



**Atacama
Large
Millimeter /
submillimeter
Array**

ALMA Power Costs and non-ALMA projects

ALMA-20.05.01.00-0044-A-REP

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1 Executive Summary

This document contains two major parts. The first part (Section 4) analyses the generating capacity of ALMA and the ALMA power consumption to derive the available free capacity in the system. The second part (Sections 5–7) details the various contributors to the cost of generating power and derives formulae by which the cost of electricity can be predicted as a function of load, fuel costs, etc.

Finally, in Section 8 there is a summary of the projected power consumption for each of the external projects that have expressed an interest in obtaining power from ALMA. Table 17 reflects the status as of June 2018.

All consumption and costs are based on actual values for 2018 unless otherwise stated. This report is only intended to present the proposed framework to be used to apportion the costs and as an illustration of the cost of generating electricity. It is expected that the actual framework used to charge external projects would form a part of the agreement between ALMA and the external projects.

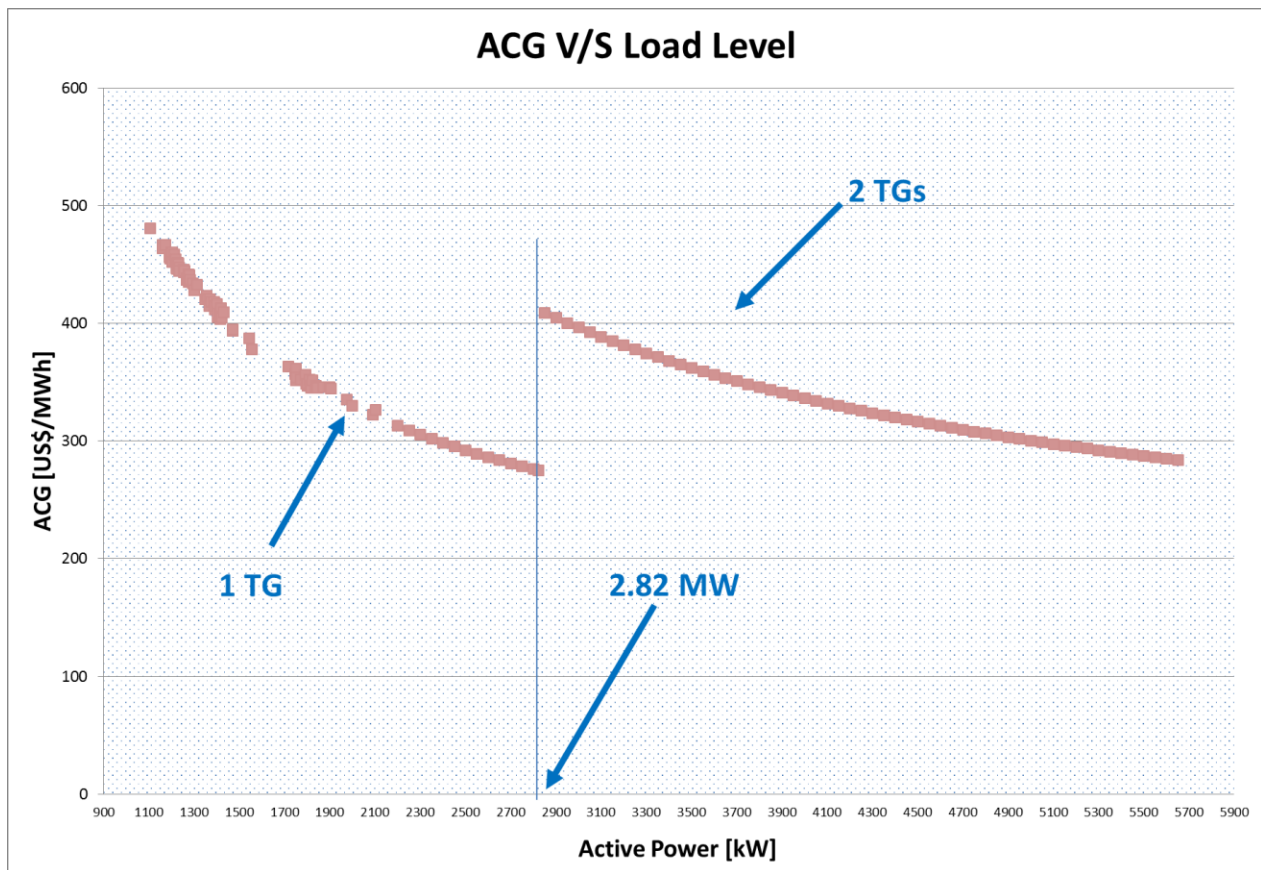
During 2018 the average power consumption of ALMA was 2.41 MW¹ for the whole year and 2.54 MW excluding the month of February (Section 4.3.3). Adding in the expected increased power consumption due to the sports facility (operational by the end of 2019) and the HiL Simulator (expected operational ~2022) gives a best estimate of the average ALMA power consumption after 2022 of **2.59 MW** (Section 4.3.3) **assuming no other additional loads** as a result of additions to the ALMA observing system as a result of, for example, the Development Roadmap.

The power generation capacity of a single gas turbine at the ALMA power station after allowances for derating, load variation, fouling and other effects is estimated to be **2.82 MW** (Section 4.3.4). Therefore, the available excess capacity (when supplying the load from a single turbine) during 2018 was estimated to be **0.29 MW** and this is expected to fall to **0.23 MW** by 2022 (Section 4.3.4).

This is the maximum power that remains available from a single GT at ALMA today and does not consider any future expansion of ALMA capabilities resulting in more power demand e.g. correlator upgrade, more antennas, different cryo-coolers etc. Clearly, both in the case of expanded ALMA capabilities or providing electric power to other observatories, the net power capacity of one GT may be exceeded in which case two GTs running simultaneously in a load-sharing mode would be required.

The unit cost to generate electricity in US\$/MWh is a function of load, lower heating value of fuel, specific fuel cost, and generating plant maintenance & operation costs (consumables, external maintenance contract, and staff; Sections 5 & 6). In 2018 the actual unit electricity cost of supplying the ALMA load with a single turbine was **302.21 US\$/MWh** (Section 6.5). The following graph shows the unit cost of electricity as a function of combined average load using the actual costs from 2018 and an extrapolation of the load-dependent costs based on the observed heat rate as a function of load for a single turbine (Section 5).

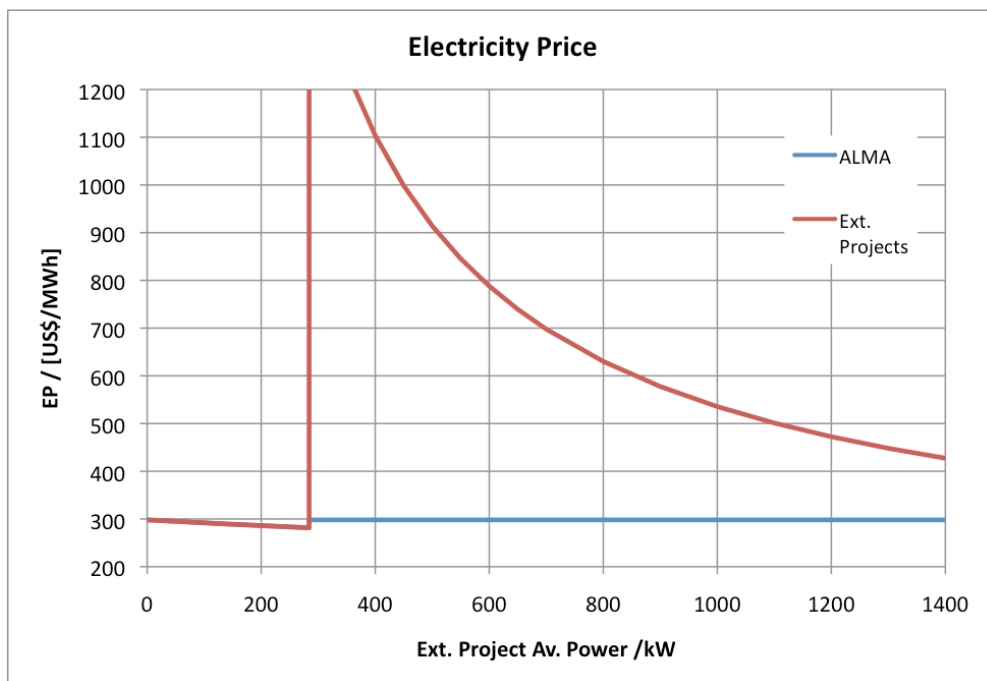
¹ The average power supplied during the February maintenance shutdown in 2018 and earlier years was significantly lower than the rest of the year because there was a period of about 2 weeks when the AOS loads were supplied from temporary diesel gensets at the AOS. This is not foreseen for future years and so the average consumption in February is expected to be similar to the rest of the year.



Graph 1: Electricity price as a function of generated power (see Sections 6.5 and Graph 20).

It is proposed that the unit price of electricity charged to external users and ALMA would be the same if the combined load can be supplied by one turbine alone.

If the combined average load exceeds the capacity of a single turbine, i.e. 2.82 MW, then the proposed price to ALMA would revert to the single-turbine cost ALMA would have to pay if there were no other users. In this case the price external users would be charged will be much higher than ALMA since they will have to bear the full cost of operating the second turbine at an inefficient low loading. The two prices are shown in the following graph as function of external project power consumption and for an ALMA consumption at the average 2018 level of 2.41 MW (Section 4.3.3).



Graph 2: Electricity price for ALMA and external projects as a function of external projects load based on ALMA's 2018 average consumption of 2.41 MW (Section 4.3.3) and the generation costs from 2018 (see Section 6.5 and Graph 21).

2 Introduction

2.1 Purpose

Over recent years the interest in using the Chajnantor plateau for astronomy has grown, most especially with the development of the Parc Astronomia by CONiCYT. Given that ALMA has three substantive gas-turbine generators at the ALMA Operations Support Facility, each potentially capable of generating up to 3.6 MW, the question of whether ALMA can provide power to other projects on the Parc has been raised.

The purpose of this document is three-fold:

- to determine the capabilities of the ALMA gas turbines to deliver power, and
- to calculate the cost for generating that power, and
- to propose the price at which the power should be sold to non-ALMA projects.

2.2 Scope

The scope of this study is limited to the operating costs of power generation.

The capital costs associated with building the ALMA power generation and distribution system are not in the scope of this study.

The operating costs associated with the maintenance of the distribution networks are outside the scope of this study.

3 Related Documents and Drawings

3.1 Related Documents

The following list of documents is applicable to this document to the extent specified. In the case of applicable documents, which are identified as “AD” numbers, the most recent version of the document is valid. For all reference documents, which are identified as “RD” numbers, the version shown is valid.

RD	Title	Number
[RD01]	Turbine & Gearbox Test Report, CTR_103051_TBM0780_GT	SITE-20.05.07.00-0201-A-REP
[RD02]	GT Taurus 60 O&M manual, Turbomach (English)	1B025
[RD03]	On-site measurements, load characterization and Power Quality analysis at ALMA Observatory, Laborelec	ALMA-1-GC-ITE-0003
[RD04]	Turbine #1 Power Measurement report	MO-T-006 TG1
[RD05]	Turbine #2 Power Measurement report	MO-T-006 TG2
[RD06]	Turbine #3 Power Measurement report	MO-T-006 TG3
[RD07]	910107-MA-MIN-PL-0004_01 Test Results	910107-MA-MIN-PL-0004
[RD08]	Gas Turbine Performance, Rainer Kurz, Solar Turbines Incorporated	Not-ALMA doc
[RD09]	GE Gas Turbine Performance Characteristics	Not-ALMA doc
[RD10]	Monthly Energy Report – several months	IMG-31
[RD11]	Gas Turbine Taurus 60 Datasheet	Not-ALMA doc
[RD12]	<i>Evaluacion de rendimiento y mejoras de eficiencia en Turbinas de Gas</i>	IMG-905
[RD13]	Gas Turbine performance deterioration and compressor washing	Not-ALMA doc
[RD14]	<i>Norma técnica de seguridad y calidad del servicio para Sistemas Medianos</i>	Not-ALMA doc
[RD15]	<i>Guía de Aplicación: Estudio de Control de Frecuencia y Determinación de Reserva</i>	Not-ALMA doc
[RD16]	<i>Estudio de control de frecuencia y determinación de reservas</i>	Not-ALMA doc
[RD17]	Indoor Sports Facility at ALMA OSF, Design and construction, Demand Study and Feeder Calculation, Electrical	ALMA-20.08.15.07-0010-A-REP

3.2 List of Acronyms and Abbreviations

The list of acronyms and abbreviations used within this document are given below.

Acronym or Abbreviation	Definition
CWG	Chajnantor Working Group
VFC	Variable Fuel Costs
BSG	Black-start generator (diesel)
VNFC	Variable non-Fuel Costs
MVC	Maintenance Variable Costs
OVNFC	Operational Variable non-Fuel Costs
FC	Fixed Costs
ACG	Average Costs of Generation
GT	Gas Turbine
LPG	Liquefied Petrol Gas

Acronym or Abbreviation	Definition
ISO	Standard conditions for Gas Turbines: Ambient Temperature – 15°C, Relative Humidity – 60% and Ambient Pressure at Sea Level
PPS	Permanent Power Station
PVC	Present Value of Cost flow
PVE	Present Value of Energy flow
kWe	Kilowatt-electric: One thousand watts of electric capacity
BTU	British Thermal Unit
MMBTU	Million BTU
LHV	Lower Heating Value
PF	Power Factor

4 Power Generation at ALMA

4.1 Multi-Fuel Power Generation System

The Permanent Power Station (PPS) is the main generation station at ALMA, and the only source of electric power in normal ALMA operations. The PPS consist of three TurboMach “Taurus 60” Gas Turbine (GT) power generators: one unit working in stand-alone mode supplying the total power needs of ALMA, with the second and third units in stand-by to assure the ability to changeover to another generator in case of problems, failures or maintenance of the running unit.

In addition, a group of twin diesel generators (BSG) is located close to the GTs, in hot standby allowing a “black-start” after a power failure.

The GTs are able to run with gaseous fuels, e.g. Natural gas, at 100% of their capability, as well as with liquid fuels, diesel oil and one chosen among Kerosene, LPG, Naphtha at 100% of the capability. LPG is considered the primary fuel among these last three. Though multi-fuel capable, there are only two sources of fuel being used at the PPS at the moment -- LPG and diesel.

The PPS is not interconnected to any external grid and is currently always operated in island mode.

4.2 Gas Turbine Taurus 60

The Taurus 60 Gas Turbine (T60-7901) is a multi-fuel turbine for industrial service in power generation facilities. The power output is 5670 kWe for gas fuel and 5513 kWe for liquid fuel in ISO conditions, with an efficiency (energy generated per energy consumed) of 31.50%.

Gas Turbine Data Plate	
MODEL NO.	TAURUS 60
VERSION	7901 GSC
ENGINE ID	TF0KAC-1100-006
SERIAL NO.	1988T
POWER [G/L]	5670/5513 kWe
NGP [RPM]	14944 (50Hz) / 14951 (60Hz)
IGV SETTING [DEG]	+5.0
T5 BASE UNCOMP [F] [G/L]	1341 / 1338
SETPOINT FULL LOAD [F] [G/L]	T5 1250/1250

Table 1: Data plate of the GT#1, serial number 1988T [RD01].

TYPE OF TURBINE	T60
INSTALLATION	OUTDOOR
FUELS	TRIFUEL
EMISSIONS REDUCTION	Conventional
BOILER	Without
AIR FILTER SYSTEM	Self-cleaning
OIL COOLING	Oil-Air
ONLINE COMPRESSOR WASHING	With
REMOTE CONTROL	With
REMOTE COMM. PROTOCOL	MODbus TCP/IP
GENERATOR MANUFACTURER	Leroy Somer
GENERATOR TYPE	LSA 56 BVL80 / 4p
GENERATOR NOMINAL POWER	5260 kVA at 1000 m.a.s.l
FREQUENCY	50 Hz
GENERATOR VOLTAGE	10500 V
BACK SYNCHRO	Without
GEN. CB DIRECT INSERTION	Without

Table 2: GT T60 [RD02].

4.3 Available Active Power Generation

4.3.1 De-rated Power Capacity (DPC)

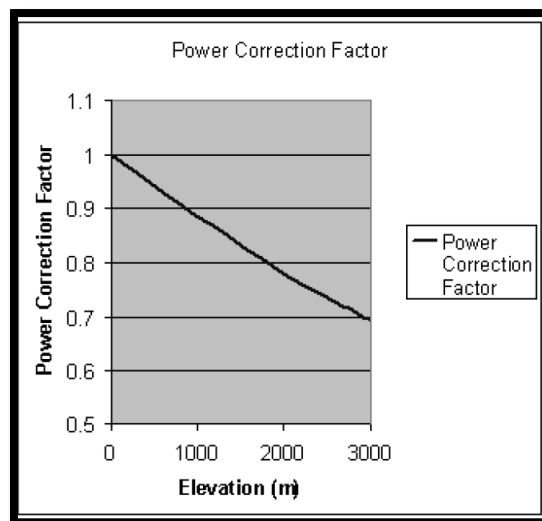
The following is the nominal power capacity of our GTs:

- Nominal Power Capacity at ISO conditions (Liquid Fuel): **5,513kW**

The nominal power capacity must be de-rated due the OSF environmental conditions.

Ambient Pressure

The main factor which decreases the Power Capacity is the altitude (ambient pressure). The correction factor can be determined using the following graph:



Graph 3: Power Capacity Correction factor per site elevation [RD08].

The most direct way of calculating the correction factor for atmospheric pressure is through the following formula:

$$\delta = \frac{P_{\text{ambient}} (\text{in } " \text{Hg})}{29.929" \text{Hg}}$$

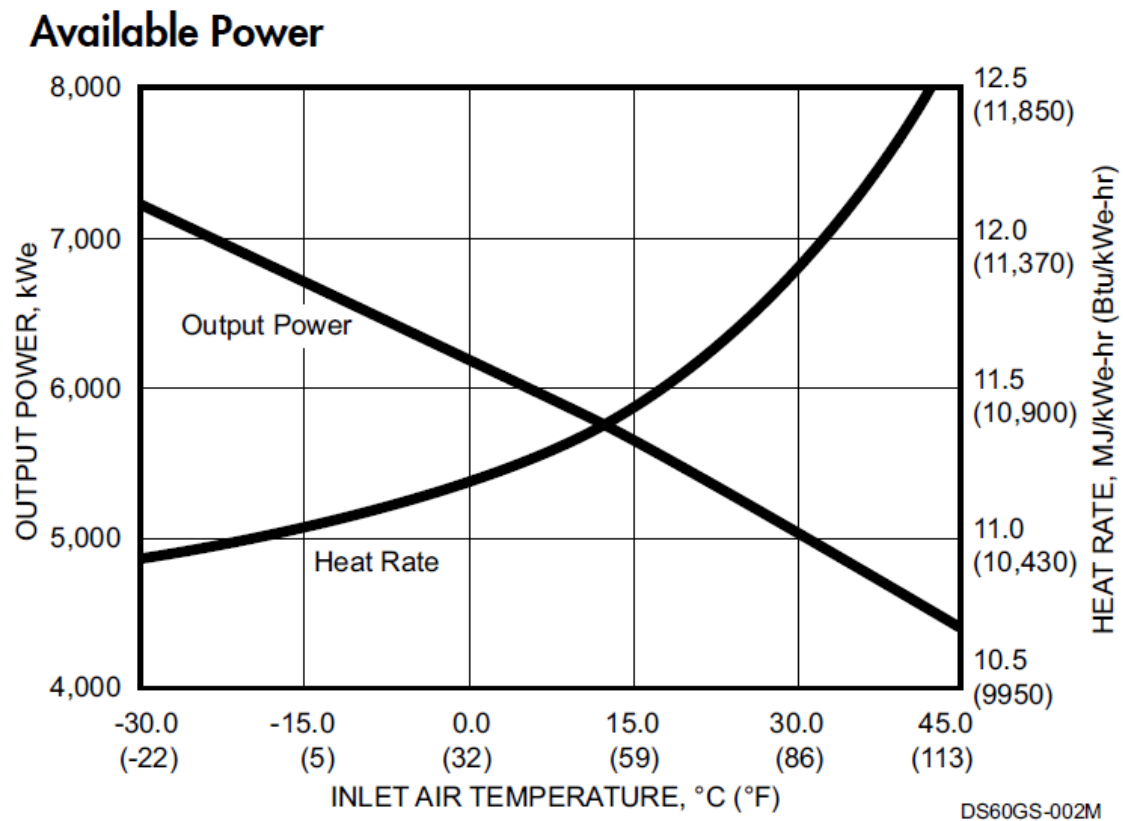
Source: Gas Turbine Performance, Rainer Kurz, Solar Turbines Incorporated. [RD08]

The correction factor calculated is **0.7**. Therefore, the theoretical **De-rated Power Capacity** is **3,859 [kW]** at the ISO temperature (15°C). Higher ambient temperatures decrease the power capacity and lower temperatures increase it.

- **De-rated Power Capacity (DPC)** of a GT at ISO temperature (15°C): **3,859kW**

Ambient Temperature

The power capacity of the GT for temperatures different to 15°C can be determined with the following graph:



Graph 4: Gas Turbine Taurus 60 - Performance graph. [RD08]

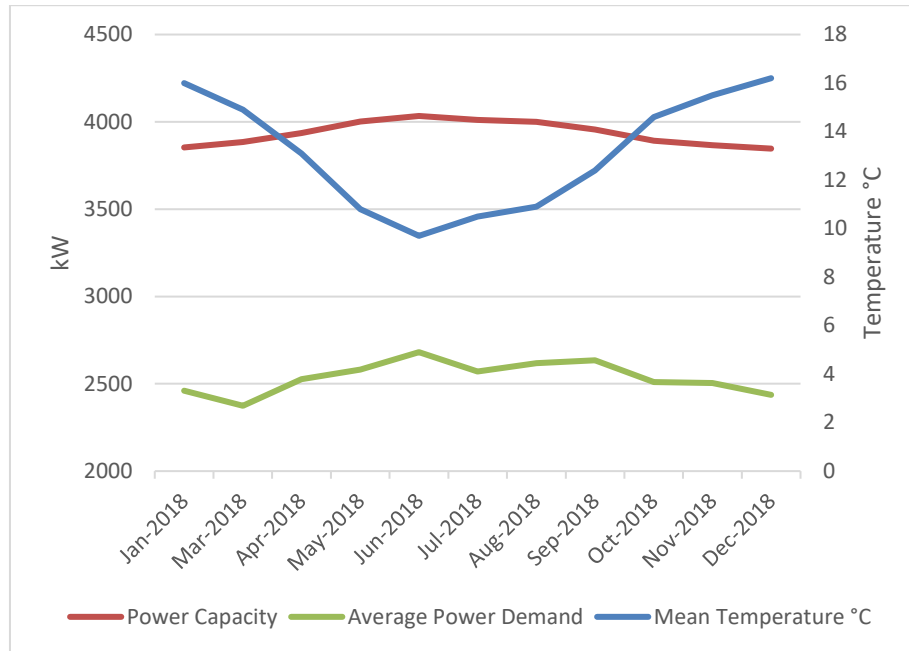
By polynomial interpolation we determine the following formula to determine Power Capacity of the turbine (at OSF altitude) for a given ambient temperature:

$$DPC = -0.0862T^2 - 36.034T + 4392.2$$

The average temperature at OSF during 2018 was 13.4°C.

- **De-rated Power Capacity (DPC)** of a GT at the average temperature: **3,920kW**

It's important to consider the effect of ambient temperature in the power capacity of the GTs given the fact that the power demand varies inversely proportional to the ambient temperature. The load profile determined in [RD03] clearly shows the high demand occurs between 10 pm and 7 am local time, and with lower ambient temperatures during these hours which implies a higher power demand of the boilers and HVAC system. The same applies for the power demand during the year, since the average power demand is higher during the coldest months and lower during the hottest months. The following graph shows the power capacity of the turbine due to ambient temperature¹, the monthly average ambient temperature and the monthly average power demand for 2018.



Graph 5: Effect of ambient temperature in Gas Turbines. [RD09]²

	Jan-18	Feb-18	Mar-18	Apr-18	May-18	Jun-18	Jul-18	Aug-18	Sep-18	Oct-18	Nov-18	Dec-18
Mean Temperature °C	16	15.9	14.9	13.1	10.8	9.7	10.5	10.9	12.4	14.6	15.5	16.2
Power Capacity [kW]	3852.5	3855.4	3884.1	3935.9	4002.0	4033.7	4010.7	3999.2	3956.0	3892.8	3866.9	3846.8
Average Power Demand [kW]	2460.9		2374.2	2527.3	2581.1	2681.1	2570.8	2617.9	2634.5	2509.2	2505.3	2436.9
Power Capacity minus Power demand [kW]	1391.6		1509.9	1408.6	1420.9	1352.5	1439.9	1381.3	1321.5	1383.6	1361.6	1409.8

Table 3: Power capacity of the turbine modified due to ambient temperature, monthly average ambient temperature, monthly average power demand, and the difference between power capacity and average power demand for 2018. February is not considered.

¹ The ambient temperature is measured by a meteorology station in Calama:

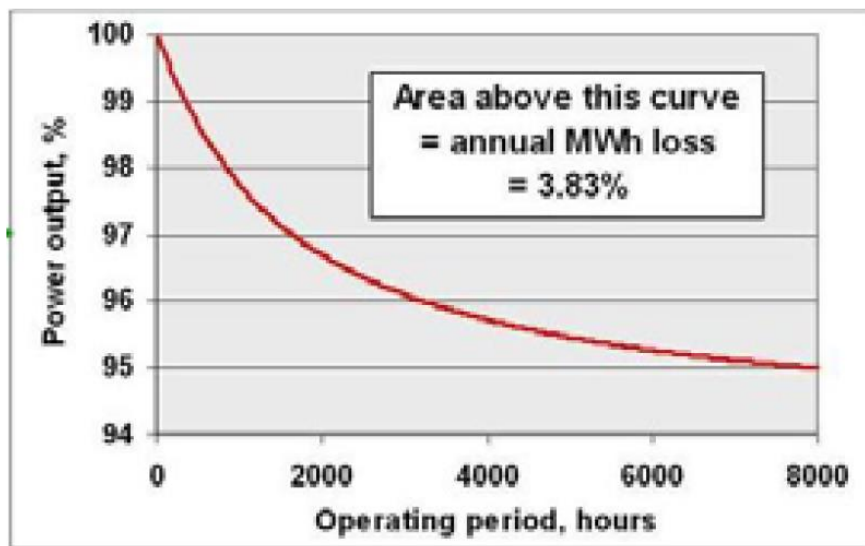
<https://climatologia.meteochile.gob.cl/application/index/procesaFormularioEstacionAno>

² The firsts five days of March, the AOS was power fed by local generators due to the yearly maintenance, this is the reason why the average power demand (which considers the whole month) has a lower value.

Note that the higher power demands due to lower temperatures and then the eventual reduction in spinning reserve (see Section 3.3.2) is almost fully compensated by the higher power capacity of the GT. Therefore, a higher average power demand in the coldest months is not a concern.

Fouling and wear

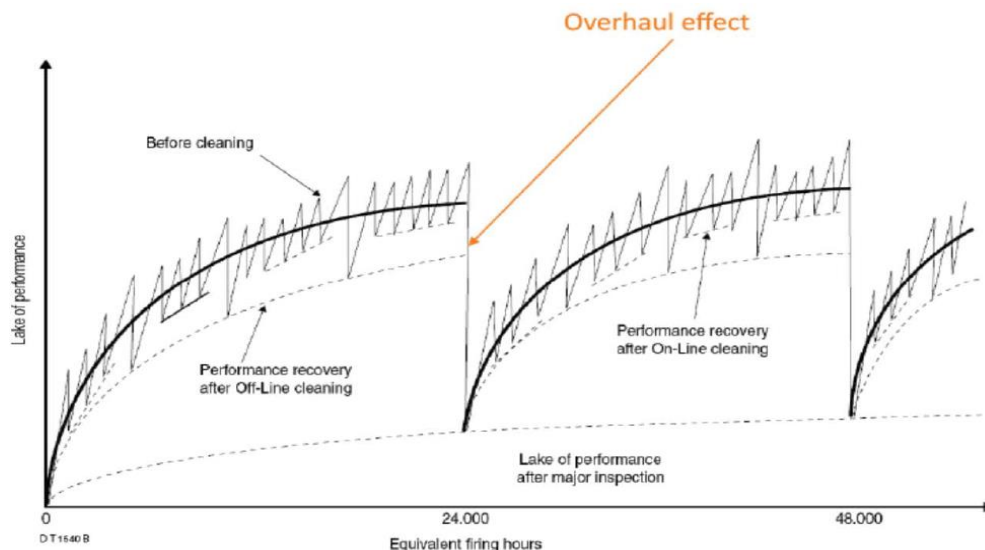
The fouling of axial flow compressors is a serious operating problem and its control is of critical importance to gas turbine operators. Foulants in the parts per million (ppm) range can cause deposits on blades, resulting in severe performance deterioration. The effect of compressor fouling is a drop in airflow and compressor isentropic efficiency, which results in a “rematching” of the gas turbine and compressor causing a drop in power output and thermal efficiency. Due to fouling a reduction in 5% of the power output of a GT is expected.



Graph 6: Effect of ambient temperature in Gas Turbines. [RD13]

This loss in power capacity is recovered by compressor washing, performed during the scheduled preventive maintenances. However, 100% is never recovered, and there is an accumulated loss which by the 30,000 hours (overhaul time) of operation can be ~ 10%.

The following graphic shows the accumulated loss in performance due the fouling and wear of the GT:



Graph 7: Effect of fouling and wear in Gas Turbines. [RD12]

On February 15th, 2019 the operational hours of the three ALMA GTs are the following:

- GT1 : 19,776 hours
- GT2 : 18,517 hours
- GT3 : 23,066 hours

The 30,000 hours of operation will be reached and the 10% of power capacity loss due to fouling must be considered. Since the de-rated power capacity of a GT at the average ambient temperature is 3,920kW, allowing for the 10% loss due to fouling gives:

- **De-rated Power Capacity (DPC) of a GT: 3,528 kW**

Inlet and exit losses

Another losses in the power capacity to consider are those due to the drop of pressure in the air inlet of combustion caused by the air filter, and also losses of combustion gasses.

These two losses have been determined for the GT Taurus 60 and are 0.98 and 0.99 respectively [RD12]. Therefore, the total De-rated power capacity is:

- **Total De-rated Power Capacity (DPC) of a GT: 3,423 kW**

4.3.2 Spinning Reserve

The need to maintain the balance between power supply and demand at all times, in order to compensate for the instantaneous imbalances produced by the natural variation of consumption or disturbances such as untimely disconnection of generation (flywheels) or consumption, determines the need to maintain at all times a quantity of spinning reserve, also called primary reserve. The spinning reserve is the primary regulation of power frequency (50 Hz) and in this way, maintains the balance between the power generation and the electric demand. In simple words, the spinning reserve is the unused capacity of the running GT which can be used instantly to supply increases in the power demand.

Two types of spinning reserve are identified, one of them to attend the instantaneous natural variations of the demand, and the other to restore the generation-demand balance provoked by the untimely disconnection of generation or consumption of the system. [RD14][RD15][RD16]

Currently, one running GT is sufficient to supply the whole ALMA observatory power demand (OSF and AOS), with enough spinning reserve available in case of increases in the power demand.

4.3.2.1 Spinning Reserve for random variations of the consumption

Method

The occurrence of random fluctuations in demand originates at all times of the day. There are consumptions that present important random fluctuations of their load, as electronic devices, lights or several other domestic characteristics.

Some load variations have a certain occurrence periodicity. For example, the consumption of the HVAC system increases directly with the decrease of the ambient temperature; this has a clear daily periodicity and also a clear monthly periodicity as seen in chapter 3.3.1.

We need to extract the random variations component from the demand. When there are no consumption records the recommended method uses the generation records because the power generation responds directly to the variations of the power demand. Defining:

$PInst_i$: Power generation data of the record “i”.

$PFilt_i$: Filtered power generation data of the record “i”, corresponds to the trend component of the demand.

$PRand_i$: Power generation data of random variations of the record “i”.

$PFilt_i$ is calculated as:

$$PFilt_i = \frac{\sum_{k=-L}^L PInst_{i+k}}{2L + 1}$$

The variable L corresponds to the period or mobile time window considered to extract the component corresponding to the lineal trend of the demand.

Then the random variation component of the demand is calculated as:

$$PRand_i = PInst_i - PFilt_i$$

where the $PRand_i$ values can be positive and negative, with an average close to zero.

The statistical value to be considered as power reserve to meet the untimely changes in demand used by the method in [RD10] will be such that the range considered contains 95% of the events. However, this method is for an interconnected system where several generators participate in the primary control of power frequency and the spinning reserve is prorated in all of them. This method also looks for a spinning reserve value which minimize the cost of operating at a lower capacity of the generators plus the cost of having some power outages at a respective cost of non-supplied energy. In the case of ALMA and considering only one GT in operation, the range considered will contain 100% of the events.

Results

Here we have considered a generation data with the following characteristics:

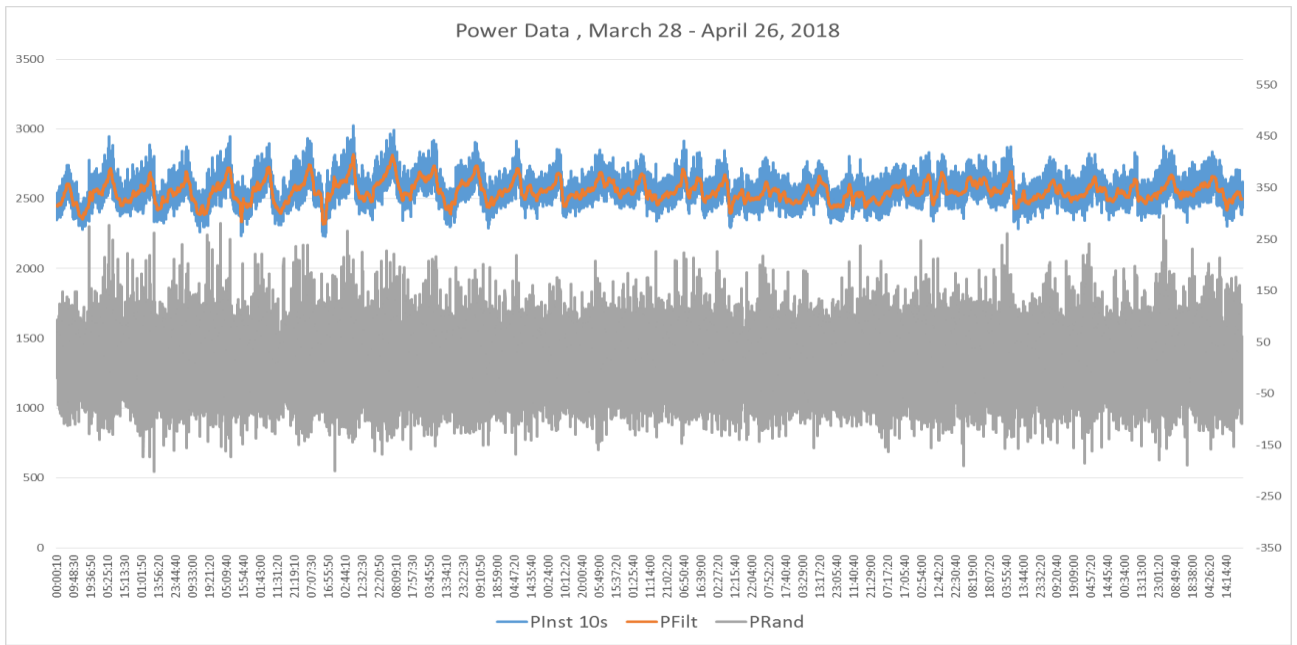
- Sampling rate of 10 seconds. This is the maximum resolution of the data stored in our GTs.
- Sampling period between March 28, 2018 and April 26, 2018.
- Generation records with power outages or with two GTs in operation or disconnection of loads due to maintenance have not been considered.

Power generation in this period varies as shown in Graph 5 where,

$PInst_{10s}$: power demand in [kW] with 10 seconds resolution. (Left axis)

$PFilt$: trend of power demand in a period of 30 minutes. (Left axis)

$PRand$: random variation component of the power demand. (Right axis)



Graph 8: Power records of ALMA (Local time) between March 28, 2018 and April 26, 2018.

PRand (Total period)	
Average, Max and Min values	Active Power kW
Max	296.50
Average	7.10
Min	-201.74
RSR	289.40

Table 4: Average, min and max values of instantaneous variations component of the power demand and RSR.

4.3.2.2 Spinning Reserve for periodic variations of the consumption

Method

We have periodic variations of power demand and most of them are due to the periodic variation of the ambient temperature as explained in section 3.3.1. These variations are mostly compensated by the increase in the power capacity of the GTs. Therefore, we need to extract the periodic variation which are not related to temperature variations.

The method is similar to the previous case. Here we will use the PFilt already calculated for one day and then compare it with the respective power capacity of the GT calculated according to the variation of the temperature. Then we will determine the difference between both.

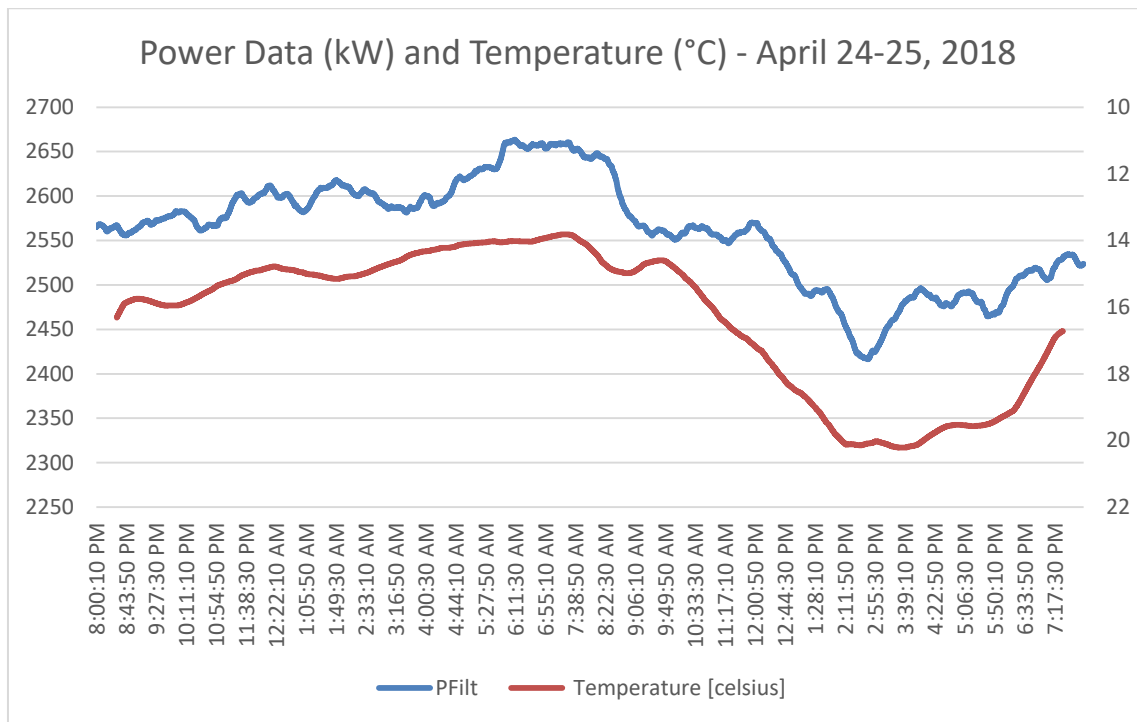
$$PPer_i = PCap_i - PFilt_i$$

Results

In the study we have considered a generation data with the following characteristics:

- 30 minutes trend of a sampling rate of 10 seconds.
- Sampling period between 8:00 PM (local time) of April 24th and 8:00 PM of April 25th, 2018.

The following graph shows the variation of the power demand and temperature in the indicated period.



Graph 9: Trend of Power Demand of ALMA (Local time) and Temperature.

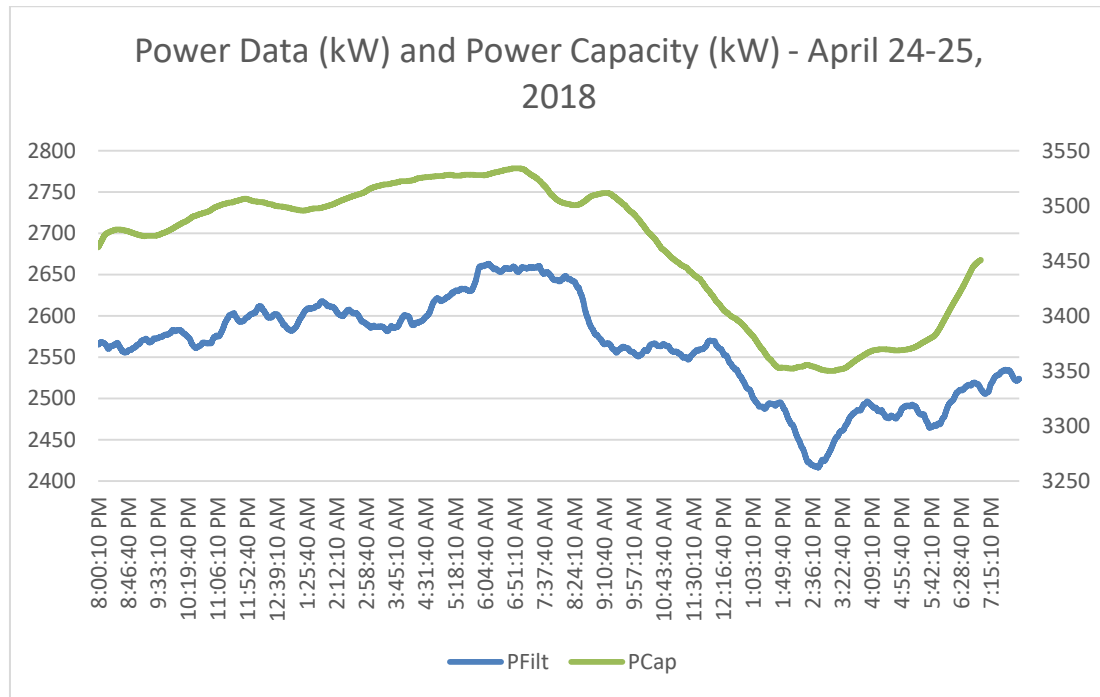
where,

PFilt : trend of power demand in a period of 30 minutes. (Left axis)

Temp : trend of temperature in a period of 30 minutes. (Right axis)

Note the high correlation between the power demand (left axis) and temperature (right axis). The values in right axis are in reverse order to see easily the correlation. Despite this correlation, there are changes in the power demand that are not related to the temperature and that were not filtered in the previous step. These changes could be periodic variations of some loads, e.g. some components of the HVAC system which in spite of working more when the temperature decreases, these components start and stop periodically. The same happens with air compressors which work to keep the pressure in a range and also start and stop periodically.

The following graph shows the variation of the power demand and power capacity (calculated in function of the temperature) between 8:00 PM (local time) of April 24th and 8:00 PM of April 25th.



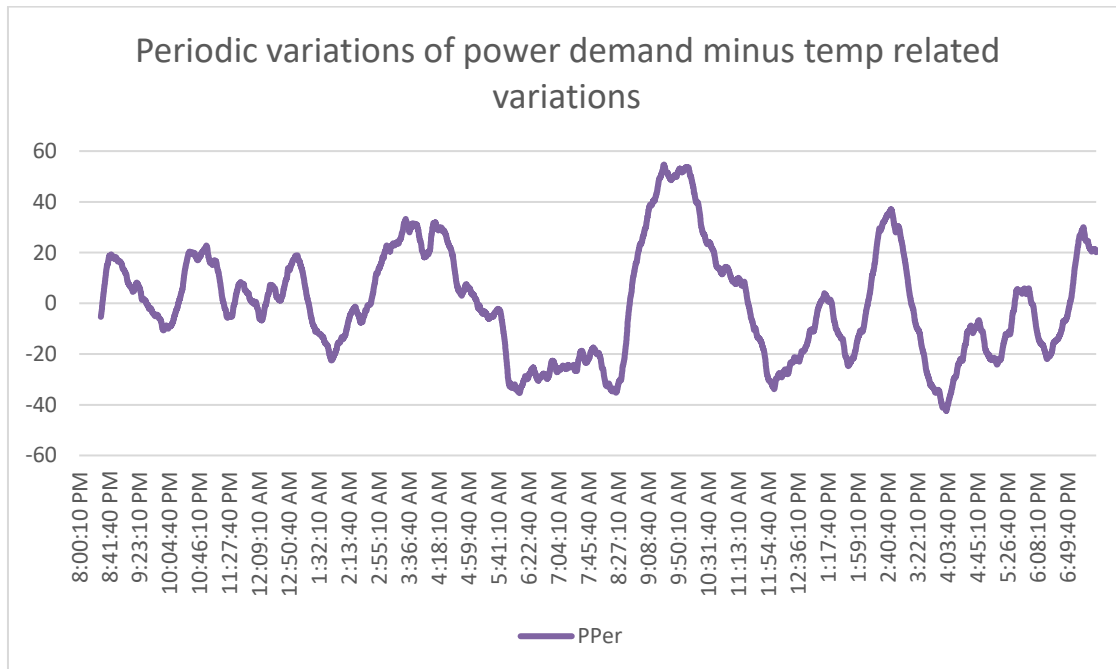
Graph 10: Trend of Power Demand of ALMA (Local time) and Power Capacity (due to temperature) of the GT.

The following graph shows the difference between PFilter and PCap.

where,

PFilter : trend of power demand in a period of 30 minutes. (Left axis)

PCap : power capacity of the GT according to temperature variation. (Right axis)



Graph 11: Difference of power capacity (due to temperature) of the GT and trend of power demand ALMA (Local time) minus temperature related power variations of the GT.

where,

PPer : Periodic variations of power demand minus temperature related variations.

PPer (Total period)	
Average, Max and Min values	Active Power kW
Max	54.66
Average	0
Min	-42.41
RSR	54.66

Table 5: Average, min and max values of periodic variations component of the power demand and RSR.

4.3.2.3 Spinning Reserve for power generation losses

We have only one source of generation, however, the UBT units (flywheels) behave as another generator. The UBTs work with a “Power Bridge” which store energy in order to absorb some transient peak of demand, improve the power quality, provide short circuit capacity to the grid, etc., and also supply power to the load (AOS antennas) when the power from the GTs is outside of a certain range of power quality by disconnecting the input breaker. When this happens, and the UBTs are connected back to the mains (GTs) they must recharge the energy of the power bridge; this recharging process demand around **200kW** from the GT. Therefore we need to consider an additional spinning reserve for disconnections (and then reconnection) of UBTs of **200kW**.

4.3.2.4 Total Requested Spinning Reserve

The total sum of RSR of random variations, periodic variations, and generation losses is 544kW. However this value just considers the spinning reserve required for the ALMA load. If we add additional load, this load will have also peaks which are unknown and could coincide in time with ALMA power demand peaks, so we consider an additional 10% of spinning reserve. Therefore, the RSR to consider is around 600kW:

$$\underline{\underline{\text{RSR} = 600 \text{ kW}}}$$

Please note this value is a worst case scenario in which the peaks of random and periodic power demand, and generation losses happens at the same time. Load profiles of new possible loads are unknown therefore its peaks shall be considered as if it would coincide in time with ALMA load peaks.

4.3.3 Average Power Generation

The following table shows the monthly energy generated for 2016, 2017 and 2018. To determine the available active power generation we will omit any consideration of the power use during the annual February maintenance shut-down, when many systems are turned off.

	Energy 2016 [kWh]	Energy 2017 [kWh]	Energy 2018 [kWh]
January	1,730,689	1,787,950	1,830,918
February	1,117,608	1,140,146	624,980
March	1,720,515	1,767,738	1,766,404
April	1,650,353	1,759,784	1,819,660
May	1,720,044	1,904,434	1,920,344
June	1,773,323	1,851,628	1,930,412
July	1,914,698	1,917,854	1,912,673
August	1,908,514	1,978,351	1,947,687
September	1,821,060	1,873,166	1,896,846
October	1,754,352	1,927,698	1,866,832
November	1,685,162	1,819,110	1,803,836
December	1,776,234	1,863,998	1,813,072
Total [MWh/year]	20,572.55	21,591.86	21,133.66
Power Average [kW] with February	2,349	2,465	2,413
Power Average [kW] without February	2,405	2,529	2,536

Table 6: Monthly energy generation - years 2016, 2017 and 2018. All the monthly data has been taken from [RD10]

The yearly power average including February of 2018 (**2,413 kW**) will be used only for costs calculation purposes¹. This is because the total generation costs in one year must consider the total energy generated by the GTs in that year. While to determine the available active power generation we will consider the yearly power average of 2018 excluding February (**2,536 kW**).

We need to consider the expected power consumption of the sport facility which is under construction and will add an additional average load of **43 kW** [RD17]. The HiL Simulator project will also increase consumption by an estimated 10 kW when it becomes operational ~2022. Then the total average power demand of ALMA to determine the available active power generation is **2,589 kW**.

4.3.4 Net Power Capacity

The De-rated Power Capacity (DPC) which will be used as nominal value to determine how much new load can be added, it's the one determined at the OSF geographical altitude, the average temperature of 2018, and the fouling and wear of the GTs (3,423 kW).

As a result, the Net Power Capacity of a GT, defined as the difference between the De-rated Power Capacity (DPC) of the GT and the Requested Spinning Reserve (RSR), is:

- **Net Power Capacity of a GT: = 2,823 kW**

Note this value above is in a yearly basis and must not be used for daily/monthly operational purposes but only for estimate how much new load (average) can be added. Quick load variations are supported

¹ The average power supplied during the February maintenance shutdown in 2018 and earlier years was significantly lower than the rest of the year because there was a period of about 2 weeks when the AOS loads were supplied from temporary diesel gensets at the AOS. This is not foreseen for future years and so the average consumption in February is expected to be similar to the rest of the year.

by the spinning reserve and slow load increases due to temperature decrease are covered by the corresponding power capacity increase.

As determined in Section 4.3.3, the ALMA load to consider is 2,589 kW. Therefore, the available active power generation in one GT, taking into account the ALMA load, and a RSR of 600 kW, is:

Available power capacity remaining in a single GT currently providing power to ALMA:

$$= \mathbf{234\ kW} \ (= 2823\ \text{kW} - 2589\ \text{kW})$$

This is the maximum power that remains available from a single GT at ALMA today. It includes no safety margin other than those already included in the RSR and generator de-rating. Further, it is important to note that this capacity is based on the expected ALMA power demands as known today, and does not consider any future expansion in ALMA capabilities resulting in more power demand e.g. correlator upgrade, more antennas, different cyro-coolers etc. Clearly, both in the case of expanded ALMA capabilities and in providing electric power to other observatories, the net power capacity of one GT may be exceeded in which case two GTs running simultaneously in a load sharing mode would be required.

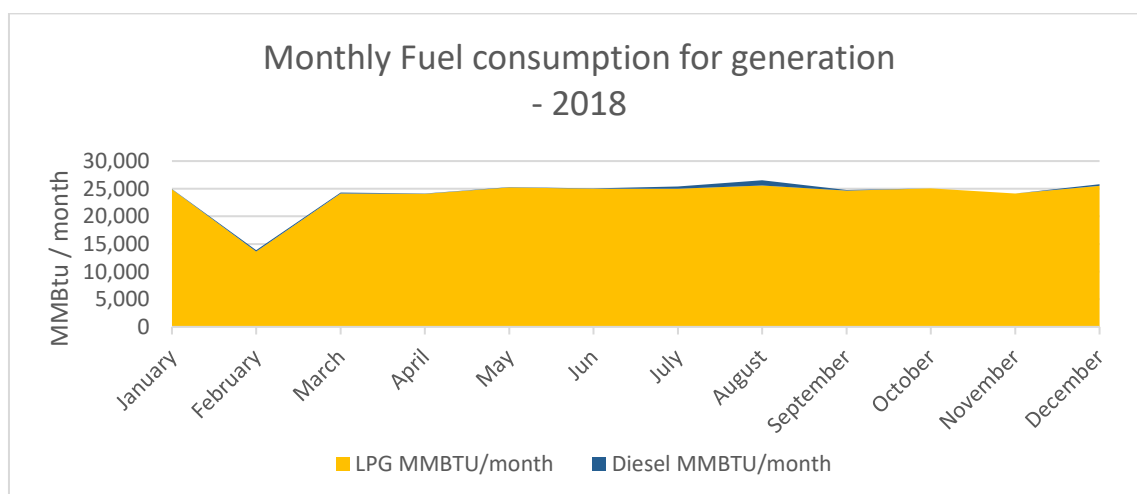
5 Heat Rate of the ALMA Gas-turbines

The Heat Rate is the amount of heat from the fuel (MMBtu) to produce a unit of energy (MWh). It's a measure of the efficiency of a power plant: the lower the heat rate the more efficient the GT in supplying power. Hence, the heat rate is an important consideration in calculating the cost of power generation.

The monthly fuel consumption in terms of energy for power generation is shown in the following table and graph. In general, the fuel consumption is flat; only February has an important difference due to the yearly maintenance of the observatory during this month.

Months	Monthly Generation [kWh]	Monthly Generation with LPG [kWh]	LPG [kg]	LPG [MMBtu]	Monthly Generation with Diesel [kWh]	Diesel [kg]	Diesel [MMBtu]	Total Fuel consumption [MMBtu]
January	1,830,918	1,829,592	524,363	22,574	1,326	572	25	22,599
February	624,980	620,266	287,053	12,358	4,714	5,246	229	12,587
March	1,766,404	1,760,252	508,373	21,886	6,152	4,222	184	22,070
April	1,819,660	1,817,728	506,488	21,805	1,932	1,786	78	21,883
May	1,920,344	1,918,982	531,215	22,869	1,362	1,647	72	22,941
June	1,929,082	1,924,618	526,735	22,676	4,464	1,370	60	22,736
July	1,912,237	1,901,585	526,851	22,681	10,652	9,151	399	23,081
August	1,946,345	1,926,025	538,913	23,201	20,320	21,611	943	24,143
September	1,851,396	1,845,116	518,655	22,329	6,280	3,849	168	22,497
October	1,866,832	1,866,832	527,229	22,698	0	0	0	22,698
November	1,803,836	1,803,240	508,535	21,893	596	250	11	21,904
December	1,813,072	1,806,356	538,001	23,161	6,716	2,223	97	23,258
TOTAL	21,085,106	21,020,592	6,042,411	260,132	64,514	51,927	2,265	262,397

Table 7: Power Generation and Fuel consumed for LPG and Diesel – 2018. Source: Own elaboration / data taken from IMG monthly energy reports (<https://jira.alma.cl/browse/IMG-31>)



Graph 12: Monthly energy consumption by the ALMA power plant – year 2018. Source: Own elaboration

The following are the energy equivalences used:

- LHV (LPG)¹ = 0.04305 MMBtu/kg
- LHV (diesel) = 0.04362 MMBtu/kg

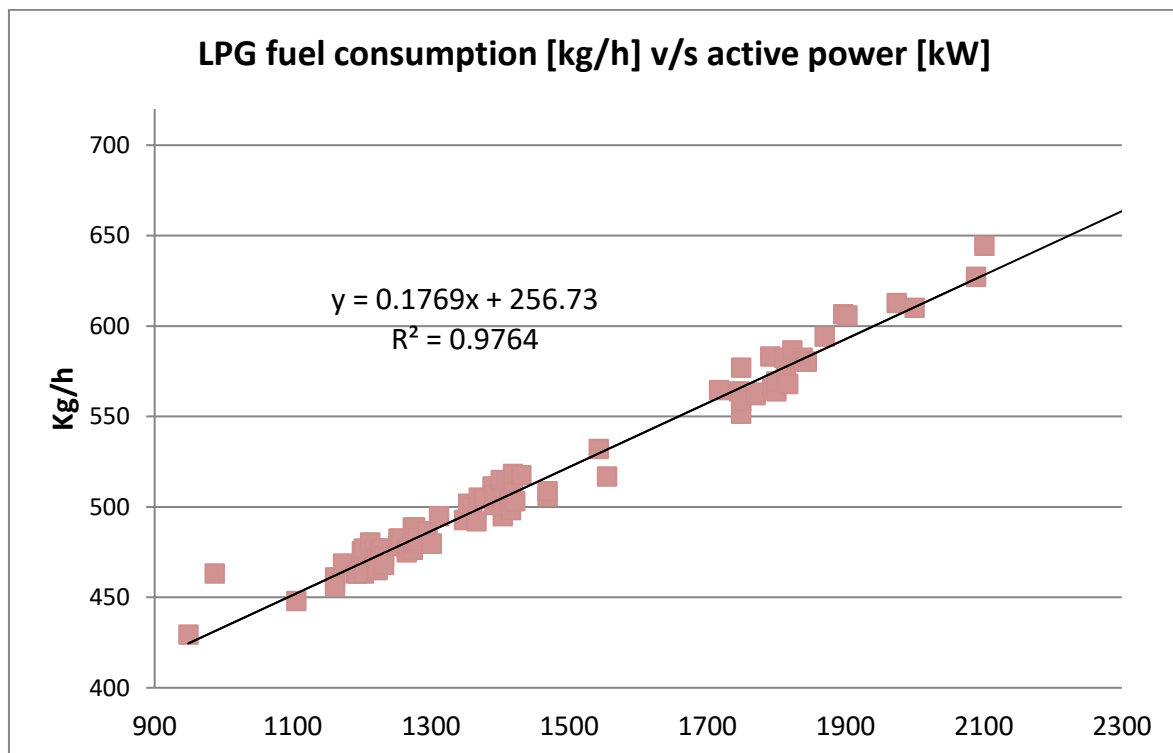
The average Heat Rate of 2018 is the total fuel consumption in MMBtu divided by the Total Energy generated in MWh. Then the average Heat Rate of the ALMA Power Plant for 2018 is the following:

Heat Rate (LPG)	
0.28542	kg/kWh
12.14559	MMBtu/MWh

Table 8: Average Heat Rate of ALMA Power Plant in 2018. Source: Own elaboration

The average heat rate above is of the power plant, which worked with two GTs in parallel some of the time, and therefore is not the case for 1 GT.

The Heat Rate with LPG of a single GT is determined from the following graph; LPG fuel consumption [kg/h] versus active power [kW].



Graph 13: LPG Fuel consumption v/s Active Power load of a GT.

The following graph shows the heat rate with LPG of an ALMA GT per active power load level.

First we need to convert the LPG fuel consumption [kg/h] to [MMBtu/h], to do that we multiply it by the LHV in [MMBtu/kg]. Then to have the heat rate (the amount of heat from the fuel (MMBtu) to produce a unit of energy (MWh)) we divide this value by the active power (P) in kW and multiply by 1000 in order to have the total value in MMBtu per MWh. This is:

¹ This value is informed by Lipigas in each invoice, however the variation is very low and can be considered fixed for the purpose of this study.

$$\text{LPG fuel consumption} \left[\frac{\text{kg}}{\text{h}} \right] = (0.1769 \times P + 256.73)$$

$$\text{LPG fuel consumption} \left[\frac{\text{MMBtu}}{\text{h}} \right] = (0.1769 \times P + 256.73) \times \text{LHV} \left[\frac{\text{MMBtu}}{\text{kg}} \right]$$

$$\text{Heat Rate} \left[\frac{\text{MMBtu}}{\text{MWh}} \right] = \frac{(0.1769 \times P + 256.73) \times \text{LHV} \times 1000}{P}$$

Therefore, the following formula has been determined to calculate the heat rate for one running GT:

$$\text{Heat Rate} \left[\frac{\text{MMBtu}}{\text{MWh}} \right] = \left(176.9 + \frac{256,730}{P} \right) \times \text{LHV},$$

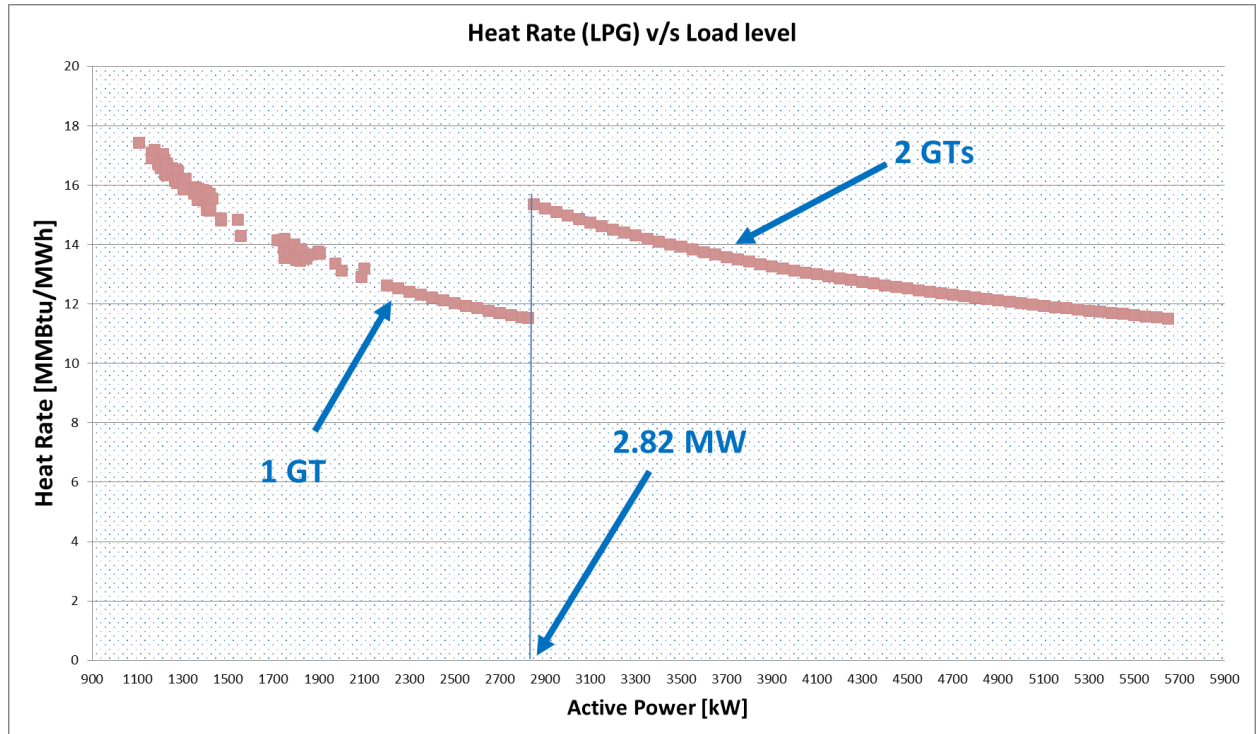
where,

P: load level of the power plant in [kW].

LHV: lower heating value in [MMBtu/kg], here we used 0.04305 MMBtu/kg

To obtain the formula for 2 GTs in load sharing mode, we just replace P by P/2, because the formula is in function of the total P of the plant.

$$\text{Heat Rate}_{2GT} \left[\frac{\text{MMBtu}}{\text{MWh}} \right] = \left(176.9 + \frac{513,460}{P} \right) \times \text{LHV},$$



Graph 14: Heat Rate (LPG) v/s Active Power load level for an ALMA GT. Source: Own elaboration

6 Average Cost of Power Generation

The average cost of power generation includes the following costs:

- Variable Costs:
 - Fuel (VFC)
 - Non-Fuel (VNFC)
- Fixed costs:
 - Staff

6.1 Variable Fuel Costs

The Variable Fuel Costs (VFC) are calculated as the multiplication of the Heat Rate by the unit cost of fuel. The following tables shows the LPG and diesel consumption and the energy produced during 2016, 2017 and 2018.

	2016						
	LPG		Diesel		Energy 2016	Monthly Cost	VFC 2016
	Kg	USD/Kg	Kg	USD/Kg	kWh	USD	USD/MWh
January	514,650	0.522	2,970	0.426	1,730,689	270,157	156
February	398,697	0.487	7,170	0.426	1,117,608	197,299	177
March	517,163	0.528	6,034	0.426	1,720,515	275,711	160
April	485,068	0.505	4,219	0.426	1,650,353	246,642	149
May	501,160	0.530	4,526	0.426	1,720,044	267,393	155
June	497,608	0.529	3,812	0.426	1,773,323	264,977	149
July	549,345	0.530	16,787	0.426	1,914,698	298,132	156
August	538,922	0.510	7,630	0.426	1,908,514	278,142	146
September	518,182	0.517	8,857	0.426	1,821,060	271,492	149
October	508,703	0.537	8,743	0.426	1,754,352	276,753	158
November	488,067	0.543	4,526	0.426	1,685,162	267,084	158
December	508,840	0.545	13,156	0.426	1,776,234	282,935	159

Table 9: Fuel consumption and energy generation and monthly VFC - year 2016

	2017						
	LPG		Diesel		Energy 2017	Monthly Cost	VFC 2017
	Kg	USD/Kg	Kg	USD/Kg	kWh	USD	USD/MWh
January	519,325	0.611	303	0.426	1,787,950	317,453	178
February	383,368	0.677	4,908	0.426	1,140,146	261,694	230
March	513,466	0.621	6,186	0.426	1,767,738	321,268	182
April	505,079	0.571	290	0.426	1,759,784	288,772	164
May	536,608	0.575	3,229	0.426	1,904,434	309,993	163
June	527,457	0.561	7,206	0.426	1,851,628	298,952	161
July	529,079	0.550	2,697	0.426	1,917,854	292,258	152
August	523,913	0.615	19,043	0.426	1,978,351	330,485	167
September	518,619	0.669	1,234	0.426	1,873,166	347,553	186
October	536,780	0.723	2,513	0.426	1,927,698	388,974	202
November	479,160	0.739	23,632	0.426	1,819,110	364,384	200
December	525,408	0.744	1,655	0.426	1,863,998	391,384	210

Table 10: Fuel consumption and energy generation and monthly VFC - year 2017.

	2018						
	LPG		Diesel		Energy 2018	Monthly Cost	VFC 2018
	Kg	USD/Kg	Kg	USD/Kg	kWh	USD	USD/MWh
January	524,363	0.734	572	0.426	1,830,918	524,363	210
February	287,053	0.692	5,246	0.426	624,980	287,053	322
March	508,373	0.720	4,222	0.426	1,766,404	508,373	208
April	506,488	0.660	1,786	0.426	1,819,660	506,488	184
May	531,215	0.713	1,647	0.426	1,920,344	531,215	198
June	528,735	0.713	1,370	0.426	1,930,412	528,735	196
July	526,851	0.715	9,151	0.426	1,912,673	526,851	199
August	538,913	0.738	21,611	0.426	1,947,687	407,009	209
September	518,655	0.786	3,846	0.426	1,896,846	409,362	216
October	527,229	0.784	-	0.426	1,866,832	413,342	221
November	508,535	0.664	250	0.426	1,803,836	337,551	187
December	538,001	0.600	2,223	0.426	1,813,072	323,821	179

Table 11: Fuel consumption and energy generation and monthly VFC – year 2018

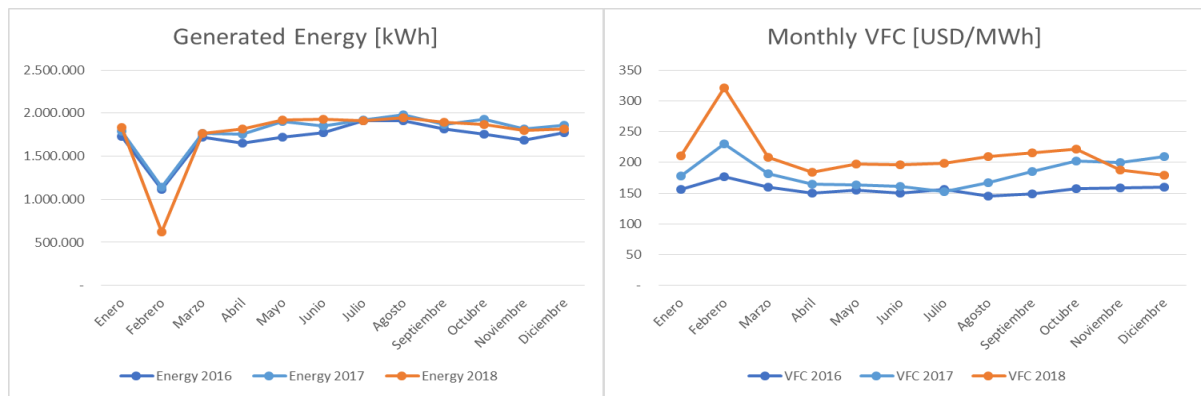
With the data from the tables above, we can calculate the average VFC for each of these years.

Year	Fuel Cost (USD)	Energy (MWh)	VFC (USD/MWh)
2016	3,196,718	20,573	155.38
2017	3,913,171	21,592	181.23
2018	4,317,823	21,134	204.31

Table 12: Fuel costs, energy generated and yearly VFC – 2016, 2017, 2018

The increases in the VFC each year are due to increasing fuel prices.

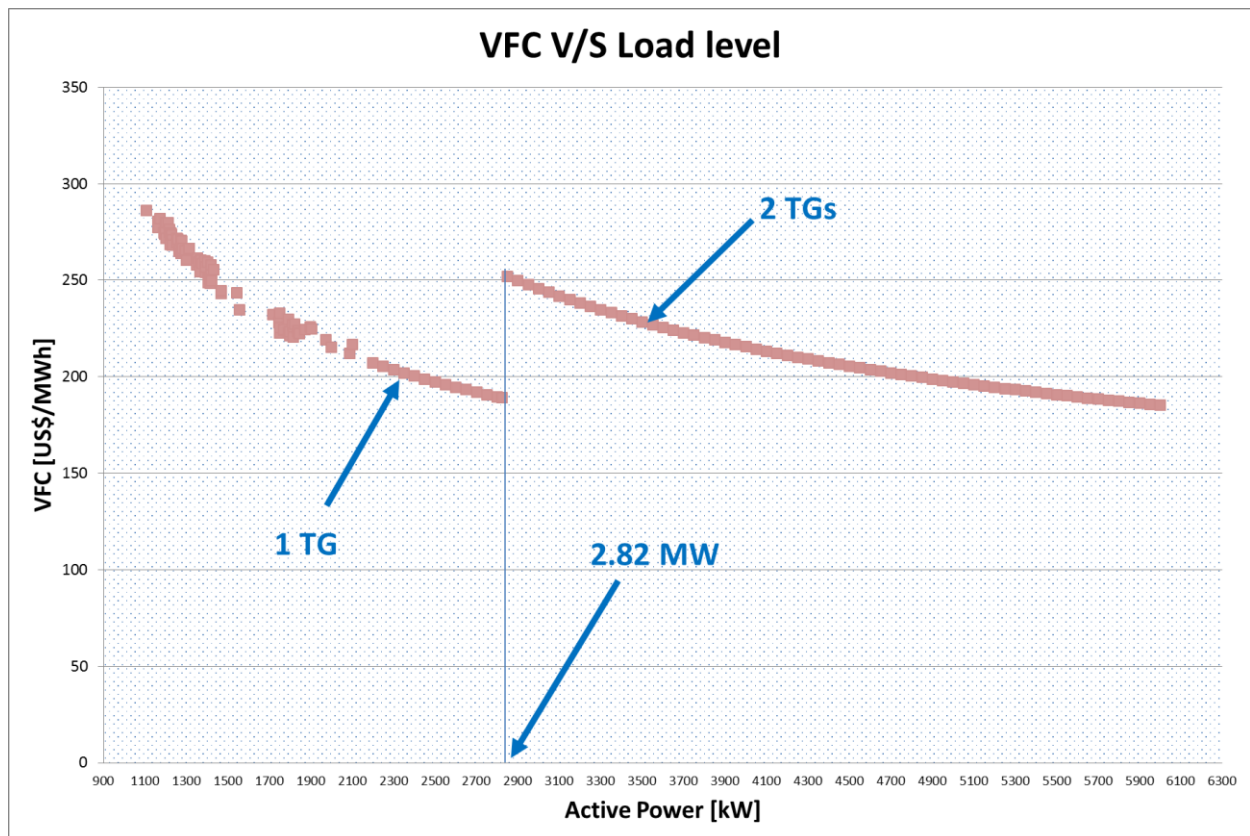
The following two graphs show the ALMA energy generation and the related from the data in the tables above, where it is evident that for a similar level of energy generation, the energy generation costs are higher due to higher fuel prices. Also evident is the increased costs in February due the low level of energy generation, and hence an increase in the heat rate (decrease in the efficiency) of the GTs.



Graph 15: Energy generated and generation costs for 2016, 2017 and 2018.

Since these values are monthly and annual averages, it is important to determine the variable fuel costs for different levels of power generation. Specially, there is interest of some non-ALMA projects in connecting to the ALMA network, and it is important to consider future ALMA expansions, such as the current construction of the sports center and others.

The Variable Fuel Cost [US\$/MWh] corresponds to the Heat Rate [MMBtu/MWh] multiplied by the fuel price [US\$/MMBtu]. The following graph shows the Variable Fuel Cost per load level for a fixed fuel cost of 16.41 [US\$/MMBtu] (average 2018 fuel price). The jump observed in the curve to the 2.82 MW of load is due to the fact that over this level, we must operate with two GTs, so the cost increases due to the higher heat rate of each GT running at a lower load level.



Graph 16: VFC (LPG) v/s Active Power load level for the ALMA. Source: Own elaboration

6.2 Variable Non-Fuel Costs (VNFC)

The VNFC are the costs of supplies like lubes and preventive maintenance (spares included) which are a function of the operational time of the GTs. The VNFC is calculated as the sum of Maintenance Variable Costs (MVC) and Operational Variable Non-Fuel Costs (OVNFC), namely:

$$VNFC = MVC + OVNFC$$

Maintenance Variable Cost (MVC): Variable Cost due to preventive maintenance activities on the GTs in order to ensure the operability of the machine over its life time, is driven by its time of use. This cost is due to the scheduled maintenance according to the following table, which shows the maintenance requirements as specified by the manufacturer.

The maintenance level I is performed with our own personnel and is considered a fixed cost. The maintenance levels A, B and IV (overhaul) are performed by the manufacturer according to the operational time of each GT, and hence the quantity of these maintenances are simply multiplied by the number of running turbines.

NIVEL		I	A	B	IV
TIPO DE INTERVENCIÓN		Mantenimiento de servicio	Mantenimiento intermedio	Mantenimiento principal	Revisión general
MES	1	X			Cada 30.000 Hasta 35.000 Horas de funcionamiento
	2	X			
	3	X			
	4	X			
	5	X			
	6	X	X		
	7	X			
	8	X			
	9	X			
	10	X			
	11	X			
	12	X		X	
TIEMPO NECESARIO		3 h	24 h	48 h	
PARADA TURBINA		0 días	3 días	6 días	8 días

Figure 1: Maintenance Program GT Taurus 60 Source: in the GT Taurus 60 operation and maintenance manual

Operational Variable Non-fuel cost (OVNFC): Variable Cost due to related actions with the power generation of a GT, from the purchase of supplies which is a function related to the power generation quantity. It is considered as OVNFC for those supplies (electrical, mechanical or chemical) that are consumed, added, or replaced during the power generation process (filters, lube, hoses, valves, diaphragms, cleaning products, etc.).

6.2.1 MVC calculation

The MVC is calculated with the following formula:

$$MVC = \frac{PVC}{PVE}$$

where PVC is the present value of cost flow, and PVE is the present value of energy flow.

The PVC is calculated by the following formula:

$$PVC = \sum_{i=1}^{Nm} \frac{C_i}{(1+r)^{M_i}}$$

$$r = (1+a)^{\frac{1}{12}} - 1$$

where:

- C_i : the corresponding cost to the i-th Preventive Maintenance, expressed in USD.
- a : the update rate indicated in letter d) of article 165° from the “*Ley General de Servicios Eléctricos*” and is equal to 10% real.
- r : the monthly interest rate.
- M_i : accumulated time expressed in chronologies months from the beginning of the maintenance cycle to the i-th Preventive Maintenance.
- Nm : Number of preventive maintenance that includes the maintenance cycle,

and where:

$$M_i = \frac{HO_i}{\left(\frac{8760}{12}\right) * f_d} ,$$

with:

- HO_i : the hours of operation of the GT to the i-th maintenance.
- f_d : the availability factor of the GT.

Given that ALMA has a total of three GTs, and operate with only one almost all of the time, and the operation of the three GTs is interchanged to keep the hours of operation at a similar level between each of them, the value of the availability factor is 1/3. The remaining 2/3 of the time when the GTs are not running includes the time for programed maintenance and downtime due to failures.

We calculate the value of M_i for the four levels of maintenance defined by manufacturer:

Maintenance level	I	A	B	IV
Periodicity (months)	1	6	12	44.44
HO_i (hours)	720	4,000	8,000	32,000
M_i	2.96	16.44	32.88	131.51

Table 13: Chronologic months of the maintenance cycle

The manufacturer proposes between 30.000 to 35.000 hours for the *overhaul*, or maintenance level IV; ALMA has chosen to use a value of 32.000 hours.

The maintenance of level I is performed monthly in a fixed way, without consideration of operational hours and therefore is a fixed cost and won't be considered in calculation of the VNFC.

Hence we can calculate the PVC for 2018, as follows, note that in case we use 2 GTs instead of 1 the accumulated time between maintenances (M_i) is the half:

Maintenance level	A	B	IV
Periodicity (months)	6	12	44.44
HO _i (hours)	4,000	8,000	32,000
M _i (1 GT)	16.44	32.88	131.51
M _i (2 GTs)	8.22	16.44	65.75
C _i (US\$)	\$ 24,143.13	\$ 151,329.38	\$ 1,500,000
PVC _i (US\$) (1 GT)	\$ 21,188.06	\$ 116,551.70	\$ 527,804.14
PVC _i (US\$) (2 GTs)	\$ 22,617.38	\$ 132,806.99	\$ 889,778.74
PVC (US\$) (1 GT) ¹			\$ 665,543.90
PVC (US\$) (2 GTs) ²			\$ 1,045,203.11

Table 14: PVC calculation for 1 and 2 GTs

The PVE is calculated by the following formula:

$$PVE = \sum_{i=1}^{Nm} \frac{E_i}{(1+r)^{M_i}}$$

where:

PVE: present value of the energy flow.

E_i: the energy generated between the i-th preventive maintenance and his antecessor i-1, applying the following formula.

$$E_i = P_{average} \cdot (HO_i - HO_{i-1}) ,$$

where

P_{average}: the average power of the plant in MW, which for ALMA in 2018 was 2.413MW.

Hence, the PVE for 2018 can be calculated.

Maintenance level	A	B	IV
Periodicity (months)	6	12	44.44
HO _i (hours)	4,000	8,000	32,000
M _i (1 GT)	16.44	32.88	131.51
M _i (2 GTs)	8.22	16.44	65.75
E _i (MWh) 1 GT	9,652	9,652	57,912
E _i (MWh) 2 GTs	4,826	4,826	28,956
PVE _i (MWh) 1 GT	8,470.62	7,433.83	20,377.46
PVE _i (MWh) 2 GTs	4,521.02	4,235.31	17,176.29
PVE (MWh) 1 GT			36,281.91
PVE (MWh) 2 GTs			25,932.61

Table 15: PVE calculation

With PVC and PVE as calculated above, the MVC for one GT is:

¹ This is the present value of costs of one GTs when it is running alone

² This is the present value of costs of one GTs but when two are running in parallel all the time

$$MVC = 18.34 \left[\frac{US\$}{MWh} \right]$$

The value above is the cost of one GT, the total cost of the three GTs is three times this value, namely 55.03 US\$/MWh.

6.2.2 Calculation of OVNFC

The OVNFC it's calculated with the following consumption function:

$$OVNFC = \sum_{supply\ i=1}^n r_i \times c_i ,$$

where:

- r_i : the consumption of the i-th supply per unit energy generated (gal/MWh, m³/MWh, liters/MWh, etc.)
- c_i : the unit cost of the i-th supply (USD/gal, USD/m³, USD/liters, etc.)

However, we have simplified this calculation by taking the total spent by ALMA in 2018 on all supplies for the GT that are directly related with energy production. The value for 2018 was around US\$336,000. This value was reached using one GT most of the time, then we can assume that for two running GTs in load sharing mode the whole year, the amount to spent would be the double, namely US\$672,000. Dividing by the total energy generated in the year 2018 (21,134 MWh), we have the OVNFC:

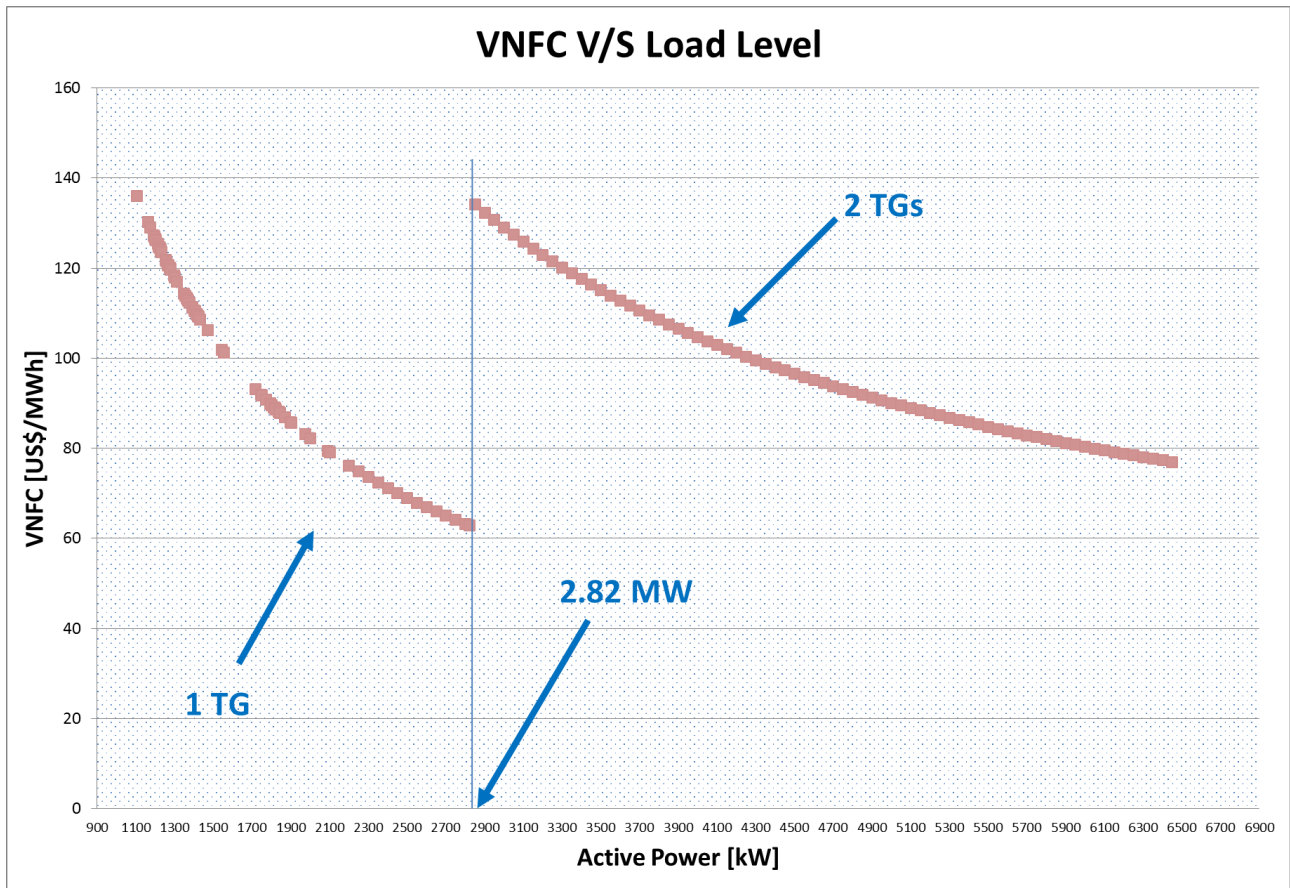
$$OVNFC = 15.90 \left[\frac{US\$}{MWh} \right]$$

6.2.3 Calculation of VNFC

Finally, now with the MVC and OVNFC, the VNFC for 2018 was:

$$VNFC = MVC + OVNFC = 70.93 \left[\frac{US\$}{MWh} \right]$$

Since this value is for an average power of 2.413 MW, and as the case of the VFC, we have determined the curve of the VNFC per load level (see following graph). The jump that is observed in the curve to the 2.82 MW of load is due to the fact that at this level we must operate with two GTs, and therefore the maintenance expenditure almost doubles, as does the supplies and spare parts.



Graph 17: VNFC (LPG) v/s Active Power load level for ALMA. *Source: Own elaboration*

6.3 Calculation of the Variable Cost

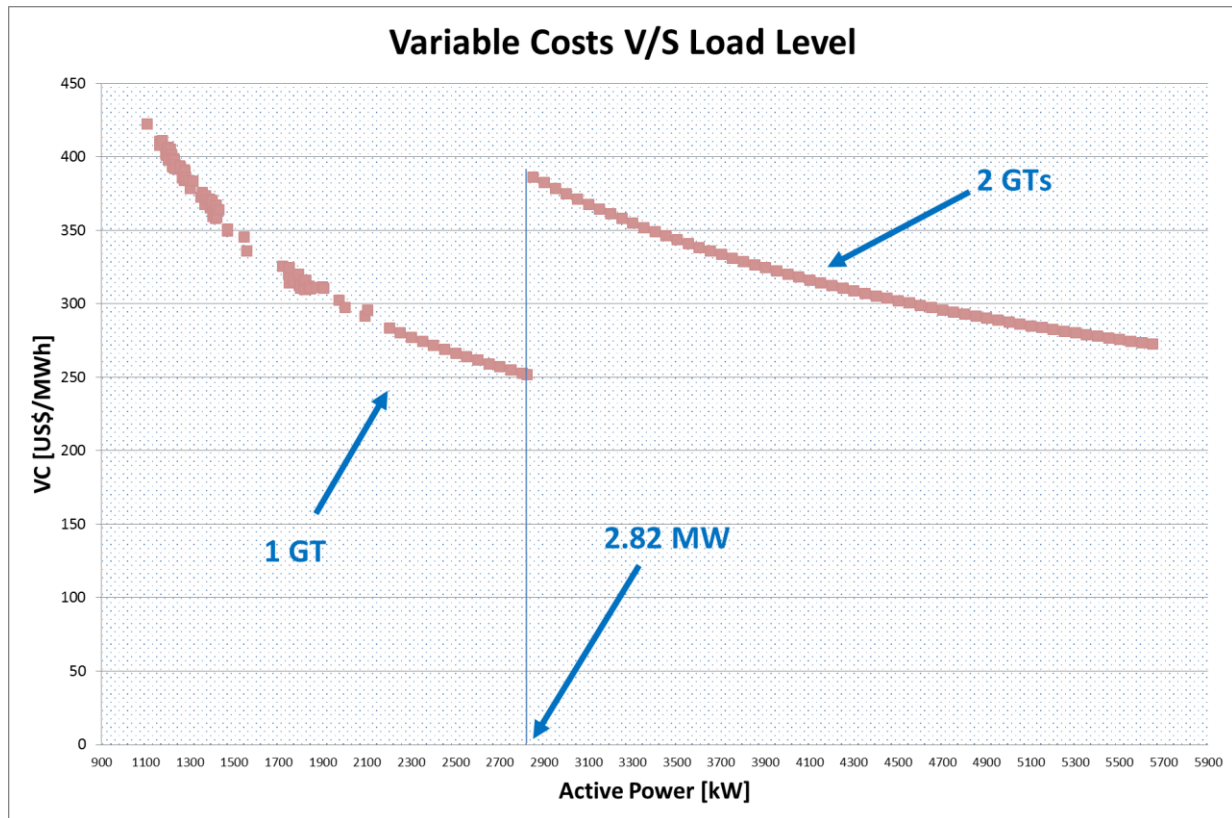
Given we have VFC and VNFC, we can calculate the variable cost (VC) which is the sum of both:

$$VC = VFC + VNFC$$

The value of VFC is the average of 2018, then variable cost is the average variable cost of 2018:

$$VC (2018) = 275.24 \left[\frac{US\$}{MWh} \right]$$

However, the VC changes with the load level. The following graph shows how VC change per load level.



Graph 18: VC (LPG) v/s Active Power load level for ALMA. Source: Own elaboration

6.4 Fixed Cost

The fixed costs (FC) related to power generation for 2018 were US\$570.000. Given the yearly energy generated which was 21,134 MWh in 2018, we have the fixed costs in US\$/MWh.

$$\text{Fixed Cost}(2018) = 26.97 \left[\frac{\text{US\$}}{\text{MWh}} \right]$$

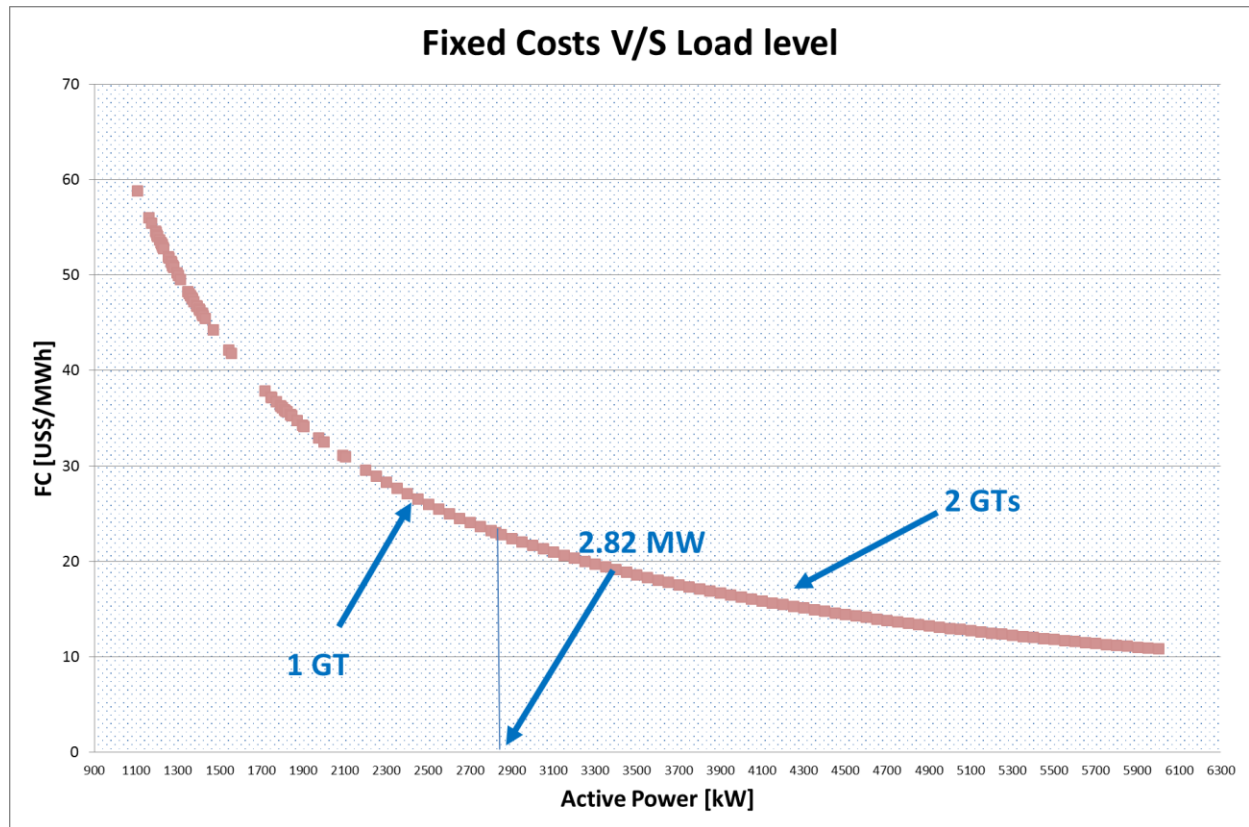
In the case where the power generated is different then the fixed cost per MWh can be calculated using this formula (8760 operating hours per year).

$$\text{Fixed Cost} = \left(\frac{570,000}{P \cdot 8.760} \right) \left[\frac{\text{US\$}}{\text{MWh}} \right] = \left(\frac{65,068}{P} \right) \left[\frac{\text{US\$}}{\text{MWh}} \right]$$

where,

P: average load level of the GT in [kW].

The following graph shows how FC change per load level.



Graph 19: FC v/s Active Power load level for ALMA. Source: Own elaboration

As seen in the above graph, this annual cost is independent of the number of turbines in operation.

6.5 Calculation of the Average Cost of Generation

Finally, we have the Average cost of Generation (ACG) for 2018 which is the sum of variable costs plus fixed costs:

$$ACG_{1GT} = 302.21 \left[\frac{US\$}{MWh} \right]$$

This was the average cost of generation for ALMA in 2018.

7 Calculation of the electric energy price to non-ALMA projects

A principle constraint on providing energy to non-ALMA projects is the price at which ALMA must sell its electric energy has been determined in order the cost that ALMA pays currently (the ACG determined in chapter 5) will not change due to the new costs related to sell Electric Energy to the CWG. This price will consider only the generation costs and will not consider any kind of profits nor investment costs.

One of the most important matters which affects the energy price, is the amount of GTs that must run simultaneously.

The following values are common for both cases, 1 GT and 2 GTs running in load sharing mode:

- Fixed Costs:

$$\text{Fixed Cost} = \left(\frac{570,000}{P \cdot 8.76} \right) \left[\frac{\text{US\$}}{\text{MWh}} \right]$$

7.1 One GT in operation

In this case, the energy price (EP) is exactly the ACG, which is calculated as the Variable Fuel Costs plus Variable non-fuel costs plus fixed costs.

$$EP \left[\frac{\text{US\$}}{\text{MWh}} \right] = VFV + VFNC + FC$$

In section 5.1 (6.1) we saw that the VFC is the Heat Rate multiplied by the fuel price (FP).

$$VFC \left[\frac{\text{US\$}}{\text{MWh}} \right] = \text{Heat Rate} \times \text{Fuel Price}$$

As seen in Section 5, the heat rate comes from the formula obtained by linear interpolation of the LPG fuel consumption graph 13, which came from real records taken from the GTs. The heat rate is LPG fuel consumption in [MMBtu/h] divided by active power in [MW], the heat rate is,

$$\text{Heat Rate} \left[\frac{\text{MMBtu}}{\text{MWh}} \right] = \left(176.9 + \frac{256,730}{P} \right) \times LHV,$$

Therefore, the VFC is:

$$VFC \left[\frac{\text{US\$}}{\text{MWh}} \right] = \left(176.9 + \frac{256,730}{P} \right) \times LHV \times FP$$

Therefore, the formula to calculate the energy price in case of one running GT is:

$$EP \left[\frac{US\$}{MWh} \right] = \text{Heat Rate} \times FP + VNFC + FC$$

And replacing we have:

$$EP \left[\frac{US\$}{MWh} \right] = \left(176.9 + \frac{256,730}{P} \right) \times FP \times LHV + VNFC + \frac{570,000}{P \cdot 8.76}$$

where:

- EP: energy price in [US\$/MWh], also ACG for 1 running GT.
- P: average active power load level in [kW].
- FP: fuel price paid by ALMA in [US\$/MMBtu].
- LHV: lower heating value in [MMBtu/kg].
- VNFC_{1GT}: Variable non-fuel costs in [US\$/MWh] determined with the method detailed in Section 6.2 for one GT.

For example, for an average load level of 2600 [kW], with a fuel price of 16.41 [US\$/MMBtu] and a LHV of 0,043051 [MMBtu/kg] the energy price is 286.73 [US\$/MWh]. Which price structure would be:

EP Structure	US\$/MWh	%
VFC	194.73	67.92%
VNFC	66.97	23.36%
FC	25.03	8.73%
Total	286.73	100%

Table 16: EP Structure for 2600kW.

Therefore, the energy price for the CWG in this example would be:

$$\text{Energy Price} = 286.73 \left[\frac{US\$}{MWh} \right]$$

7.2 Two GTs simultaneous in load sharing mode

In this case, different energy prices will be charged to ALMA and the external projects. The principle is that ALMA will be charged the same price as if there were no external projects drawing power and that the external projects will have to carry the increased costs due to the need to operate two turbines.

The following formula was determined to calculate the ACG in case of two running GT in load sharing mode:

$$ACG_{2GT} \left[\frac{US\$}{MWh} \right] = \left(176.9 + \frac{513,460}{P} \right) \times FP \times LHV + VNFC + \frac{570,000}{P \cdot 8.76}$$

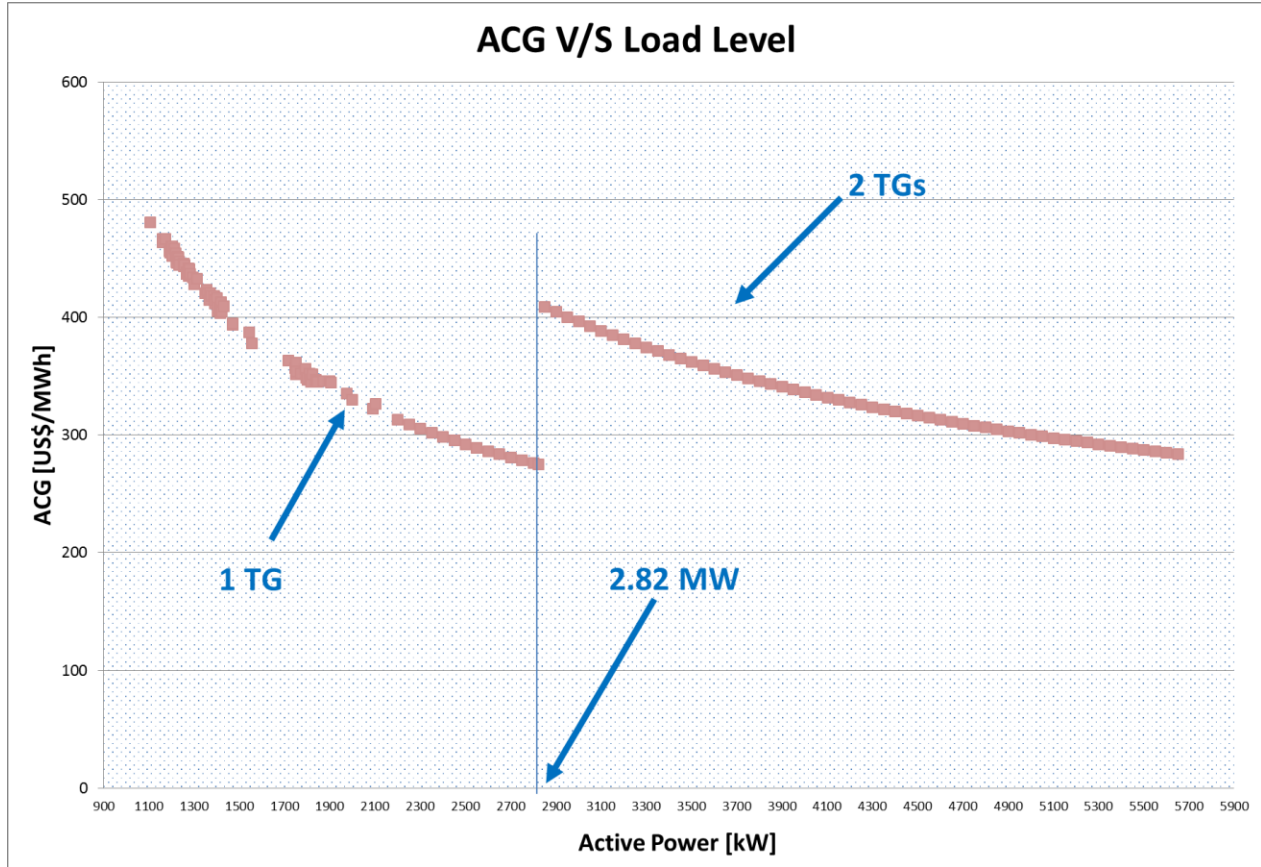
where:

- ACG_{2GT}: average cost of generation in [US\$/MWh] with two GTs sharing the load.
- P: average active power load level in [kW].
- FP: fuel price paid by ALMA in [US\$/MMBtu].

LHV: lower heating value in [MMBtu/kg].
 VNFC: Variable non-fuel costs in [US\$/MWh] determined with the method explained in Section 6.2 for two running GTs in load sharing.

This is the cost of generating power that needs to be covered if the power consumption exceeds the capacity of a single turbine and as long as the total load does not exceed the capacity of two turbines.

The following graph shows how the ACG change per load level.



Graph 20: ACG v/s Active Power load level for ALMA. The points below ~2.2 MW are based on actual fuel consumption, the curve above 2.2 MW is an extrapolation based on the measured data. The break in the curve at 2.82 MW corresponds to the power level above which 2 turbines are needed. Source: Own elaboration

However, the ACG_{2GT} is not the energy price for external projects since the energy price for non-ALMA projects must compensate the increase in the costs for ALMA. Therefore, the energy price is calculated with the following formula.

$$EP_{2TG} \left[\frac{US\$}{MWh} \right] = \left(\frac{ACG_{2TG} \times P_{Total} - ACG_{1TG} \times P_{ALMA}}{P_{CWG}} \right)$$

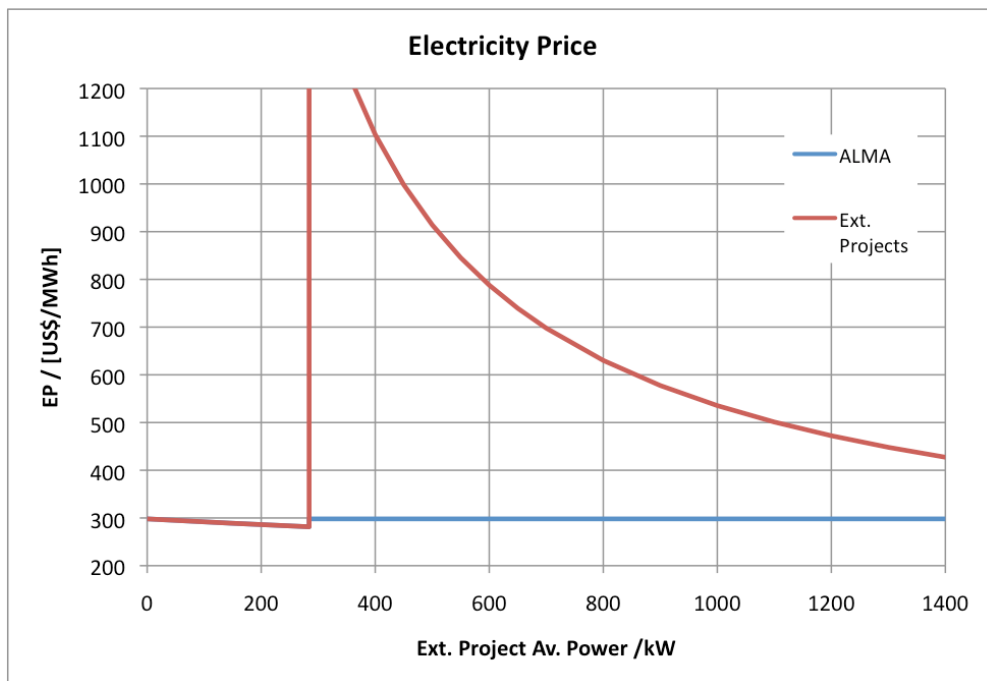
where:

EP_{2GT} : energy price to external projects in [US\$/MWh]
 ACG_{2GT} : average cost of generation in [US\$/MWh] with two GTs sharing the total load.
 ACG_{1GT} : average cost of generation in [US\$/MWh] calculated with the formula for 1 running GT (chapter 7.1), and considering only the load of ALMA.
 P_{ALMA} : ALMA average active power load level in [kW], which can be supplied with 1 GT.
 P_{CWG} : CWG average active power load level in [kW].
 P_{Total} : total average active power load level in [kW].

For example, supposing that ALMA has a load level of 2600 [kW], with a fuel price of 16.41 [US\$/MMBtu] and a LHV of 0,043051 [MMBtu/kg], the ACG_{1GT} is 286.73 [US\$/MWh]. Then we connected to ALMA grid several non-ALMA projects (CWG) with an average load of 800 [kW], which increases the total average load to 3400 [kW], which means run with two GTs. Then the ACG_{2GT} would be 368.41 [US\$/MWh].

Using the previous formula, the energy price for external projects would be 633.88 [US\$/MWh]. ALMA would pay the single-turbine energy price, ACG_{1GT} , which is 286.73 [US\$/MWh] in this example.

The following graph shows the electricity price for ALMA and external, non-ALMA projects as a function of external project power consumption plus a fixed ALMA consumption at the average 2018 level of 2.41 MW (Section 4.3.3) and with fuel and other costs at the 2018 levels. Below an average external project load of 0.29 MW, corresponding to a combined load of 2.82 MW, the two prices are identical. Above the 1 turbine limit, the price to ALMA reverts to the value for a single turbine with no external, non-ALMA loads whereas the price to external, non-ALMA projects increases substantially to cover fully the cost of operating the second turbine.



Graph 21: Electricity price for ALMA and external projects as a function of external projects load based on ALMA's 2018 average consumption of 2.41 MW (Section 4.3.3) and the generation costs from 2018 (see Section 6.5).

8 Chajnantor Working Group

In the Chajnantor area, the following non-ALMA projects have expressed interest in purchasing power from ALMA; these are members of the Chajnantor Working Group (CWG)¹:

- ASTE (Atacama Submillimeter Telescope Experiment)
- ACT (Atacama Cosmology Telescope)
- LCT (Leighton Chajnantor Telescope)
- CLASS (Cosmology Large Angular Scale Surveyor)
- SO (Simons Observatory)
- PolarBear
- CCAT-prime (Cerro Chajnantor Atacama Telescope)
- TAO (Tokyo Atacama Observatory)
- NANTEN2

The power consumptions of these observatories estimated by them as of June 2018 are listed in the following table. From this it can be concluded that only the combined load of ASTE and NANTEN2 is certainly less than the available capacity with a single turbine. It can also be concluded that two turbines have sufficient capacity to support the combined loads of ALMA with all the listed projects at the Chajnantor site.

<i>Project</i>	<i>Construction</i>	<i>Average Demand [kVA]</i>	<i>Maximum Demand [kVA]</i>
Simons Obs., ACT, PolarBear & CLASS ²	2018 – 2020	<500	500
TAO	2017 – 2019	125	150
CCAT-Prime	2019 – 2021	215	350
LCT	2018 – 2019	<300	300
ASTE, NANTEN2	operation	74	100
<i>Total</i>		<i>1414</i>	<i>1600</i>

Table 17: Non-ALMA projects. Average and maximum power demand estimated.

Source: <https://wikis.alma.cl/bin/view/ALMASafety/AgendaCWG2018>

Note 1: Simons Observatory is proceeding with implementing its own generating plant.

Note 2: CCAT-prime and TAO are jointly seeking power from ALMA so the combined average consumption is expected to be 340kW and the worst-case maximum demand is 650kW.

¹ Some of these observatories are already in operation, and generate electric power from their own local gensets.

² ACT, PolarBear y CLASS are already in operation. The SO will be located in the same site of the other 3 observatories, and are considered as a single load.