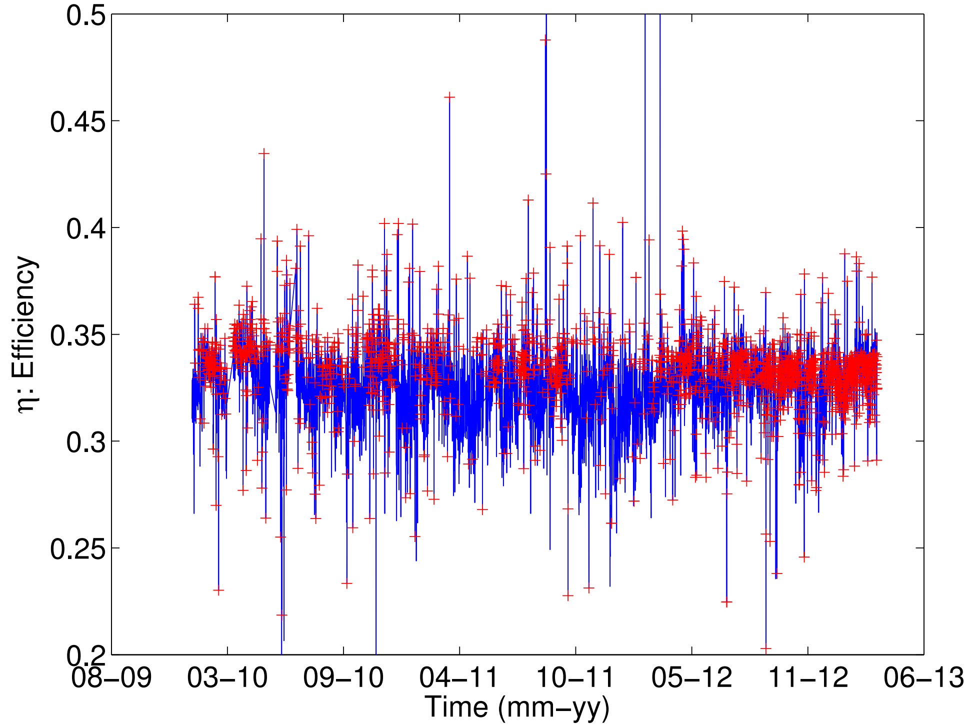

Figure 19: Time series for the First-law efficiency

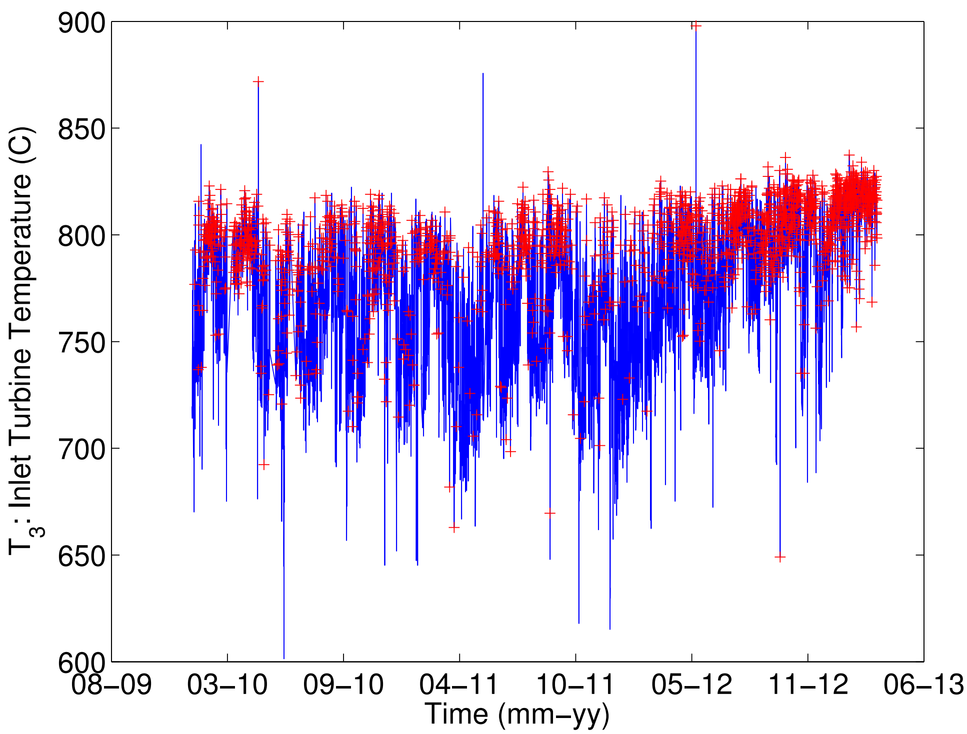

Figure 20: Time series for the T_3 : Inlet Turbine Temperature

Relation of T_1 and T_3 with η_I

Practical experience in the oilfield suggests that the turbine load can be increased when ambient temperature is low to have higher efficiency. Also, from the basic Carnot efficiency (Equation 3.5), it can be seen that efficiency is affected by the ambient temperature.

From the daily experience in the oilfield, the relations presented in Section3.5 and the results in the article presented by Oyedepo and Kilanko (2014), it was expected that most of the variables would be directly related to the the T_1 : Inlet Compressor Temperature (ambient temperature). However, the results obtained in this analysis (Fig 21) do not show a conclusive relation.

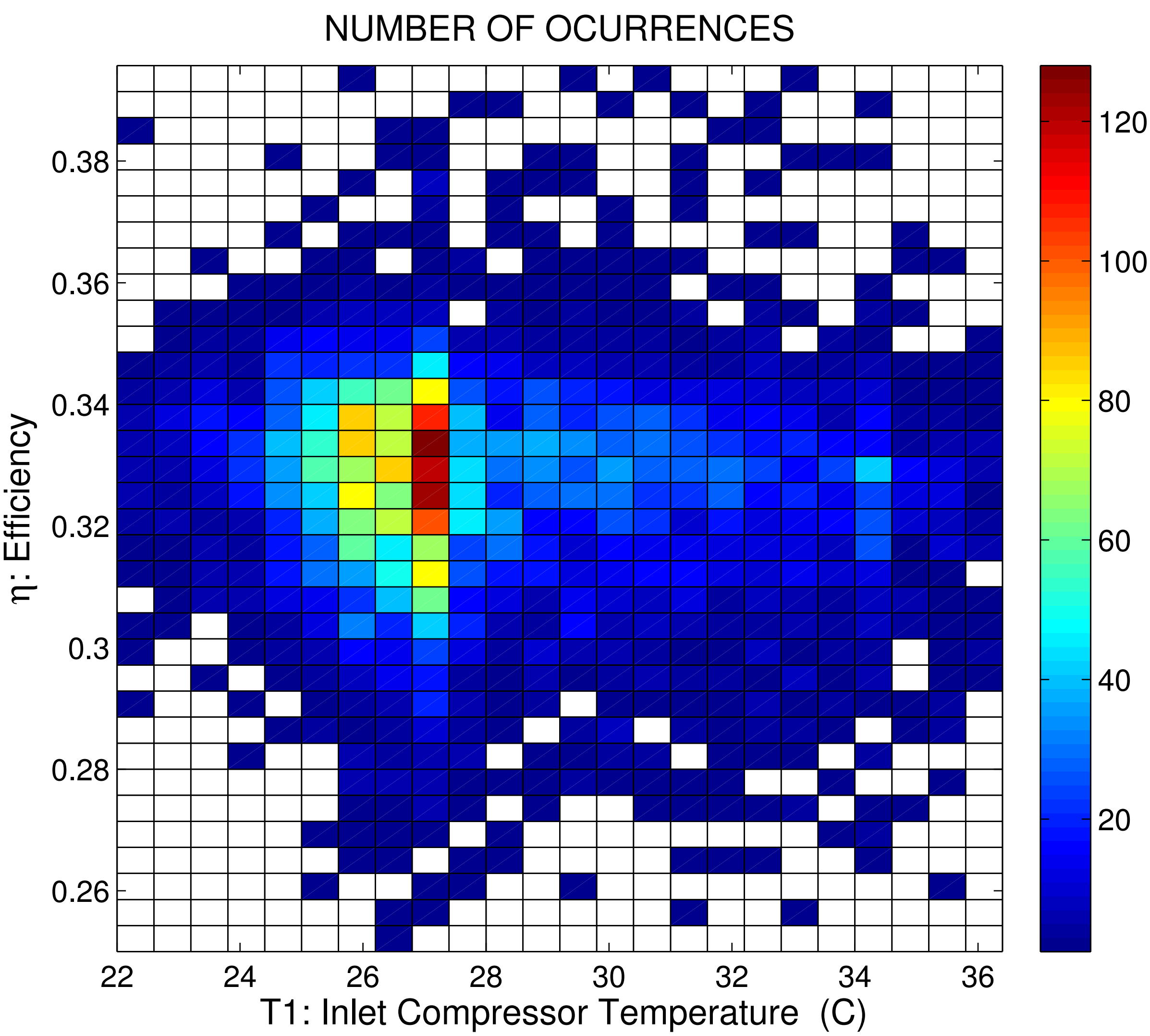

Figure 21: Relation between Inlet Compressor Temperature and Efficiency

Appendix B shows figures that relate T_1 with other variables. All those plots do not provide clear conclusions about the influence of T_1 in the performance of the turbine. Nevertheless, those conclusions do not mean that T_1 does not affect the performance of the turbine. In this case T_1 drives the attention and it is suggested to check the accuracy of the measurement instruments or to extract new data from this variable since it is vital for all the calculations.

On the other hand, T_3: Inlet turbine temperature has a direct influence in the performance of the turbine. Fig 22 is consistent with the results reported in the literature of Oyedepo & Kilanko (2014) . It is worthily noticeable that the turbine has better efficiency when T_3 is high.

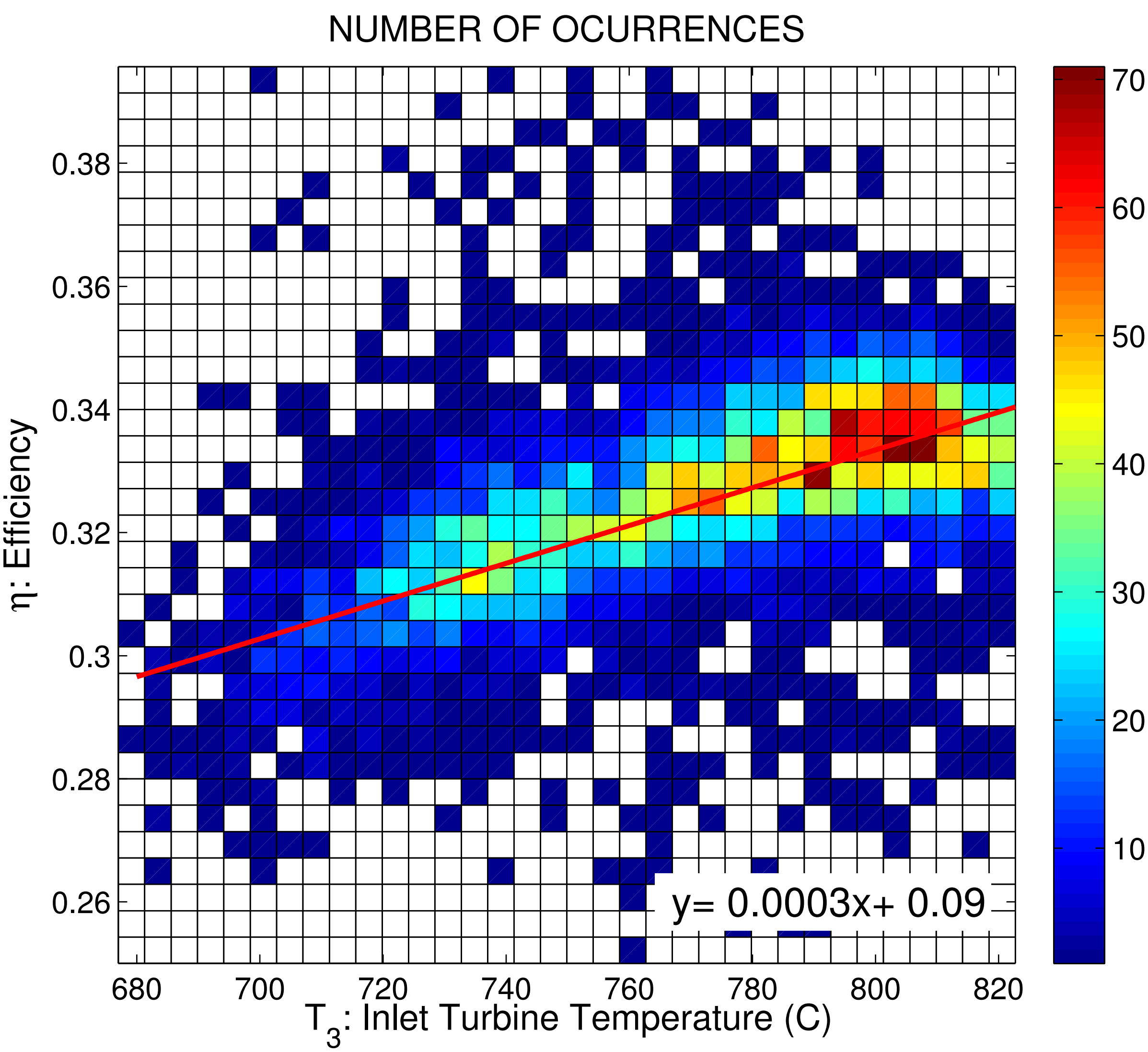

Figure 22: Relation between Inlet Turbine Temperature and Efficiency

Assessment of high efficiency cases

In this section, high efficiency values with relatively low fuel consumption were found. These outstanding points of high efficiency and low fuel consumption are enclosed in the magenta rectangle in Fig 23 where Fuel Mass Flow and Efficiency are related. The data points of interest are between $\eta : 0.325 - 0.38$ and $m : 0.805 - 1.05\frac{kg}{s}$. Getting these data points allow to identify them in the time series of the efficiency and later on, mark them in the time series of the temperatures to find a pattern.

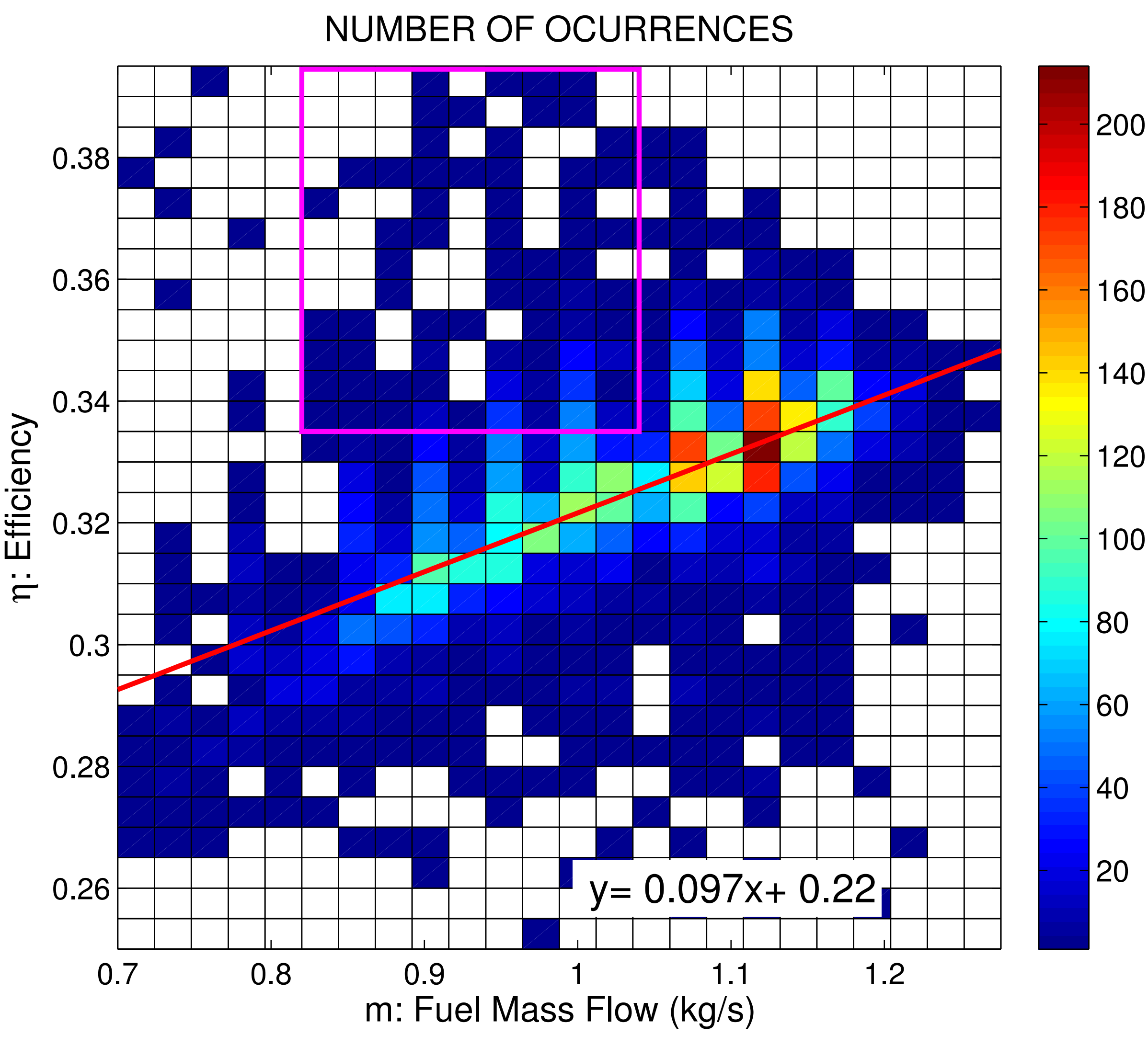

Figure 23: Relation between Fuel Mass Flow and Efficiency and possible cases of operation

Fig 24 shows in red the natural dispersion of the data that meet the aforementioned conditions. It is noticeable that a gathering of points is situated between the dates October

24^{th}, 2011 and December 24^{th}, 2011. These same points are highlighted (in green) in the time series of T_1 (Fig 25 and 26). These figures do not show a recognizable pattern or trend between the dates mentioned before.

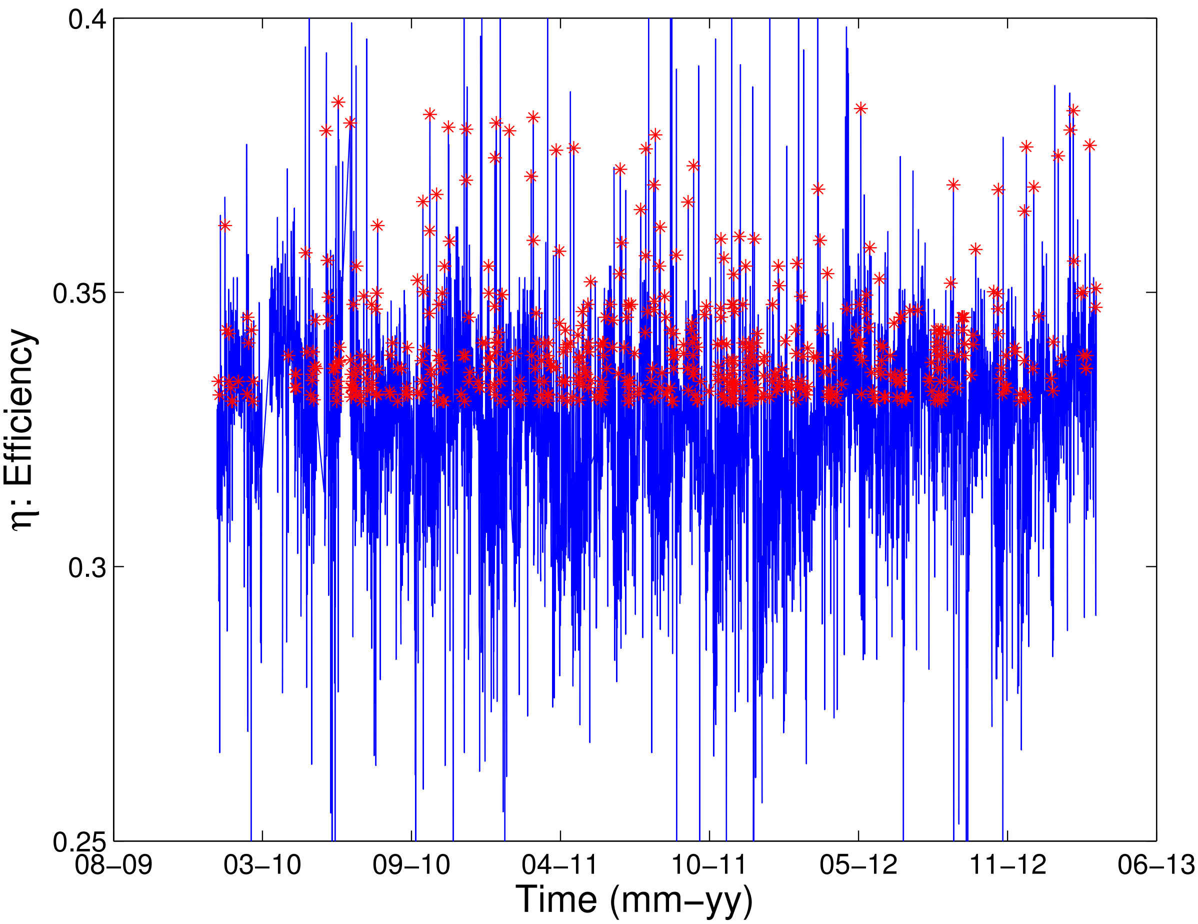

Figure 24: Time series of efficiency marking the cases when the mass flow is low and the efficiency is high

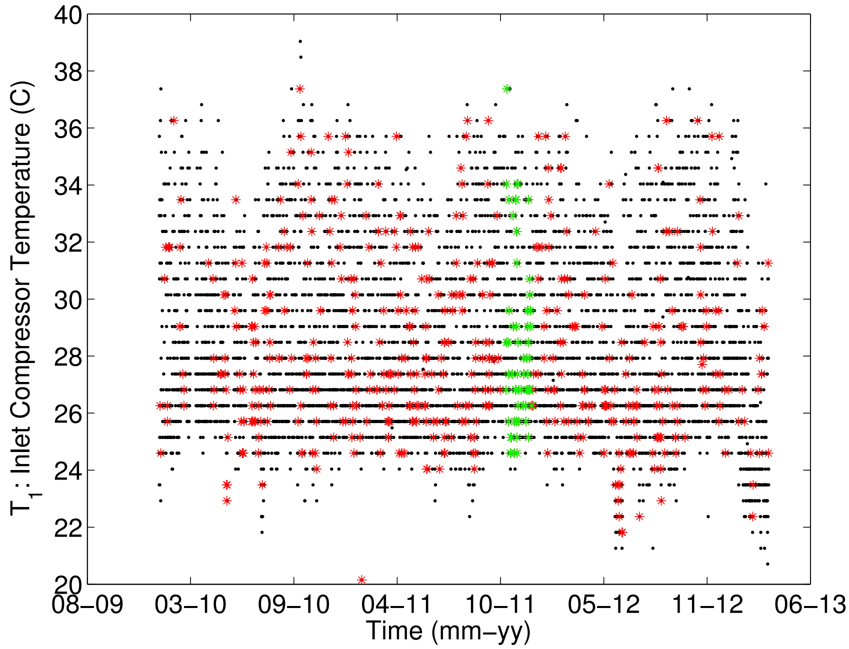

Figure 25: Time series of the Inlet Compressor Temperature marking the cases when the mass flow is low and the efficiency is high

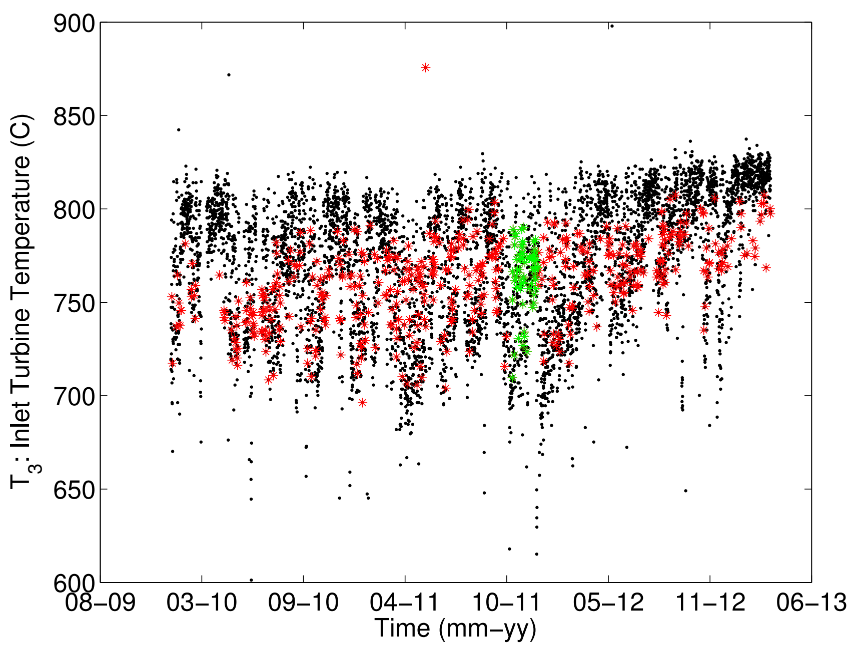

Figure 26: Time series of the Inlet Turbine Temperature marking the cases when the mass flow is low and the efficiency is high

Relation between P_2 and Power Output

An enhancing of the turbine's performance is achieved through the rise in the compressor pressure ratio in consistency with previous works (Oyedepo & Kilanko, 2014). Fig 27 and 28 show a strong relationship between variables and it can be concluded that the turbine output power is explained in an optimal way by the compressor's pressure.

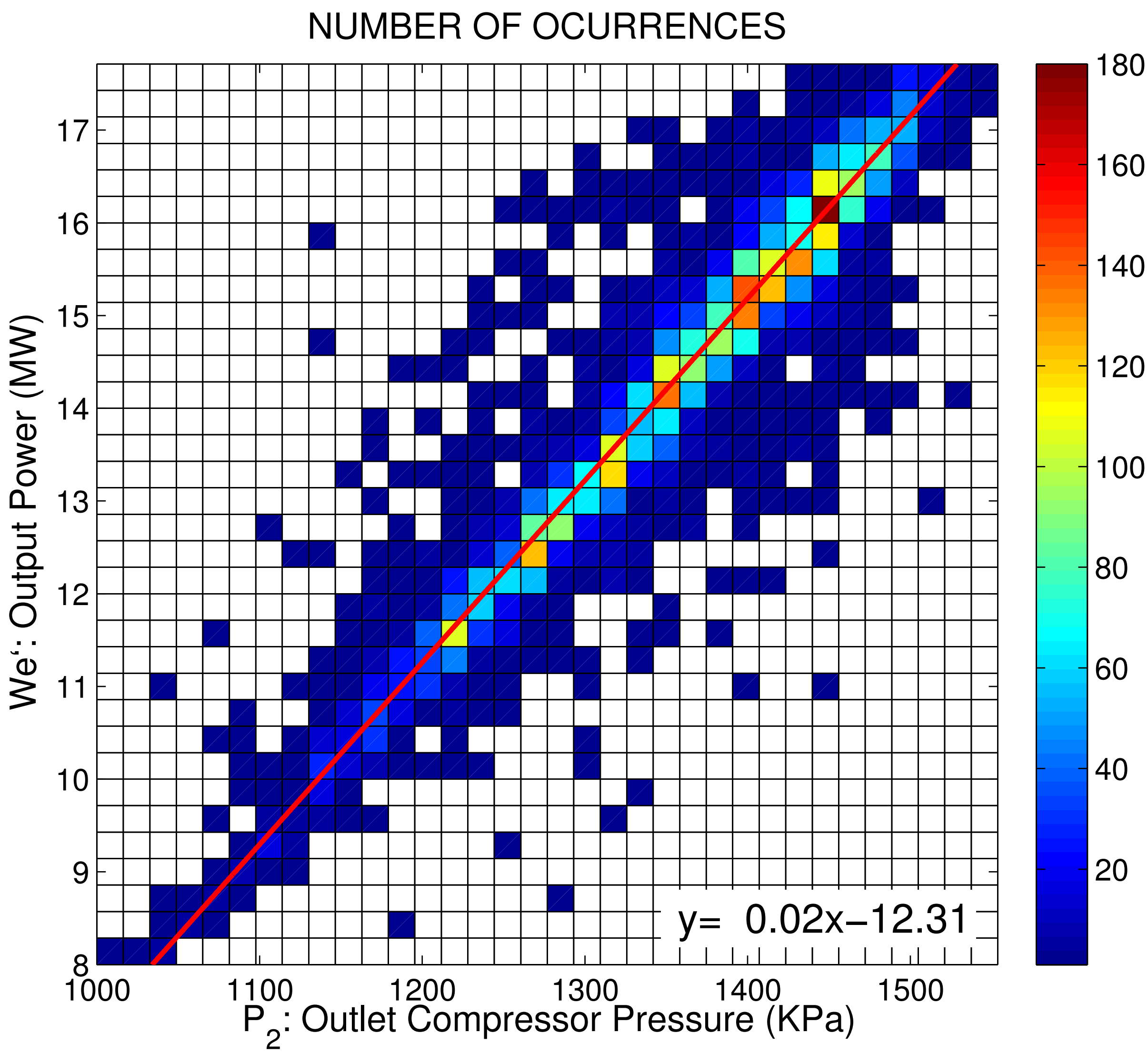

Figure 27: Relation between Outlet Compressor Pressure and Power Output

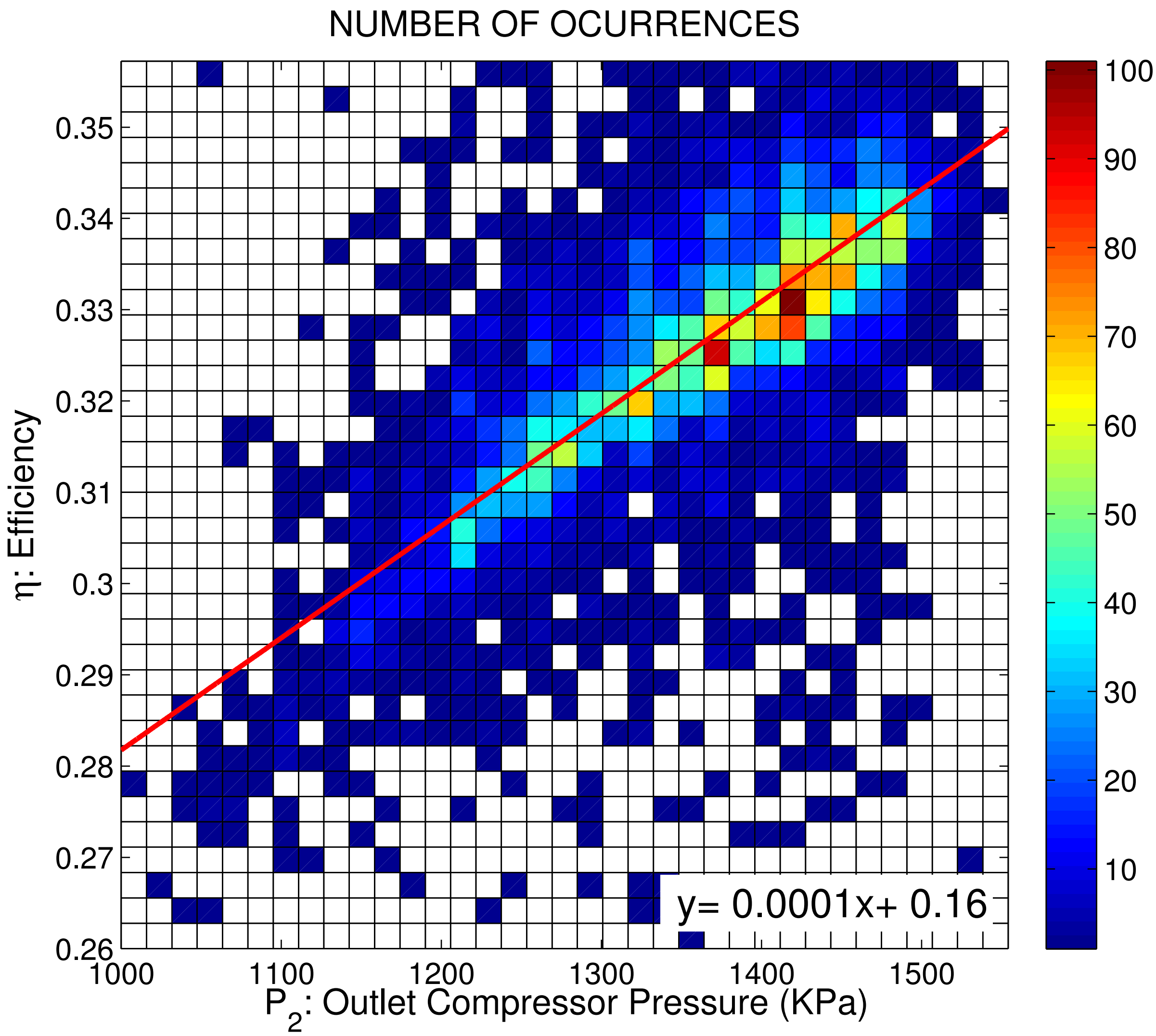

Figure 28: Relation between Outlet Compressor Pressure and Efficiency

Three variable plot

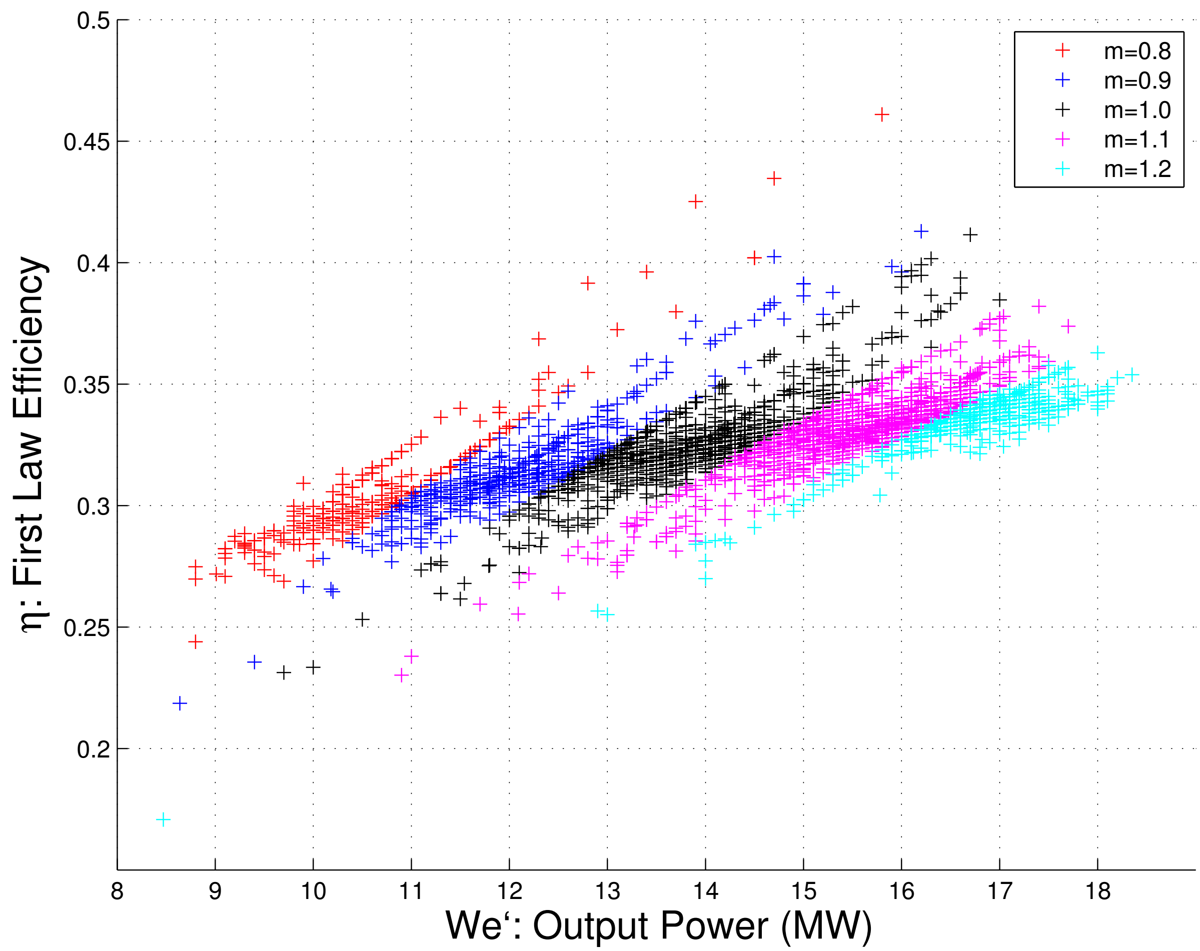

Figure 29: Relation between Power, Efficiency and Fuel Mass Flow

In Fig 29, the relation between $\dot{W}_e - \dot{m} - \eta_I$ shows the defined trend that each group of data follows. For example, it can be seen that high power production (until ∼16MW) can be reached using low fuel mass flow (0.8 $\frac{kg}{s}$). For each mass flow value exists an independent relation (points in different colours) and it is noticeable that with every mass flow value high efficiency and high power can be achieved. This means that efficiency and power output are dependent variables of the mass flow. Also, different combustion conditions probably associated with different air flows could explain that relation between power production and fuel mass flow.

Indicator BDPD/MWD

In the context of the ISO 50001 standard, it is required to enhance the power production consuming less energy during the process. Therefore, in order to get the standard's certification Repsol fixed an indicator value of 48.3 BDPD/MWD (diesel barrels per day/ Megawatts per day) to establish a base line to reduce the energy consumption and to achieve better efficiency while performing their activities (see Appendix D). However, an indicator line was calculated using the oilfield data of the present study and the results are presented in Fig 30.

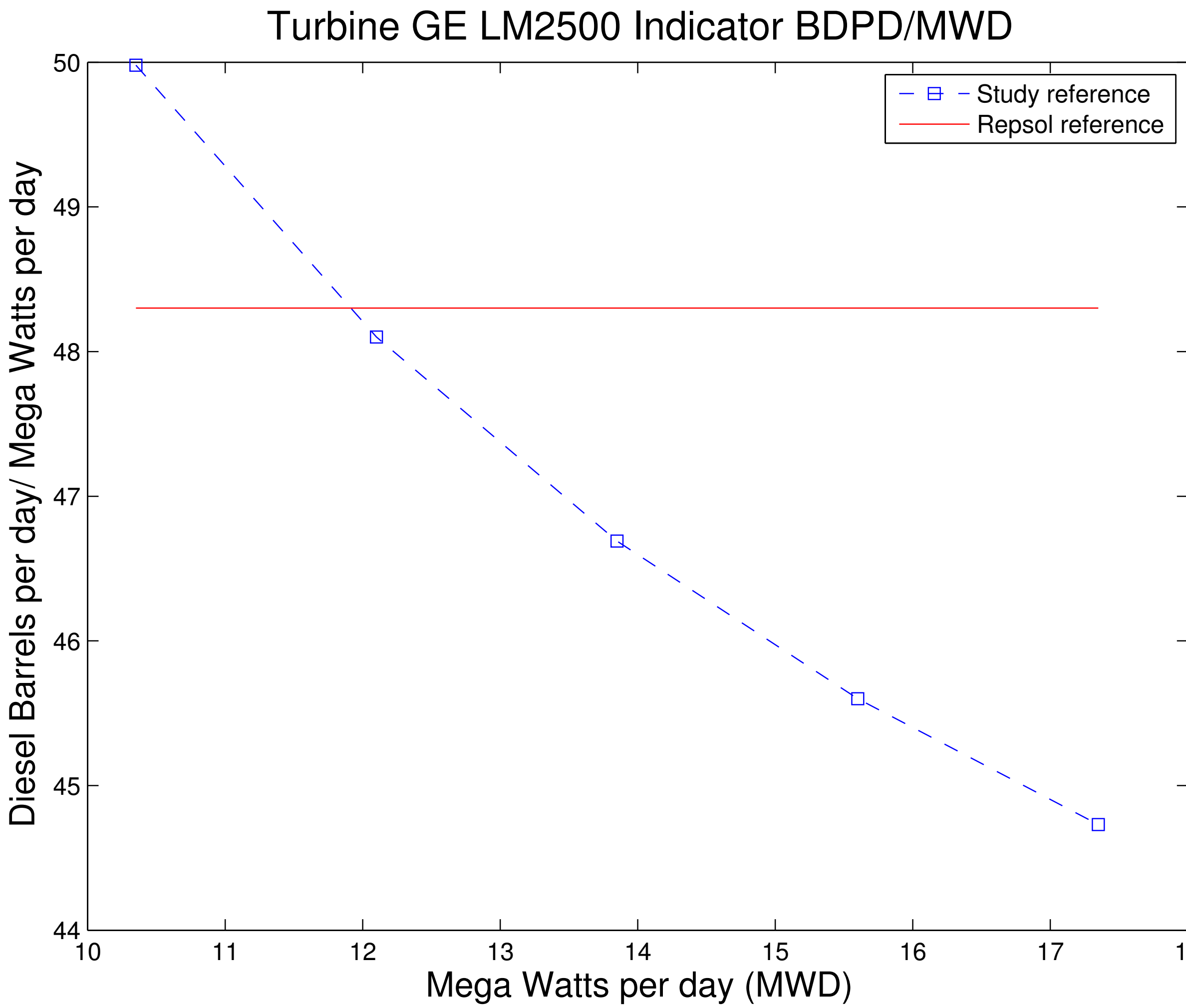

Figure 30: ISO Indicator BDPD/MWD

As a general requirement, it is desirable to minimize this indicator during operation. From Fig 30 it is clear that the indicator is lower when operating at nominal load, and indeed this indicator is under the base line (48.3). However, even though this indicator is useful to settle basic ideas, the figures presented throughout this study contribute in a better way to visualize the turbine's panorama .

5 Summary and Conclusions

-The performing conditions of the 17MW GE LM2500 turbine were analyzed. Initially, the aim of the study was the complete analysis of the thermodynamical cycle, including indicators of the second law of thermodynamics. Unfortunately, not all the required variables were available so a different analysis was performed. An important recommendation is trying to measure all the necessary variables for the analysis that was originally proposed. These variables are displayed below:

$\dot{m}_a$: Air mass flow

P_1 : Inlet Compressor Pressure

T_2 : Outlet Compressor Temperature

P_3 : Inlet Turbine Pressure

P_4 : Outlet Turbine Pressure

T_4 : Outlet Turbine Temperature

-A variable relation analysis was chosen since a large quantity of real data was available. The main tool used in this study was bi-variate plots.

-In general, it can be seen that the variables present linear relation while others present a weak quadratic relation. Thus, this study just considered linear relations, such as the ones displayed in Fig 11 and 27. It is remarkable that the data dispersion was relatively low. Therefore, these two aspects allowed to use the linear relations throughout the analysis.

-One of the main relations was $\dot{W}_e \quad vs. \quad \eta_I$, from this relationship was possible to estimate the economical consequences of operating at different loads. It can be seen that it is possible to save up to \$1000 per MW per day in fuel costs by operating close to nominal load (17 MW), chiefly due to the important increase in efficiency (6%). At this stage, just from the economical point of view it is recommendable to operate as close as possible to nominal load. However, additional factors such as power requirements, power flow control (generation and demand) and safety operation of equipment in the oilfield, must limit this possibility.

-A direct conclusion is that operating at higher load values (close to the nominal) enhances the First and Second-law efficiency of the turbine. Therefore, it is convenient to analyse if this condition is easily applicable in the oilfield.

-The aforementioned condition is explained partially by the Fig 16, since it shows that there is a minimum requirement of heat input. The value of heat input is $Q_{in}(0) = 9.01MW$ and its equivalent in fuel mass flow $\left(m(0) = 0.72\frac{kg}{s}\right)$. This fact led to prove that when the machine is working at low load, the base load will be more representative in comparison to the power output, so that the efficiency will be lower since that minimum load will not do useful work.

- In the Second-law analysis, Fig 17 suggests that there are two trends of data with different behaviour. When the data with greater slope is identified on the time series, it can be seen that a consistent group of data appears from the second half of 2012. It is convenient to identify the operating conditions from that date onwards. Those conditions may be maintenance, a change in the fuel's quality or a change in the turbine components.

- The results from the relation of $T_1 \;\; vs. \;\; \eta_I$ do not show a conclusive relation as was expected from the daily experience in the oilfield. The η_I and $\dot{W}_e$ decrease while specific fuel consumption increases at higher ambient temperature. It is suggested to collect new data, in order to check the accuracy of the instruments and the way the data were collected.

- In the assessment of high efficiency cases Section, the data of Fig 26 did not provide a clear behaviour pattern of T_3 through the time, thus, a conclusive result was not obtained.

- The relation between $\dot{W}_e \; - \; \dot{m} \; - \; \eta_I$ (Fig29) shows the defined trend that each data group follows. For example, it can be seen that high power production (until ∼16MW) can be reached using low fuel mass flow ($0.8 \, \frac{kg}{s}$). Different combustion conditions probably associated with different air flows could explain that relation between power production and fuel mass flow. It would be useful to measure the air flow for future reference.

- The indicator of fuel consumption and production per day settles basic ideas, but it is not enough to come out with clear conclusions about the turbine performance since deeper details about the turbine working cycle are not included. However, it can be seen that the indicator reference is 48.3 and it is located approximately three units above the best possible value if the operation takes place at 16MW. Also, to identify more details regarding the relations between fuel consumption and performance of the turbine it is recommended to use Fig 29 and 15 to highlight the number of occurrences of the certain performance conditions.

-In general, the life span of any equipment affects negatively its performance and it is expected that long service times cause deratings (nominal power decreases) of the device. Furthermore, routine maintenance and overhauling are necessary to improve or at least maintain the nominal operating conditions. Also, there are other factors such as the condition of air filters and fuel quality that could change the performance of the device. Based on the available data it is possible to estimate the influence of some of these factors, but this analysis is beyond the scope of this project. In addition, environmental factors such as altitude, relative humidity, and ambient temperature, can affect the operating conditions. As to the last condition, the daily experience in the oilfield shows that at lower ambient temperature the load of the turbine can be higher, therefore it produces a greater efficiency. However, the data do not show this trend and it is needed a further investigation about the data quality and the way the data was measured.

6 Recommendations

- In order to carry out a complete thermodynamical analysis of the Brayton cycle and gain insight of the different processes of the generation system of it. It is very useful to have other variables measured, among which the most relevant are:

$\dot{m}_a$: Air mass flow
P_1 : Inlet Compressor Pressure
T_2 : Outlet Compressor Temperature
P_3 : Inlet Turbine Pressure
P_4 : Outlet Turbine Pressure
T_4 : Outlet Turbine Temperature

- As it has been seen from the present analysis, there is a direct relation between power output and efficiency. Therefore it is advised to operate the turbine at as high loads as possible.

- The plot of the Second-law efficiency versus the First-law efficiency (Fig. 18) suggests that there are two operating conditions. One of these has marked better efficiencies. Locating these conditions in the time series indicates that there is a sustained operation enhancement after the second half of 2012. It would be interesting therefore to find out whether any operating condition has changed in that period (e.g., scheduled maintenance, change of fuel, change of air filters, among others).

- According to field experience, there is a relationship between ambient temperature and turbine load. In general, at lower temperatures it is possible to increase load, therefore increasing also the efficiency. However, with the present data, there is not a relationship between these two magnitudes. Thus, it is important to check the quality of the current ambient temperature measurements, or otherwise, carry out a dedicated field data collection to verify or discard the hypothesis of this field experience.

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Appendix A

SGS Oil, Gas and Chemicals *SGS del Ecuador S.A. Lago Agrio Vía a Quito Km2.5 Barrio Pablo Alverca*	*Cliente: Repsol Ecuador S.A. Av. Republica del Salvador y NN UU*	*Reporte No: OGC-R-UIO-00230698-0006 Fecha: 16 de agosto del 2012*	*Descripción del producto :* ***Diesel***
ENSAYO	MÉTODO	RESULTADO	UNIDADES
Agua y Sedimentos	Cálculo	0.081	% (v/v)
Densidad Relativa (SG) a 60/60º F	ASTM D1298	0.8403	------
Punto de Inflamación PMCC-Procedimiento A	ASTM D93	55.0	ºC
Viscosidad Cinmática a 40ºC	ASTM D445	2.2	cSt
Punto Final	ASTM D86	355	ºC
Poder Calórico Superior	ASTM D240	19425	BTU/lb
Poder Calórico Inferior	ASTM D240	18286	BTU/lb

Figure 31: SGS Oil, Water&Chemicals. Report of Diesel produced in Repsol

Appendix B

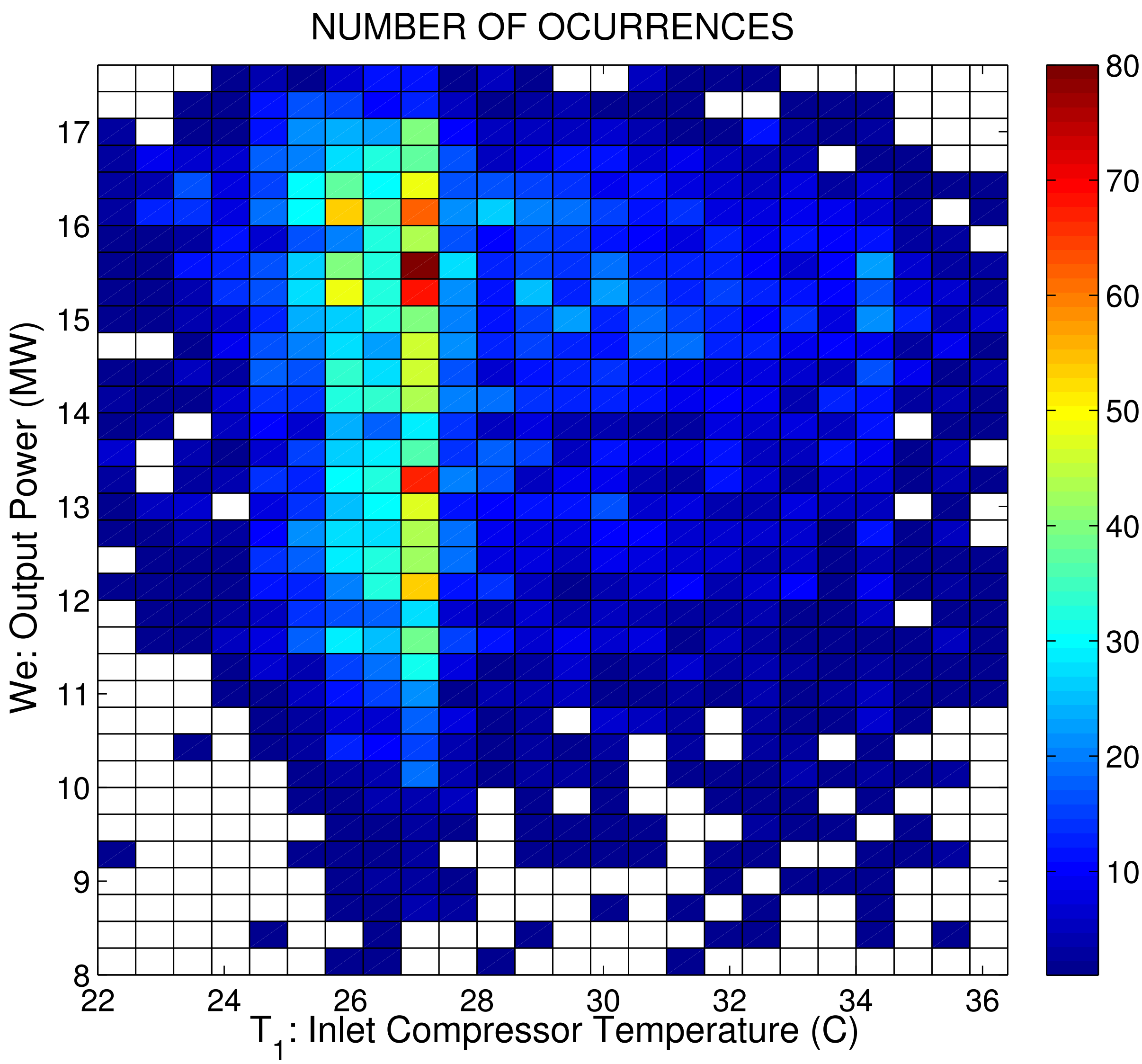

Figure 32: Relation between Inlet Compressor Temperature and Output Power

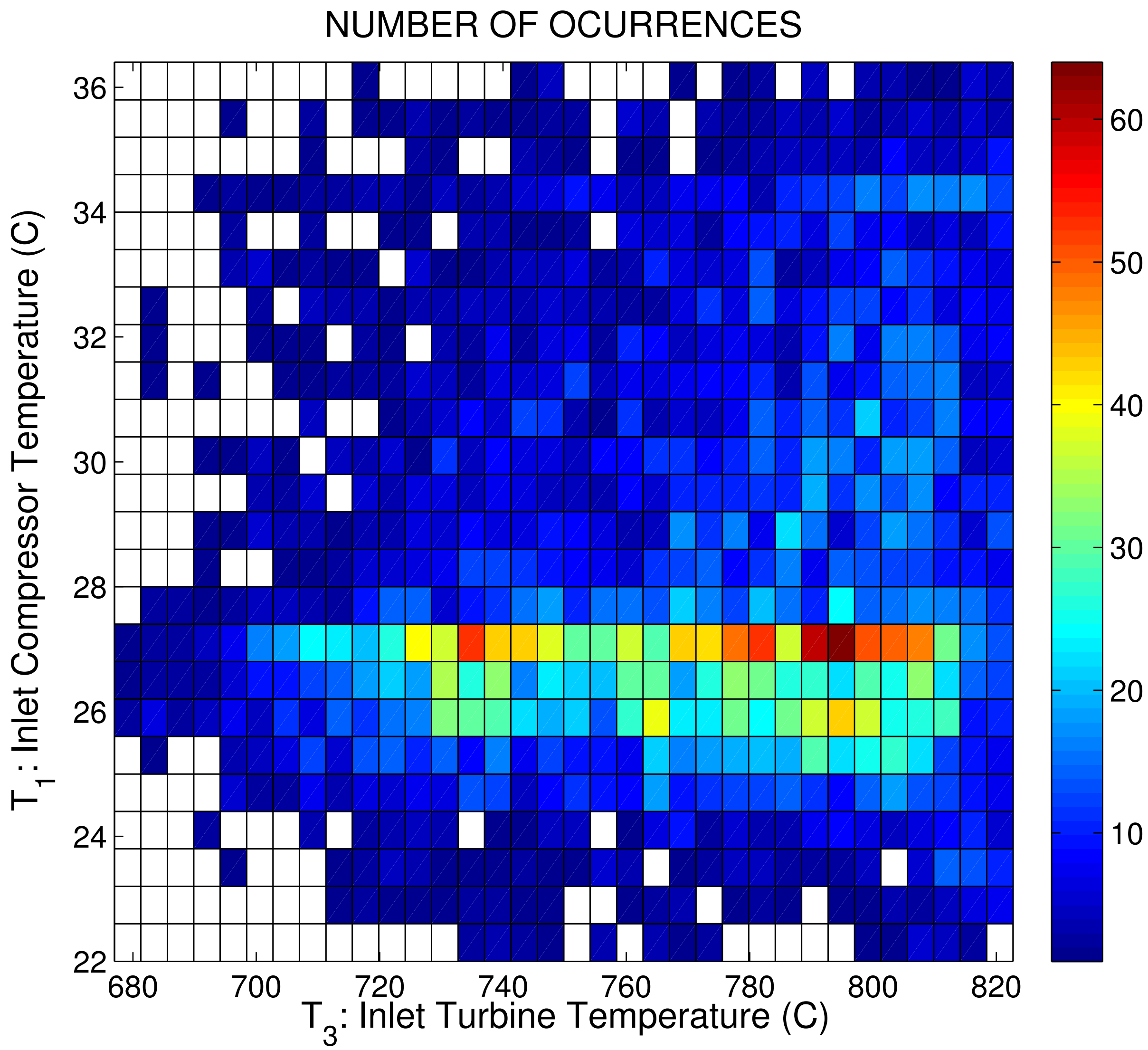

Figure 33: Relation between Inlet Turbine Temperature and Inlet Compressor Temperature

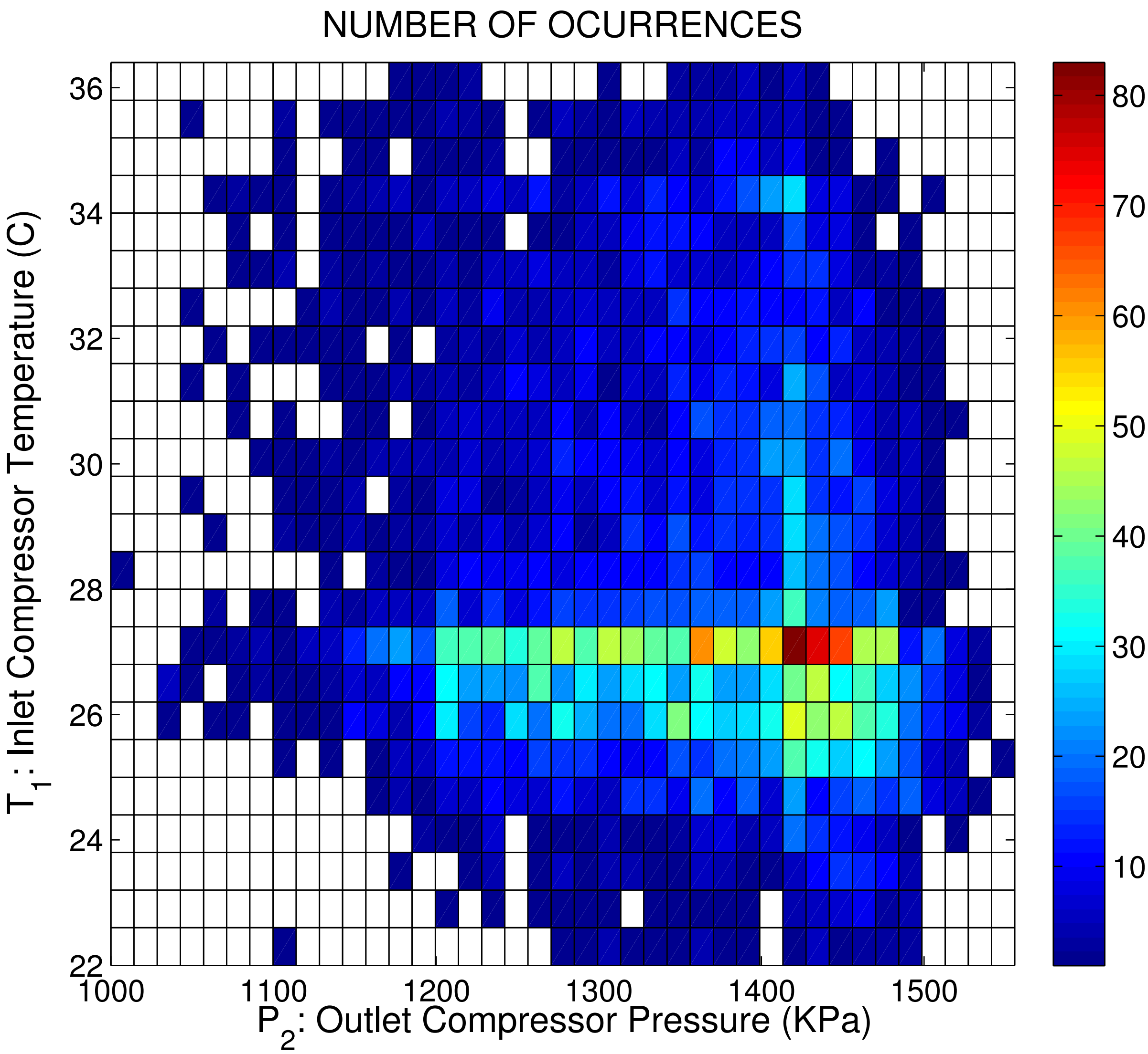

Figure 34: Relation between Outlet Compressor Pressure and Inlet Compressor Temperature

Appendix C

The calculations of the power production costs at different efficiency levels is presented below:

1. It was considered the energy production in one day.

2. Different case scenarios were considered to find the cost production working at different loads.

3. In each case the mass flow was calculated using the linear regression of Fig 15, and then a transformation was done in order to find fuel consumption per day:

$$Fuel\,consumption\left[\frac{bbl}{day}\right]=\frac{\dot{m}\left[\frac{kg}{s}\right]}{\rho_f\left[\frac{kg}{m^3}\right]}\times 24\left[\frac{h}{day}\right]\times 3600\left[\frac{s}{h}\right]\times 1000\left[\frac{l}{m^3}\right]\times\frac{1gal}{3.78l}\times\frac{1bbl}{42gal} \tag{.1}$$

4. In each case the η_I :efficiency was calculated using the linear regression of Fig 11.

6. The referential price for the diesel fuel was considered \$0.85 per liter.

7. The cost of each case scenario was calculated as follows:

$$Day\,cost\left[\frac{\$}{day}\right]=\frac{\dot{m}\left[\frac{kg}{s}\right]}{\rho_{fuel}\left[\frac{kg}{m^3}\right]}\times 1000\left[\frac{L}{m^3}\right]\times 24\left[\frac{h}{day}\right]\times 3600\left[\frac{s}{h}\right]\times 0.85\left[\frac{\$}{L}\right] \tag{.2}$$

$$Production\,cost\left[\frac{\$}{MW\,per\,day}\right]=\frac{Day\,cost\left[\frac{\$}{day}\right]}{Production\,load\,[MW]} \tag{.3}$$

Appendix D

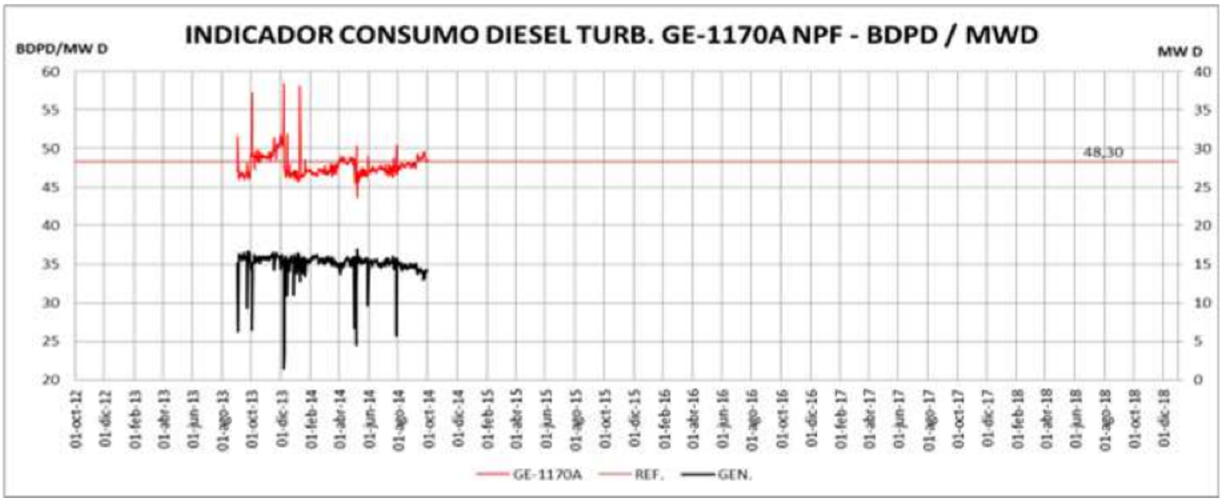

Figure 35: Repsol indicator of Fuel Consumption vs. Output Power