COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

MÁSTER UNIVERSITATIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

ANALYZING THE IMPACT OF SPOT AND RESERVE PRICE UNCERTAINTY INOPTIMIZATION MODELS FOR COMBINED CYCLE GAS TURBINES CONSIDERING FATIGUE

Autor: Carlos Escribano Delgado

Director: Sonja Wogrin

Co-Director: Andrés Ramos Galán

Madrid

Agosto de 2020

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Fdo.: Carlos Escribano Delgado   Fecha: 21/08/2020

Autorizada la entrega del proyecto

Fdo.: Sonja Wogrin, Andrés Ramos   Fecha: 23/08/2020

Resumen

Este documento contiene un análisis de sensibilidad para el modelo de optimización que minimiza los costes de operación de una central de gas de ciclo combinado considerando los efectos de la fatiga e introduce tres nuevos modelos que, basados en el de minimización de costes, tienen el objetivo de maximizar los beneficios y añadirle estocasticidad a ambos enfoques.

Históricamente el efecto de la fatiga sobre los ciclos combinados ha sido ignorado, pero con la creciente penetración de fuentes de energía renovable en el sistema comenzará a tener un mayor impacto: las plantas (y en particular los ciclos combinados, que tienen gran flexibilidad) serán forzadas a realizar encendidos y apagados con mayor frecuencia para compensar la variabilidad en la generación de las renovables. Esto implica que las plantas son sujetas a mayores cargas de fatiga, que por lo tanto estas deben comenzar a ser estudiadas.

El primer modelo matemático en el que esto ha sido incluido ha sido desarrollado por Wogrin et al. en [1]. A través de una colaboración entre el Instituto de Investigación tecnológica (IIT) y la empresa Innomerics se realizó un estudio sobre los efectos de la fatiga en una central de ciclo combinado, que permite su modelado matemático, al menos como aproximación a sus valores reales. Este modelado matemático de la fatiga dio sus frutos al realizarse el modelo contenido en [1], un modelo cuyo objetivo es minimizar los costes de operación de una planta de ciclo combinado.

La primera parte del documento explica cómo funciona el modelo de minimización de costes descrito en [1] e incluye un análisis de sensibilidad a la demanda y los costes de combustible y operación y mantenimiento.

A grandes rasgos, el modelo de minimización de costes suma todos aquellos gastos que provienen del combustible utilizado, los costes "sin carga" en los que se incurre cuando la planta está encendida independientemente de la producción total, los costes de penalización que se tienen cuando hay un desvío entre la producción real y la que se había asignado al ciclo y, como novedad, los costes de fatiga.

Los costes de fatiga se calculan como un porcentaje del mantenimiento base de la planta de ciclo combinado en cada uno de los encendidos, apagados y rampas que se realizan.

Como los costes de fatiga son el punto de estudio más importante de este modelo es necesario realizar otro cambio con respecto a los modelos tradicionales: en lugar de periodos horarios en este modelo se utilizan periodos de 10 minutos que permiten una mejor descripción de los procesos de encendido y apagado de la planta, permitiendo incluso tener varias posibles rampas, con un diferente coste asociado a cada cual.

El estudio de sensibilidad que se ha realizado tiene 3 parámetros que varían independientemente cada uno del otro, de manera que se pueden medir los efectos que tienen estos cambios sobre la totalidad del sistema: la demanda que le llega a la planta, el coste del combustible y el coste tipo del mantenimiento.

El estudio de sensibilidad a la demanda se ha realizado sobre una serie de datos de operación de una planta de ciclo combinado real. De entre esos datos se han elegido 10 escenarios a mano, elegidos porque tenían algo particular, y posteriormente se ha realizado la agrupación de todos ellos en 4 clusters que contienen alrededor del 95% de la variabilidad. En ambos casos se ha visto lo mismo: el arrepentimiento (el coste en el que se incurre por no tener en consideración la fatiga) se estima entre un 0% y alrededor de un 2% dependiendo del escenario. Pese a ser un coste pequeño en comparación con el resto de costes de operación de la planta, un 2% no debería de ser ignorado, menos aun teniendo en cuenta que con la creciente penetración de renovables las causas mayoritarias de este coste de fatiga (encendidos y apagados) van a ser también más frecuentes, y por tanto el desarrollo de modelos como este, que considera el coste de fatiga en la operación, se torna en una necesidad.

Los costes de combustible, por su parte, afectan a los costes lineales de producción de energía y a la parte de los costes de transición que significa la producción de energía bajo la curva de encendido o apagado. Lo que se ha visto es que pese a que estos cambios tienen efectos notables en los costes totales del sistema, el arrepentimiento de no considerar la fatiga es totalmente independiente de este cambio, será mayor o menor con el caso de más coste de combustible dependiendo de otros factores externos y por tanto no se puede sacar ninguna relación.

Los costes de mantenimiento, como era de esperar, son los que más afectan al arrepentimiento: como estos costes afectan a los costes de fatiga por rampas y a la parte de fatiga de los costes de transición de manera lineal, también lo hacen sobre el arrepentimiento, lo que quiere decir que aquellas plantas con costes de mantenimiento mayores serán las que tengan una mayor necesidad de considerar la fatiga en su operación.

Partiendo de este modelo de minimización de costes, el capítulo 3 explica los cambios que deben aplicársele para transformarlo en un modelo de maximización de beneficios. El objetivo de una compañía no es, después de todo, tener los costes más bajos posibles, sino tener los beneficios más altos posibles. Por ello, este enfoque será muy útil a la hora de la toma de decisiones en la operación de los ciclos combinados. Este capítulo incluye un caso de estudio para enseñar resultados obtenidos con este modelo.

Como se explica a lo largo del capítulo, la gran diferencia entre la maximización de beneficios y la minimización de costes es su objetivo. En este modelo los parámetros de entrada más importantes son los precios de la energía y las reservas (precios que se introducían también en el modelo de minimización de costes pero que no afectaban al óptimo). Estos precios irán multiplicando a la producción y la capacidad de reserva en cada periodo para obtener los ingresos. A estos ingresos se le restan los gastos tal y como se calculan en el modelo de minimización de costes y se obtiene de esta manera el beneficio que se quiere maximizar.

Las reservas no se habían introducido inicialmente en el modelo de minimización de costes, así que también se requiere una serie de nuevas ecuaciones y cambios en el modelo para su introducción. La razón por la que en el modelo de minimización de costes no se introducen es que físicamente no suponen un gasto, el gasto es simplemente "capacidad perdida", y por lo tanto no afecta a la función objetivo. Sin embargo el ingreso de las CCGT por las reservas es necesario para que salgan rentables.

Finalmente, los últimos capítulos explican cómo introducir la estocasticidad en los modelos, primero en el de minimización de costes y posteriormente en el de maximización de beneficios. Incluir la estocasticidad es importante porque en la operación de un generador nunca se tiene una total certeza de lo que va a pasar, por lo tanto para obtener el mejor resultado posible suceda lo que suceda el modelo debe poder considerar todas las posibilidades. Como los cambios que deben aplicarse a ambos modelos para incluir la estocasticidad son muy parecidos solo el caso de minimización de costes incluye un caso de estudio de validación.

La forma en que se ha modelado la estocasticidad es a través de la introducción en el modelo de escenarios con posibilidades de ocurrir. Se ha decidido que para la obtención de las decisiones de operación óptimas se utiliza la minimización del máximo arrepentimiento, es decir, la minimización de la máxima diferencia entre el óptimo resultado del escenario tomado como estocástico y la mejor solución de ese mismo escenario con los commitments y las transiciones seleccionados para todos los escenarios posibles.

En resumen, este documento incluye un análisis de sensibilidad para el modelo de minimización de costes expuesto en [1] que demuestra que considerar la fatiga en la operación de un ciclo combinado es importante y la formulación de tres nuevos modelos que son transformaciones del primero: un enfoque hacia la maximización de beneficios y ambas opciones incluyendo estocasticidad.

Abstract

This document contains a sensitivity study for one optimization model that minimizes the operation costs of a combined cycle gas turbine considering the effects of fatigue and develops three new models that, based on the cost minimization one, aim to maximize the profits and introduce stochasticity into both of the approaches.

The effect of fatigue has historically been disregarded in mathematical models, but with the growing renewable energy sources penetration it will begin to have a larger impact, since plants (and particularly the flexible CCGT plants) will be forced to start up and shut down more often to compensate the output variability of RES. This leads to the plants being subject to higher wear and tear effects which must therefore start to be considered.

The first mathematical model to include this effect of fatigue has been developed by Wogrin et al. in [1]. After a collaboration between the Instituto de Investigación tecnológica (IIT) and the company Innomerics a study was made where the effects of fatigue on a CCGT were studied, allowing for their mathematical formulation, if not 100% accurate for any CCGT it is at least a good approximation. This mathematical modelling came to fruition in [1], a model that aims to minimize the operation costs of a combined cycle gas turbine.

The first part of the document explains how the cost minimization model in [1] works and includes a sensitivity analysis to the demand, fuel and maintenance costs. This chapter demonstrates that the regret incurred when not considering fatigue in the current situation is considerable, therefore, in a future where it is going to be more important it must be considered in order not to incur in big economic losses.

In broad terms, the cost minimization optimization model sums all of the expenditures that come from the fuel used, the no-load costs of the plant, the penalty costs that come from deviations from the scheduled demand and, as a novelty, the fatigue costs.

The costs of fatigue are calculated as a percentage of the base maintenance cost of the CCGT for each of the transitions and ramps that happen in the operation.

Since these fatigue costs are the most important thing to study with this analysis it has been necessary to make another change with respect to the traditional models: instead of hourly time steps, this model uses 10-minute time steps that allow for a better description of the start up and shut down processes of the plant, which allows to have different possible ramps with different costs associated to each of them.

The sensitivity analysis has been made through the variation of three input parameters independently, which leads to the effects of each of the changes being studied: the demand of

the plant, the fuel cost and the base maintenance cost of the plant.

The sensitivity study to the demand has been done using some real operation data of a CCGT as the demand input. From all of the existing data 10 scenarios have been picked by hand because they had some particularities. Then a clustering process has been made that grouped all of the existing data into 4 clusters that contained over 95% of the variability. In both cases the same output has been obtained: the regret (the cost incurred when fatigue is not considered) is estimated between 0 and 2% depending on the scenario. Even though it is a small cost compared to the totality of the operation costs of the plant, a 2% should not be ignored, less so in a framework of growing renewable penetration. Being the major causes of that fatigue cost the transitions between on and off modes, an outlook of big renewable penetration means that those costs will need to increase, therefore turning the consideration of these costs into a necessity.

The fuel costs, for their part, affect the lineal variable costs of production and the transition costs in the term that signifies the production of energy under the transition curve. What has been seen from this analysis is that these changes have notable effects on the total costs of the system, but the regret of not considering fatigue is totally independent, being more or less depending on other external factors, therefore there is no possible relation to be seen between the fuel costs and the regret.

The maintenance costs on the other hand, as was to be expected, do affect the regret greatly. Since these costs affect the ramp fatigue costs and the transition costs lineally so do they affect the regret. This means that those plants that have higher maintenance costs will have a bigger need to consider the fatigue costs in their operations.

Parting from the cost minimization model, chapter 3 explains the changes that must be applied to it to transform it into a profit maximization model. The objective of a company, in the end, is not having the lowest possible costs, but having the highest possible profits, therefore this approach should be helpful for the decision making in the operation of the CCGTs. This chapter includes a case study to show model results.

As is explained along the chapter, the biggest difference between the profit maximization and cost minimization approaches to the CCGT operation is their objective. In this model the most important input parameters are the energy and reserve prices (prices that although were introduced in the cost minimization model did not affect the optimal). These prices will be multiplying the energy production and reserved capacity in each period to obtain the revenues. Then the costs, as were calculated in the cost minimization model, will be subtracted obtaining the profits that the model will maximize.

The reserves were not introduced in the cost minimization model, so the equations that regulate them will had to be formulated and introduced. The reason for them not being into the cost minimization model is that they do not entail any physical cost, rather a "lost capacity", therefore they do not affect the objective function. On the other hand, in the profit maximization model they are necessary for them to be profitable.

Finally, the last chapters explain how to include stochasticity in the models, first in the cost minimization model and then in the profit maximization one. Including stochasticity is important because in the operation of a generator you never have full certainty of what is going to happen, so in order to make the best out of any situation the model must be able to consider

all of the possibilities. Since the changes that need to be applied to the cost minimization and profit maximization models to include stochasticity are very similar, only the cost minimization approach includes a validation case study.

Stochasticity has been modelled through the introduction of scenarios with a possibility to occur in the model. It has been decided that to obtain the optimal operation decisions the system to be used is the minimization of the maximum difference between the optimal result of the scenario taken as stochastic and the optimal solution of that same scenario with the commitments that must be maintained for all possible scenarios.

Summing up, this document includes a sensitivity analysis of the cost minimization model in [1] that shows that the consideration of fatigue in the operation of CCGTs is important and the formulation of three new models that are transformations of the other one: a profit maximization approach and the inclusion of stochasticity into both models.

To my family, thank you for always being there for me
To Sonja, for believing in me since 3 years ago.
To my friends, for putting up with my nonsense

The purpose of our lives is to be happy.
DALAI LAMA

The best way to predict the future is to create it.
ABRAHAM LINCOLN

DOCUMENTO I

THESIS DOCUMENT

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Acronyms

ICAI	Instituto Católico de Artes e Industrias
CCGT	Combined Cycle Gas Turbine
IIT	Instituto de Investigación Tecnológica
GAMS	General Algebraic Modelling System
MIP	Mixed Integer Programming
REE	Red Eléctrica de España
NLC	No Load Costs
LVC	Linear Variable Costs
TC	Transition Costs
RFC	Ramp Fatigue Costs
PC	Penalty Costs
SDGs	Sustainable Development Goals

PART I

THESIS DOCUMENT

Chapter 1

Introduction

THE electric system has been and still is overcoming some big changes in the latest years. Among them you can count the introduction of renewables into the system, the growing distributed generation or the bigger impact of technologies such as smart grids. All of them are changing the paradigm of the electric industry and making it necessary for the older technologies to adapt.

Particularly, technologies with high levels of carbon emissions such as coal are being replaced by technologies that are more environmentally friendly.

But the power system cannot only depend on the production of renewables yet, because there is also a need for reliability and security of supply that these technologies cannot fully cover, being dependent on external factors such as wind and solar power availability. This means that for the energy transition to be completed there is still a need for technologies such as nuclear and gas in the system to be able to operate as intended and be reliable in terms of supply.

In this context is where this thesis is necessary, CCGT is a technology that can strongly contribute to this security of supply: thanks to its short start-up times and easy management it can be used to balance the variability of the renewables and any possible diversions from scheduled energy production from renewables. This, though, comes at a cost: from starting up or shutting down the plants more often there is a heavier impact on the useful life of critical plant components. This wear and tear is predominantly related to fatigue-related damage.

A collaboration between the Instituto de Investigación Tecnológica (IIT) and the company Innomerics in 2014 made it possible to include fatigue-related wear and tear cost in a unit commitment problem. [2]

That study is the departure point for the work that will be developed in this document. It will explain the cost minimization model that included fatigue for the first time developed by Wogrin et al. in [1] and carry out a sensitivity analysis to check the impact of this new consideration. Then this document will develop a model that includes this cost and the expected market prices for CCGTs to optimize their day-ahead bidding in the spot energy and reserve markets.

Both models can be classified as self-unit commitment models, since they are used to optimize the commitment decisions of a single CCGT unit. The biggest difference between them (other than the final objective of the optimization: minimizing costs or maximizing profits) is that for the cost minimization the demand is an input coming from the plant operator's bid in the day-ahead market; meanwhile the profit maximization is a model that would be run to obtain the optimal bids for the day-ahead spot energy and reserve markets, being the price estimations the input data.

In any case, both models, being for the operation of CCGTs, have a lot of similarities, including many equations that will be shared between them.

In conclusion, this document will present two optimization models for the day-ahead operation decisions of CCGTs that consider fatigue. The first model was developed by Wogrin et al. in [1] and will be used for a sensitivity analysis of some representative weeks of the operation of a CCGT, to test whether considering the impact of the fatigue analysis is relevant or not. Then the profit-maximization model will be developed from the previous one and will be tested with some spot energy and reserve price scenarios.

In the remainder of this document both of the optimization models will be explained and tested, to be later used to analyse how the spot energy and reserve prices, under conditions of uncertainty, impact the optimal operation of CCGTs.

1.1 State of the art

This section contains a brief state of the art regarding the situation of CCGTs in current power systems in section 1.1.1, and a literature review on relevant unit commitment models up to date in section 1.1.2.

1.1.1 Situation of the combined cycle gas turbines

CCGT technology was developed between the 1950's and 1960's, but it was not until the late-1990's to early-2000's that it really entered the market of electricity production, in a context where there were some reasons that made it extremely cheap and appealing:

- It was considered a clean technology compared to coal and oil electricity plants, back when the climate change impact was starting to matter in the eyes of the public.

- Gas was being thrown away at value 0 in oil fields, so any use for the gas meant an increase in the benefits of the owners of the fields.

- Combined cycle plants have a higher efficiency than the standard oil and coal plants common at the time.

But the situation has changed a lot with gas prices going up when people realized its uses, CO2 emissions being penalised more and the introduction of other cheaper and cleaner alternatives: renewables as wind and solar.

All of this, along with other reasons, such as the renewable integration policy in Spain or the crisis of 2008 has led to an overcapacity of CCGTs in the Spanish power system. CCGTs have been relegated to a secondary role of security of supply providers or even let go on mothballing by their owners, since they were making practically no benefits (and even losing money in some cases [6]).

Even with this in mind, it does not mean that gas plants are useless. In fact, with power plants of other technologies such as coal and nuclear at risk of being shut down for good under some progressive governments, the role of CCGTs in the energy transition is going to be very important. They will have the possibility of becoming firm capacity that is needed in the system.

And it is a role that fits the CCGT plants extremely well, since they are able to manage their power output very efficiently, which is going to be very important in a scenario where a lot of renewable energy can imply a lot of output variability and upward and downward reserve needed.

Of course, all of this is subject to change, and a development in other new technologies such as storage could relegate the CCGTs back to a state similar to where they are right now.

1.1.2 Unit commitment models

Unit commitment models are mathematical formulations that are used to optimize the commitment decisions of power plants and the transitions between their different modes of operation. This means that they are used to decide when a unit is on or off, when it should be started-up or shut-down and how much it should be producing.

In this thesis we want to distinguish between two different types of unit commitment models: those that consider the totality of the system and those that consider only a few plants.

The ones that consider the totality of the system are used to optimize its operation in a centralized context, when it is the regulator that decides what units must produce and how much, so that the result is as efficient as possible.

On the other hand, self-unit commitment profit maximization models are used in competitive markets by plant owners to optimize the operation of their plants so that they can make as much profit as possible:

- Cost minimization models aim at obtaining the cost-optimal dispatch and operations taking into account the technical constraints of the power plants involved. It can be used to calculate profits ex-post; however, it does not consider profits in the optimization process. These models can be used for centralized operation, technical studies and tracking the market to look for oligopolistic behaviours.

- A profit maximization model on the other hand, does simply that, it maximizes profit. So it aims to answer what are the operations and dispatch that maximize profits (this could mean not operate at all actually). These models are thereby used by plant owners to know when to bid in the markets and at what price. These models must therefore take into account another important part of the operation of the plants: operating reserves, which can be considered in cost minimization model but are usually overlooked.

Operating reserves are usually not considered in cost minimization models (except in the case that a minimum reserve requirement is set as an input, case in which the plants would have to be operating at a different point than their optimal and therefore would have an implicit loss of money) since they do not cost an extra amount of money to the producers, but they are necessary for adequate system operation, and as such they are remunerated. This gives another variable of control for the producers over their costs and revenues, and it must be included in the profit maximization models.

1.2 Motivation

In the cost minimization unit-commitment models in use right now [3][4] the costs are calculated as a sum of no load costs (those that come from the unit being in one or another mode of operation), linear variable costs (costs coming from the use of fuel), transition costs (the ones incurred when a plant is started up or shut down) and penalty costs (those that come from the deviations between the programmed power and the actual power output).

Although this is not too far from reality, this formulation does not consider some of the existing costs: those associated with fatigue. This simplification is necessary because at the moment the models were designed there was not enough information about some of the internal processes of the plants, plus not all of the CCGTs respond equally to fatigue. This means that in order to introduce this extra cost into the model a specialized company that analyses fatigue with finite element models is needed. This is not a trivial process, the information in this document has been obtained only through the collaboration between Innomerics and the IIT, [2] it is not a trivial process.

Fatigue costs come from the mechanical wearing of the plant due to its usage, particularly when there are changes in the unit's power output. These changes can be big, as in start-ups and shut-downs (a term caused by fatigue can be added to the transition costs), or smaller, such as in increases or decreases of power output in a plant that was already producing some energy. The more extreme the change, the more fatigue wearing incurred. Once a specific model is used to calculate the response to fatigue of a CCGT it can be included into the model: While the wearing in start ups and shut downs can be included in the model by changing the start up and shut down costs, for the fatigue cost that is due to ramps a mathematical definition of power output increment between two points in time must be made, so that a cost that will depend on how fast the plant changes that output can be assigned to it.

In a context where CCGTs will be needed for firm capacity [5] they must be able to adapt their power output to compensate the unavailability at certain periods of renewable technologies. Reason why these costs are going to become more and more significant and thus, not considering them could mean a big loss of money. This is the reason for this study, optimal decisions for CCGTs may change in the near future just from considering these costs, which could have a big economic repercussion.

1.3 Objectives

This project shows a cost minimization model for the operation of a CCGT plant and proposes a profit maximization approach considering fatigue.

Since the cost minimization approach was already developed in [1] the study around this model will be a sensitivity analysis where the real benefits of considering fatigue will be tested. From a set of given demand scenarios the economic loss from not considering the fatigue will be tested. This will give a value per scenario of how much the costs of operating the plant would be reduced if the fatigue was taken into account.

The second objective is turning this cost minimization model into a profit maximization model. Most electricity sectors in developed countries are organized as liberalized markets where the owners of generators bid in the market a certain production at a certain price. The way in which they behave has the objective of maximizing their profit. This is the reason why for the plant owners the profit maximization models are more interesting than the cost minimization ones. Although of course cost minimization models do have their uses, such as helping the regulator understand which is the best possible dispatch or theoretical analysis.

Finally, the last objective is the introduction of stochasticity in the models. While for purpose of studying the models it may be useful to start with a deterministic scenario, in real life the future is unknown, so stochasticity must be included in the model for it to be useful. Therefore, the third objective that will be developed in this paper is the introduction of stochasticity into the model. This stochasticity comes from the uncertain parameters introduced in the model: in the cost minimization approach from the demand curve, in the profit maximization from the market prices.

1.4 Resources

A project of such magnitude cannot be undertaken without some resources that make the investigation possible. The most obvious resource needed is the program in which the model will be coded. In this case, it is GAMS [9]. GAMS is an acronym for General Algebraic Modelling System. It is a program that lets the user code mathematically a set of equations made up of indices, parameters and variables and then optimizes the solution minimizing or maximizing one of the variables. In order to be able to solve a large scale MIP model the solver needs a license. The IIT has provided the necessary license.

There is no question that model developed by Wogrin et al. in [1] is the most important resource for this thesis. That model is the departure point for the whole investigation, firstly used for the sensitivity analysis and then to transform it into the profit maximization models described in this document.

But of course the program and the model by themselves not do anything, there is information that has to be provided to them. The parameters contain all the information that is given to the model so that it can be used to look for the optimal solution. Some of the parameters, such as the costs, were already given in the model developed in [1], although they can be changed for a sensitivity analysis, others such as the demand have been obtained from the operation of a real CCGT plant and the market prices.

Finally, the last resource used is Matlab. It is used in section 2.5.3 to group the demand data from real operation into clusters that can be analysed together.

Chapter 2

Cost minimization self unit commitment model with fatigue considerations

IN this chapter the cost minimization model developed by Wogrin et al. in [1] will be explained. All the information is contained in that document, although since it is the departure point of this document it is important to understand it, therefore it is explained in this chapter.

This model aims to minimize the cost of operation of a CCGT given a scheduled demand. This is the same as saying that the aim of the model is to optimize the commitment of the CCGT (the moments in which the plant is ON, OFF, shutting down or starting up) and the power production at each moment.

The model will calculate the commitments and power productions in order to minimize the total costs, that are composed by no load costs, variable costs, transition costs (start up and shut down costs), costs due to fatigue and penalties for producing more or less energy than scheduled.

The description of the model will be developed from general to more specific: first the indices used, then the parameters introduced (some of which will be dependant from the mentioned indices), then the variables to be solved in the optimization and finally the equations that relate all of the above.

2.1 Indices

Indices Used		
Index	Alias	Description
t	i	10-minute time steps (from t1 to t1008)
x	y, xx, μ	modes of operation
μ_x^{SU}	-	start-up modes from all possible modes of operation
μ_x^{SD}	-	shut-down modes from all possible modes of operation
μ_x^{UP}	-	ON modes from all possible modes of operation
μ_x^{DN}	-	OFF modes from all possible modes of operation
μ_{xy}^{F}	-	feasible transitions

Table 1. Indices used in the cost minimization model

It is important to further explain the modes of operation that have been modelled since it is not only ON, OFF, a trajectory for start-up and a curve for shut-down.

On the contrary, there are three OFF modes that depend on the time that the plant has been OFF (OFF+HOT when it just shut-down, OFF+WARM when it has been down for some time and OFF+COLD when it has been down for a longer period) which also makes possible the modelling of 3 different types of start-up: Start-up hot, warm and cold, which differ in time and ramp-up rate. For each of them, there have also been modelled three different curves, with different ramp-up rates, which the solver will choose depending on the need of a faster start-up or better savings in fatigue terms.

The same applies to the shut-downs, which will have three different shut-down rates for the solver to choose from.

Finally, the ON mode has two main possibilities: ON with only the gas turbine producing and ON with both the gas and steam turbines working. Evidently, the transition between the gas turbine being ON alone and both working at a time has also been modelled. Each of these modes has been modelled with the equivalent three possible ramp-up and ramp-down rates.

It is also notable that the shut-down of only the steam turbine has not been modelled, which means that for the steam turbine to be turned off the gas turbine has to shut-down too. Since the steam turbine uses the heat remaining from the operation of the gas turbine then it makes no sense to produce without that "free energy source" once the cost of the start-up has been covered.

2.2 Parameters

The parameters used, which are introduced in the model from the outside, are described in table 2, along with the units in which they must be introduced and the symbolic expressions with which they are used in the equations.

Parameters included in the model		
Parameter	Description	Units
C_x^{LV}	linear variable cost of each mode	€/MWh
C_x^{NL}	no load cost of each mode	€/h
C_x^{fat}	cost of fatigue per output difference	€/ΔMW
C_{xy}^{T}	transition cost between modes	€
C^{pen}	cost for deviating from dispatch	€
$\overline{P_x}$	maximum output of the CCGT at each mode	MW
$\underline{P_x}$	minimum output of the CCGT at each mode	MW
RU_x	ramp up rate of each mode	MW/h
RD_x	ramp down rate of each mode	MW/h
RU_{xy}	ramp up rate between modes	MW/h
RD_{xy}	ramp down rate between modes	MW/h
TU_x	minimum up-time of each mode	h
TD_x	minimum down-time of each mode	h
P_{xt}^{SU}	power output at the beginning of time-step t during start-up x	MW
P_{xt}^{SD}	power output at the beginning of time-step t during shut-down x	MW
Dem_t	demanded load for each time step	MW
DUR_x^{FIX}	fixed duration of mode x	h
DUR_x^{MAX}	maximum duration of mode x	h
$IniOut_x$	initial output	MW
$IniUC_x$	initial commitment	{0-1}
$Price_t$	exogenous market price	€/MWh

Table 2. Parameters included in the model

2.3 Variables

The variables containing the results from applying the optimization to the model are depicted in table 3.

Variables included in the cost minimization model		
Variable	Description	Units
u_{xt}	commitment of the modes of operation at each time-step	{0-1}
v_{xyt}	transition between two modes of operation at each time-step	{0-1}
p_{xt}	power output above the technical minimum at the end of time-step t	GW
Δp_{xt}	difference in power output above technical minimum in time-step t	GW
$\hat{p}_{xt}$	total power output of the CCGT at the end of time-step t	GW
e_{xt}	energy output of each mode in time-step t	GWh
$Dev_{(dn)t}$	Deviation under scheduled demand	GW
$Dev_{(up)t}$	Deviation over scheduled demand	GW

Table 3. Variables of the cost minimization model

2.4 Equations

In this section the equations that conform the model will be described. Each of the subsections that follow is devoted to the equations that describe one particular aspect of the optimization model, starting from the objective function.

2.4.1 Objective Function

The objective function is the minimization of the total costs of operating the plant throughout the whole period of study, this is conformed by the sum of all the costs: no-load, variable (fuel), transitions, fatigue and penalties.

$$\sum_{t\in T}\sum_{x\in\mu}(C_x^{NL}u_{xt} + C_x^{LV}e_{xt} + C_x^{fat}\Delta p_{xt}) + \sum_{xy\in\mu_{xy}^F} C_{xy}^{T}v_{xyt} + \sum_{t} C^{pen}(Dem_t - \hat{p}_{xt}) \quad (1)$$

2.4.2 Power System Requirements

A general requirement of power systems is that the demand has to be equal to the production. In a self-unit commitment model the same happens. If the production is lower than the dispatched demand there is a penalty. All in all, the energy dispatched must be equal to the sum of the production and the energy not served, as stated by the equation below.

$$\sum_{x}\hat{p}_{xt} + Dev_{(Dn)t} - Dev_{(Up)t} = Dem_t \qquad \forall t \quad (2)$$

2.4.3 Commitment logic

The following equations are necessary to introduce the commitment logic in the model. This means that these equations make sure that the plant is operating only in one mode at a time and that no more than one transition is taking part simultaneously.

$$\sum_{x} u_{xt} = 1 \qquad \forall t \tag{3}$$

$$u_{xt} - u_{xt-1} = \sum_{\mu^F_{yx}} v_{yxt} - \sum_{\mu^F_{xy}} v_{yxt} \qquad \forall xt \tag{4}$$

$$\sum_{\mu^F_{yx}} v_{yxt} \leq 1 \qquad \forall t \tag{5}$$

$$\sum_{\mu^F_{yx}} v_{yxt} \leq 1 \qquad \forall xt \tag{6}$$

$$\sum_{\mu^F_{xy}} v_{yxt} \leq 1 \qquad \forall xt \tag{7}$$

2.4.4 Minimum time up or down

The operation of a CCGT is not always straight forward, but through expertise, there are some limitations that have to be taken into account. For instance, it may not be good for the turbines that they are started-up too quickly after a shut-down, or viceversa, that they are shut-down after being on for only a small amount of time. This is the reason behind the minimum up and down time requirements that are included in the model through this equations.

In practice, for the analysis made, this equations have not supposed any real constraint, since the minimum up and down times have been set up at 1 time-step, so they are irrelevant.

$$u_{xt} \geq \sum_{\mu^F_{yx},\ (i \leq t) \wedge (i \geq t - TU_x + 1)} v_{yxi} \qquad \forall xt, \qquad t \geq TU_x \tag{8}$$

$$1 - u_{xt} \geq \sum_{\mu^F_{xy},\ (i \leq t) \wedge (i \geq t - TU_x + 1)} v_{xyi} \qquad \forall xt, \qquad t \geq TD_x \tag{9}$$

2.4.5 Ramping limits

The operation of the plant is complex, among other things, because it cannot change its power output at any rate. Instead it has a maximum rate at which it can increase or decrease its production, which is given by the following equations.

$$RU_x u_{xt} - \sum_{i\mu^F_{yx},\ x \neq y} v_{yx}(RU_x - RU_{yx} - (\underline{P_x} - \underline{P_y})) \geq p_{xt} - p_{xt-1} - \sum_{i\mu^F_{yx},\ x \neq y} p_{yt-1} \qquad \forall xt \tag{10}$$

$$RD_x u_{xt} - \sum_{i\mu^F_{xy},\ x \neq y} v_{xy}(RD_x - RD_{xy} - (\underline{P_x} - \underline{P_y})) \geq -p_{xt} + p_{xt-1} - \sum_{i\mu^F_{yx},\ x \neq y} p_{yt} \qquad \forall xt \tag{11}$$

It is important to note here that there are 3 different ramp-up rate limits for each of the main modes of operation, the solver decides which one to use at each point in time depending on the impact on the objective function.

2.4.6 Generation limits

The following constraints model the maximum and minimum capacity of the CCGT at each mode of operation, since there is no cost associated to reserves they do not have to be modelled for the cost minimization, but they will be added farther down this document, when instead of a cost minimization the objective will become a maximization of the profits (which obviously includes the benefits associated to the reserves).

$$u_{xt} - \sum_{\mu^F_{xy} \ \$ \ \mu^{SD}_y} v_{xy(t+1)} \geq \frac{p_{xt}}{\overline{P_x} - \underline{P_x}} \tag{12}$$

$$0 \leq p_{xt} \tag{13}$$

2.4.7 Total power and energy output

Although the demand is given as total MW of capacity that must be producing, for the internal calculations it is easier to use the demand above the minimum production of the mode of operation in which the plant is working. That said, it is also important to know the absolute production, since it is necessary for constraints such as the power system requirement one.

The same happens with the total energy production, it is necessary to know it for some internal calculations. In fact, the total energy production is even more important since it is one of the terms of the objective function, used to calculate the variable costs of the turbine.

The following two equations are used to calculate those two values: total power and energy output of the CCGT.

$$\hat{p}_{xt} = 0 \ \ (\$ \ \mu^{DN}_x) \ + \sum_{i \ \$ \ i<(DUR^{FIX}_x+1)} P^{SU}_{xt} \cdot \sum_{\mu^F_{yx}} v_{yx(t+1-i)} \ \ (\$ \ \mu^{SU}_x) \ + \\ \sum_{i \ \$ \ i<DUR^{FIX}_x+1} P^{SD}_{xt} \cdot \sum_{\mu^F_{yx}} v_{yx(t+1-i)} \ \ (\$\mu^{SD}_x) + (\underline{P_x} u_{xt} + p_{xt}) \ \ (\$ \ \mu^{UP}_x) \tag{14}$$

$$e_{xt} = \underline{P_x} u_{xt} + \frac{p_{xt} + p_{x(t-1)}}{2} \tag{15}$$

2.4.8 Minimum and maximum time requirements for start-ups, shut-downs and off modes

The following equations make sure that those modes of operation with a fixed or maximum duration are exactly that long. This means, for example, that if the turbine is being started-up from OFF+HOT situation the start-up will have a fixed duration that is shorter than the start-up from a OFF+WARM situation.

These constraints also apply for the OFF modes, giving it a maximum time duration for OFF+HOT and OFF+WARM modes, making a transition from hot to warm and then to cold automatically if no start-up takes place.

$$\sum_{i \ \$ \ i \geq (t - DUR_x^{FIX}+1) \wedge i \leq t} (\sum_{\mu_{yx}^F} v_{yxi}) \leq u_{xt} \qquad \forall xt \tag{16}$$

$$\sum_{i \ \$ \ i \geq (t+1) \wedge i \leq (t + DUR_x^{FIX})} (\sum_{\mu_{yx}^F} v_{xyi}) \geq u_{xt} \qquad \forall xt \tag{17}$$

$$\sum_{i \ \$ \ i \geq (t+1) \wedge i \leq (t + DUR_x^{MAX})} (\sum_{\mu_{yx}^F} v_{xyi}) \geq u_{xt} \qquad \forall xt \tag{18}$$

$$\sum_{i \ \$ \ i \geq (t - DUR_x^{MAX}+1) \wedge i \leq t} (\sum_{\mu_{yx}^F} v_{yxi}) \leq u_{xt} + DUR_x^{MAX} \cdot \sum_{i \ \$ \ i \geq (t - DUR_x^{MAX}+1) \wedge i \leq t} \ \sum_{\mu_{xy}^F \wedge mu_y^{SU}} v_{xyt} \qquad \forall xt \tag{19}$$

2.4.9 Difference in power output

In order to calculate the cost of fatigue there are two terms that have to be considered. The first one is the fatigue cost that is incurred when there is a transition in the mode of operation of the turbine (start-ups and shut-downs mainly). The second one is a term that depends on the difference in power output between 2 time-steps.

The following equations must be used to calculate that power output difference. This is only calculated in the ON modes, since the start-ups and shut-downs have the fatigue cost already included in the input parameters.

$$\frac{\Delta p_{xt}}{\overline{P}_x} \geq \sum_{xx} \frac{p_{xxt}}{\overline{P}_x} - \sum_{xx} \frac{p_{xx(t-1)}}{\overline{P}_x} - (1 - u_{xt}) \qquad \forall \mu_x^{UP} t \ \ (\$ \, t > 1) \tag{20}$$

$$\frac{\Delta p_{xt}}{\overline{P}_x} \geq \sum_{xx} \frac{p_{xx(t-1)}}{\overline{P}_x} - \sum_{xx} \frac{p_{xxt}}{\overline{P}_x} - (1 - u_{xt}) \qquad \forall \mu_x^{UP} t \ \ (\$ \, t > 1) \tag{21}$$

2.5 Sensitivity analysis to the demand with the cost minimization model

This section talks about the sensitivity analysis that has been carried out for the cost minimization model changing the demand input. It has been undertaken in three phases:

1. Analysis of the base case scenario (section 2.5.1). This was already carried out in [1], so it will only be described here, so that the departure point is clear.

2. Analysis of some hand-picked demand scenarios (section 2.5.2). There was a lot of data that could be analysed, so some of the possible demand inputs were selected for a preliminary analysis. The scenarios were hand-picked, so there may be some information missing from all the data provided.

3. A scientific approach: all the data will be clustered into 4 scenarios that contain most of the information (section 2.5.3). These clusters will be the input demand data for the last sensitivity analysis.

2.5.1 Analysis of the base case scenario

This subsection aims to explain how the base case scenario was built (not only the demand data but also the rest of the parameters), the results of its optimization and the extra costs in which a current model incurs from not considering fatigue, which will be called regret.

In [1] Wogrin et al. built a base case scenario out of a set of data that can be changed to create new scenarios:

1. Demand data coming from real operation of a CCGT. Since the model is a real time operation model it uses this input to know how much power the turbines must produce in order not to get penalized. This is the main parameter changed throughout the sensitivity analysis.

2. Cost of fuel data are used to calculate the linear variable costs, the no load costs and part of the transition costs.

3. The cost of maintenance impacts the transition and ramp fatigue costs when considering the wear and tear effects on the plant.

The demand data is formed by 1008 demand points, each with a duration of 10 minutes, which amounts to a total of 1 full week of points. This division in 10 minutes pieces lets us obtain better results than the usual analysis with hourly demand periods, since it permits a better characterization of start-ups and shut-downs, which are the main sources of the fatigue costs that we are analyzing in this paper.

A last parameter that is included in the cost minimization model but that has no effect on the outcome is the price of energy in the market. The market prices have been obtained from official data, through OMIE and REE [10]. The revenues calculated will only be an approximation to the actual profits that the power plant would be making since other sources of income like payments for reserves are not considered in the cost minimization model.

Both the data for the demand and the energy price can be seen in Figure 1:

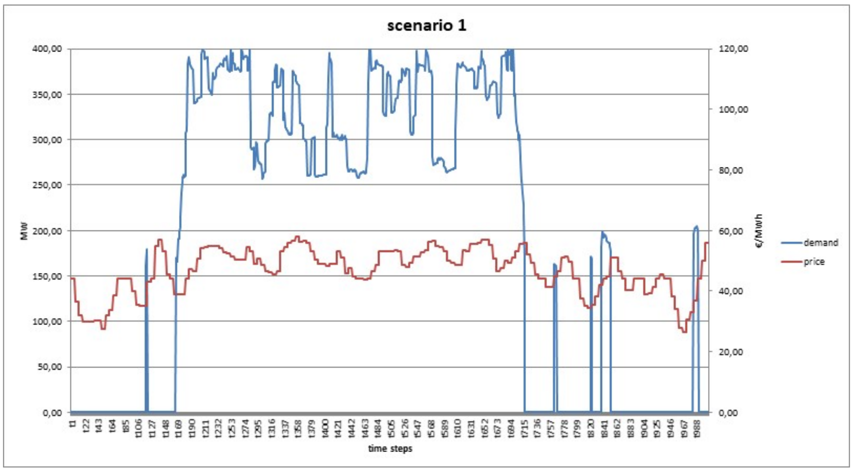

Figure 1. Data for demand and energy price for the base case scenario

Let us briefly explain how the regret is calculated. First, the costs without fatigue are introduced as inputs for the model. Then it is resolved, obtaining the commitments. Those commitments are fixed and the project is re-run with the costs of fatigue included. Then a third minimization takes place, of the model with no fixed commitments but the fatigue included.

	Fixed Unit Commitments	Optimal Unit Commitment
No load Cost	180.97	180.97
Linear Var Cost	1352.58	1352.72
Ramp Fatigue Cost	0	4.43
Transition Cost	28.5	45.98
Penalty Cost	2.84	2.84
Total Cost	1564.93	1586.96

Table 4. Operation Costs for the base scenario (k€)

The difference between the second and third values for the total cost of operation is the regret, it is the error in which a current state of the art model would incur due to not considering the fatigue.

With that in mind, the results for the cost minimization of the base case scenario are exposed in Figure 2 and Table 4.

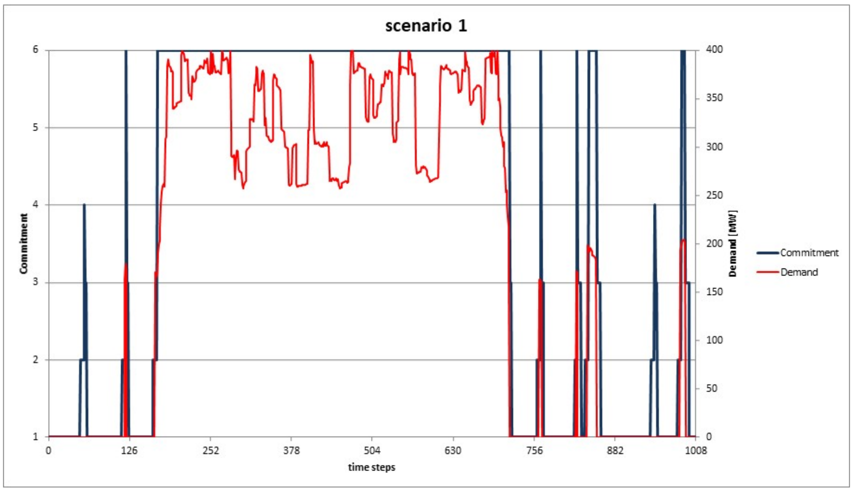

Figure 2. Commitment of the power plant for the base scenario

For Figure 2 there is some explanation that is necessary. The commitment is assigned a value from 1 to 6. OFF modes are associated to 1, Start ups to 2, Shut downs correspond to the 3, ON modes with only the gas turbine on are assigned to 4, the start up of the steam turbine is the 5 and the ON modes with both working is associated to the 6.

What can be deduced is that the plant is ON only when there is scheduled demand, depending on the amount both turbines are on or only the gas one.

The most important information that can be obtained from the costs in Table 4 is the difference between the case with and without fatigue. While the changes in the values of ramp fatigue cost and transition costs where to be expected, the slight change in the linear variable cost is interesting to look at. It means that for some reason there is a need for extra fuel in some of the time steps when the turbine is on. One possible explanation is that the new fatigue costs added to the transitions make them be taken with a different curve (there are three possible start up and shut downs to choose from) that does not end in the same point (either of power or time) and that extra fuel is needed to compensate it.

As can be deduced from Table 4 just by summing the differences between costs, the regret for the base scenario is 22.03 (1.39%). The results can be considered valid since the gap with the optimal solution is under 0.00001.

2.5.2 Sensitivity analysis of the hand-picked demand scenarios

All the scenarios have been built in the same way as the base case scenario, from different demand data but maintaining the fuel and maintenance costs of 36€/MWh and 500000€. These costs are introduced into the model through the no load, linear variable, transition and ramp fatigue costs. The demand data comes from the operation of a real CCGT in 2014, between January and July.

The demand amounts and price of the energy in the market for all the new scenarios studied can be seen on Figure 3. From the data available these scenarios were picked because they were "different" in some ways from the rest: demand scenario #10, along with the base case, was the highest demand scenario, scenarios #2 and #8 were selected because they only had one expected start up and no expected shut downs, scenarios #3 and #4 also have a single expected start up, but also one expected shut down. Demand scenario #5 was selected because it was expected to have the most start ups and shut downs among all the data, the oposite of scenario #9 which was not expected to have any start up or shut down. Finally, scenarios #6 and #7 were selected because they have a peak in demand at some point.

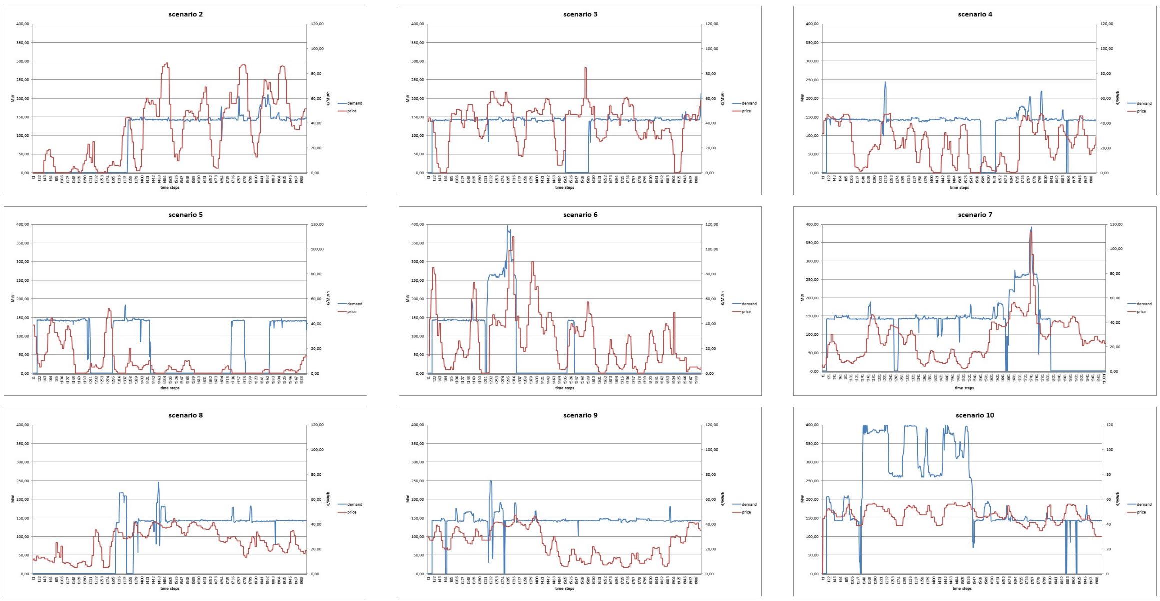

Figure 3. Demand and price data for each scenario analysed (other than the base case)

The same calculation process has been applied to these scenarios as to the base case. The calculation in 3 steps in order to calculate the regret.

The results obtained from the sensitivity analysis is described in Figure 4.

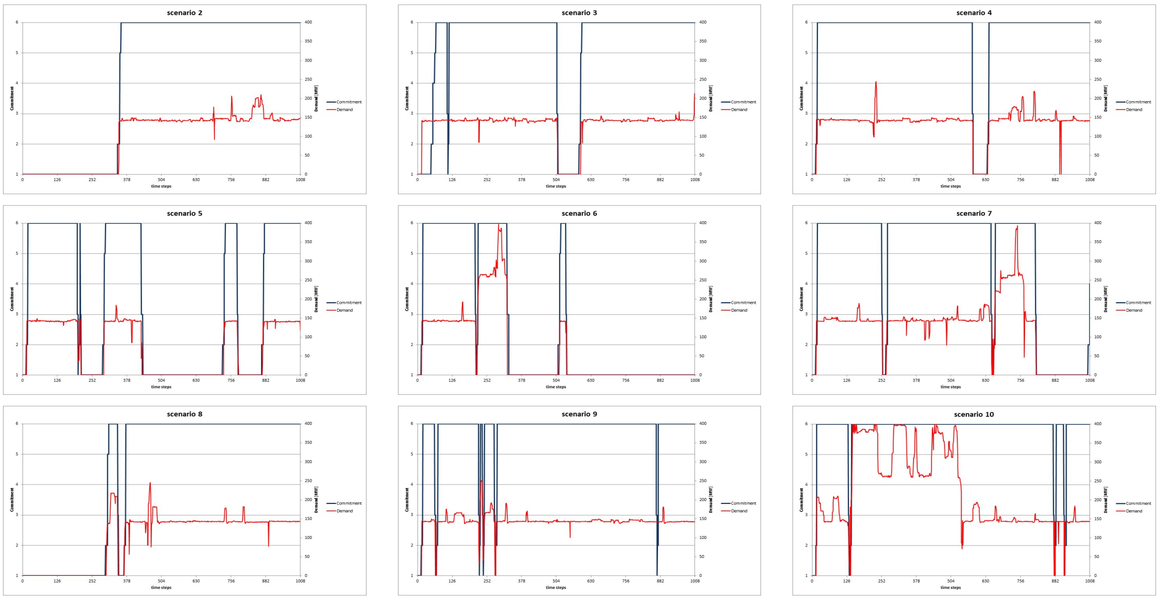

Figure 4. Commitment of the unit for each timestep and scenario

There are some things that have a clear impact on the costs. Evidently, the number of hours that the turbines are on during the week must have a direct impact on the no load costs and the total energy generation has a direct correlation with the linear variable cost as can be seen when comparing the graphs of the demand in each scenario (Figure 4) with the graphs showing the no load and linear variable costs per scenario (first two graphs in Figure 5).

This is to be expected, but there are some other correlations that can be obtained from this analysis: the relation between the number of start-ups and the transition costs can be considered pretty linear as shown in Figure 8, and the relation between the variability of the demand and the ramp fatigue costs is very important but this ramp fatigue cost is still very small compared to the total operation cost.

The graphs showing values of the costs per scenario are shown in Figure 5

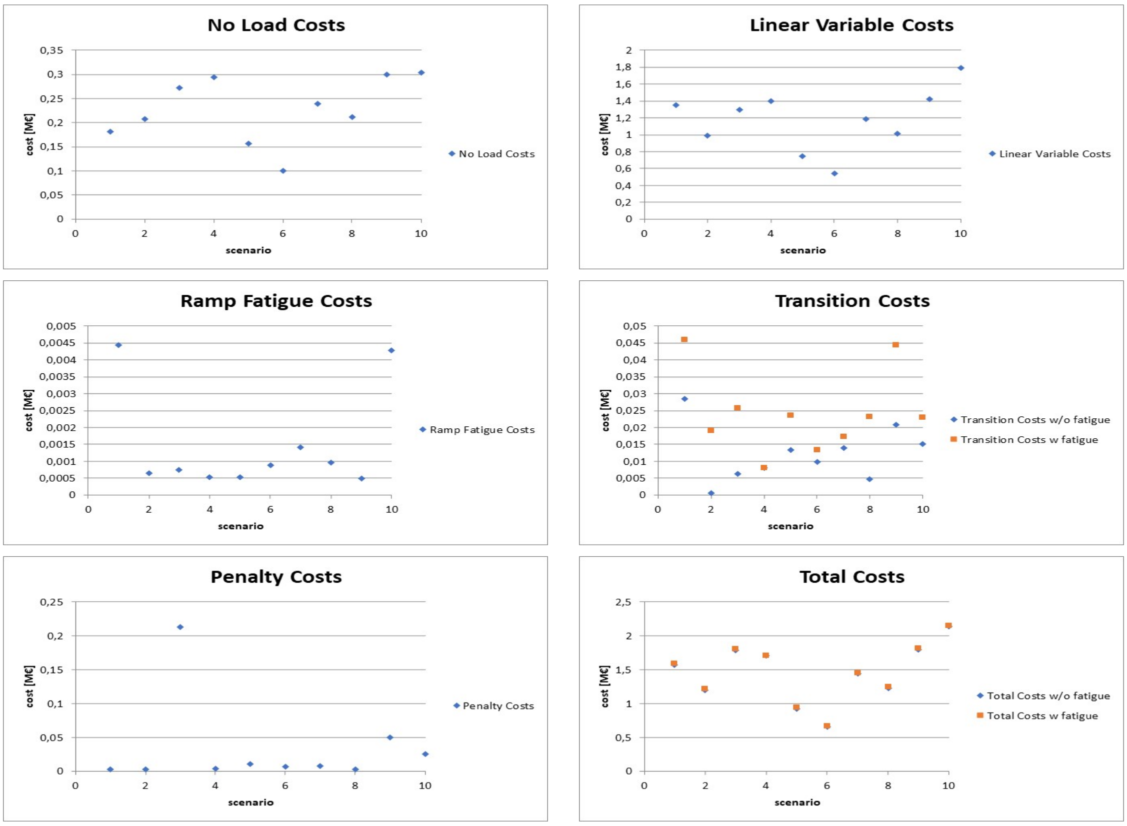

Figure 5. Results for the different costs per scenario

All in all, the most remarkable correlations found between the different costs and other variables were:

- Regression between NLC and LVC with the demand:

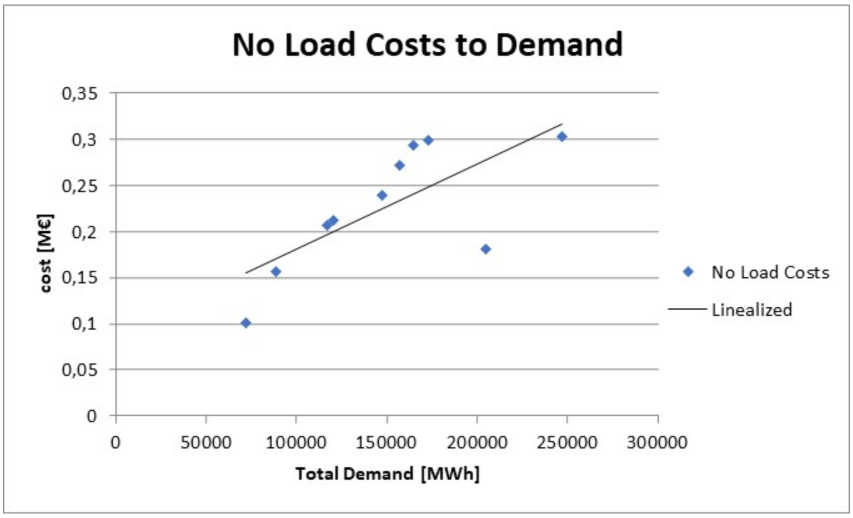

Figure 6. Relation between no load costs and demand per scenario

What can be seen is that in general there is a correlation between the no load costs and the demand. This makes sense because a higher demand implies that more penalty costs are incurred if the plant is off, therefore the plant will be on more time to avoid those extra costs, which supposes an increase in no load costs.

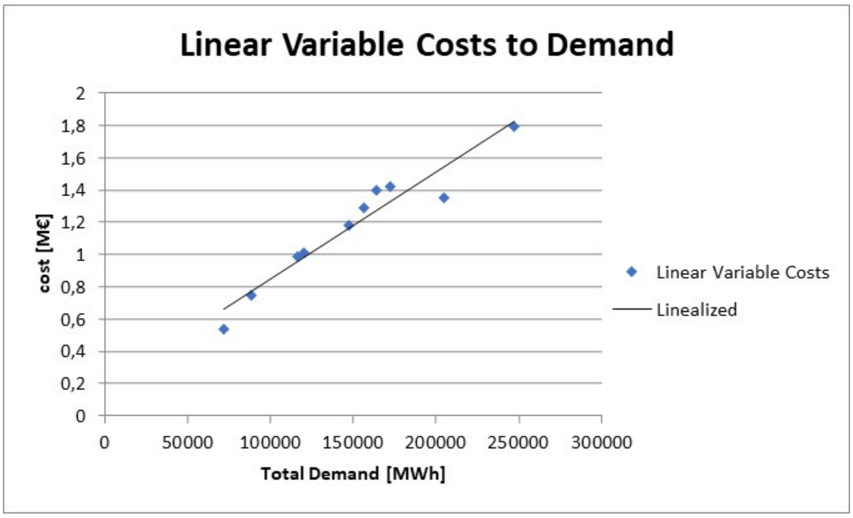

Figure 7. Relation between linear variable costs and demand per scenario

Furthermore, the correlation between linear variable costs and demand is even stronger, this is a direct result of the relation between power production and fuel expenses: More power produced means more fuel consumed and therefore more linear variable costs.

- Correlation between transition costs and number of start-ups in the week:

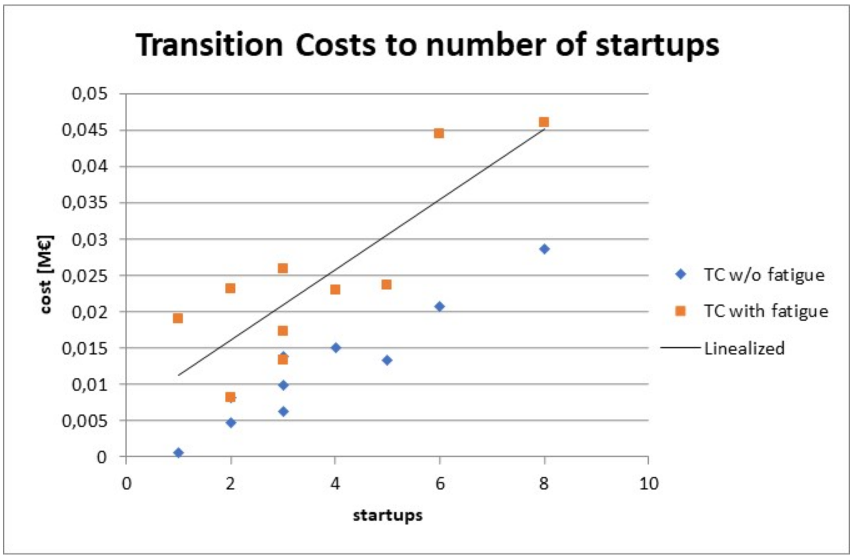

Figure 8. Relation between transition costs and number of start ups per scenario

While when not considering fatigue the lineal relation between the transition costs and the number of start ups is pretty linear, this is not so much the case when considering fatigue. The cause is that the three possible start up curves have a different fatigue cost associated, therefore there is also a dependency on whether the start ups must be fast or they can have a lower slope.

- The relation between ramp fatigue costs and demand variability is observed when comparing the RFCs and the total amount of power differential between following time steps in each of the scenarios, which can be found in Figure 9.

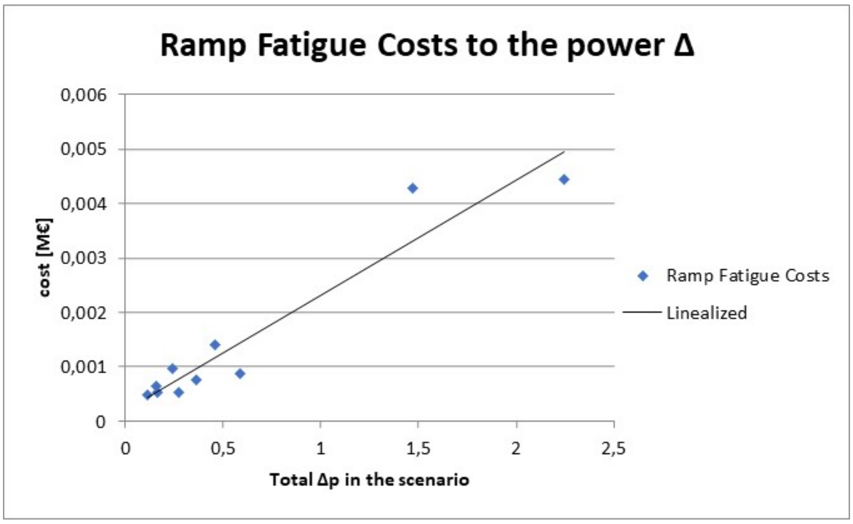

Figure 9. Relation between transition costs and number of start ups per scenario

To finish up, the cost composition per scenario can be seen in figure 10. It is the cost composition when taking into consideration the fatigue.

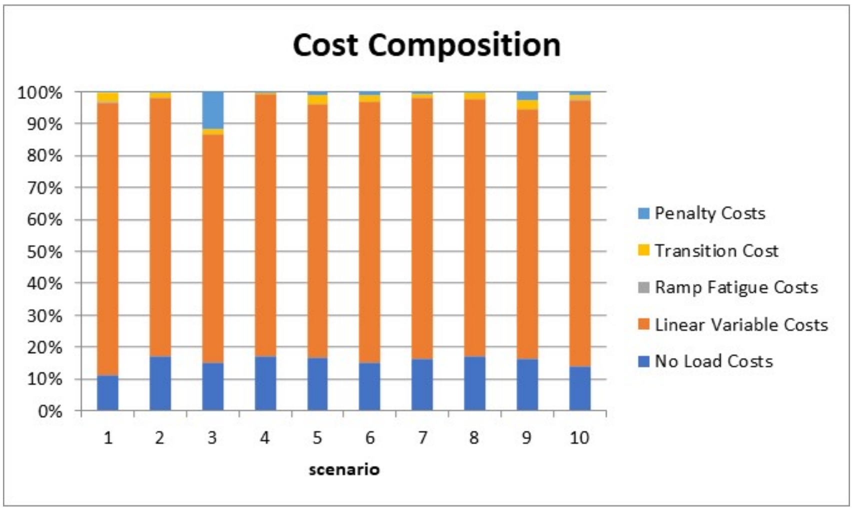

Figure 10. Cost composition of each scenario

From this cost composition can be deduced that the main costs are always the linear variable and no load costs. Among them they sum about 95% of the total costs in an average scenario. In specific scenarios there are also big penalty costs, it is when the costs of a start up are higher than the penalty for not producing at some point. But those costs are not affected by fatigue, which is the reason why the current models do work fine, fatigue affects mostly the other 1 to 5% of the costs, yet it should not be overlooked.

The important information about fatigue that comes with this sensitivity analysis can be seen in Table 5. It shows the regret of not considering the fatigue next to the total costs of the scenario.

	Total Costs (considering fatigue) [k€]	Regret [k€]
sc1	1586.96	22.03 (1.39%)
sc2	1214.68	19.09 (1.57%)
sc3	1803.26	20.19 (1.12%)
sc4	1703.70	0.53 (0.03%)
sc5	936.31	10.80 (1.15%)
sc6	661.86	4.31 (0.65%)
sc7	1447.66	4.90 (0.34%)
sc8	1249.52	19.48 (1.56%)
sc9	1818.12	24.11 (1.33%)
sc10	2148.66	12.22 (0.57%)

Table 5. Comparison between regret and total cost of operation for hand-picked scenarios

The conclusion that can be drawn from this information is that, even if in some scenarios the inclusion of the fatigue barely changes the operation and the costs (for example in scenario #4), there are other cases in which this inclusion can mean more than 1% of the total cost of operation. And in terms of real money, cutting the costs of operating a turbine more than 1% is a considerable improvement.

2.5.3 Sensitivity analysis of the representative demand scenarios

So far, every scenario analysed has been selected by hand. We now move to a more scientific scenario selection method: clustering.

Clustering is a mathematical technique that forms groups out of a set of data that contain most of the information inside the set. [12]

The most usual method of clustering is k-means, which obtains a series of "average values" in the centroid of the existing data. [13] But for this project this would not be ideal because forming "average scenarios" could end up with demand values that were under the technical minimum of the plant. Therefore, the clustering technique used is k-medoids, which selects from the existing scenarios those that gather the most information about the existing data.[14]

In order to gather the most information possible the number of clusters selected is 4. Looking at the Pareto curve about 95% of the variance from the data set is contained between these 4 clusters and an empty one (the demand set to 0 for all time steps), but to minimize the costs there you would only need the plant to be off, so it is not necessary to make this scenario analysis. The demand for each of them is shown in Figure 11 along with the commitment resulting from the optimization.

Another way to look at this, instead of with the commitment is looking at the energy produced by the plant in each moment in time. This information can be seen in Figure 12.

Finally, we show the regret for not considering fatigue in the operation of the turbine with each of the demand clusters and how much it supposes from the total costs. It is covered in Table 6.

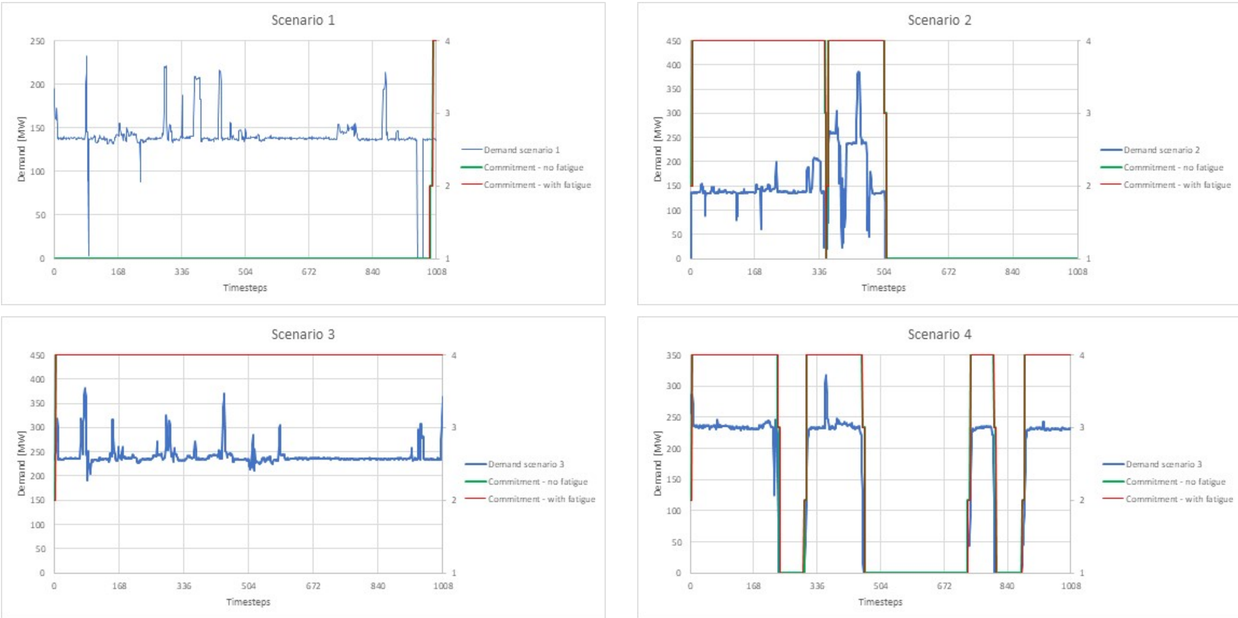

Figure 11. Demand input and commitment output for each cluster analysed

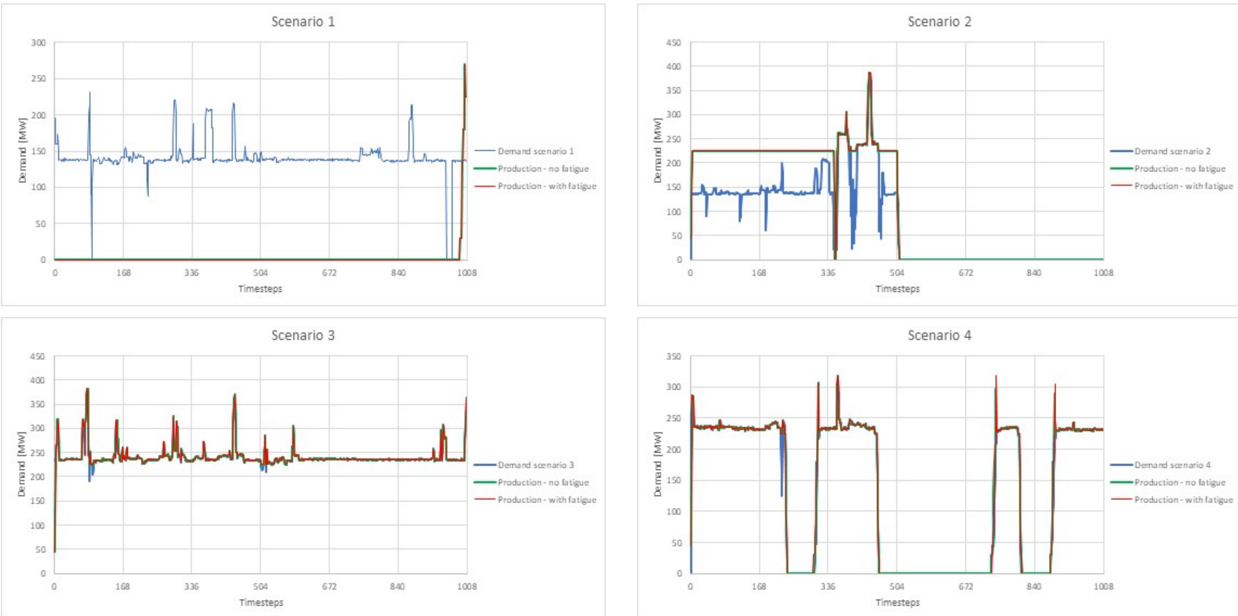

Figure 12. Demand input and production output for each cluster analysed

	Fixed unit commitment	Optimal unit commitment	Regret [k€]
cluster 1	9291.97	9291.97	0 (0%)
cluster 2	962.18	942.03	20.14 (2.14%)
cluster 3	1975.13	1968.26	6.87 (0.35%)
cluster 4	1127.09	1117.76	9.33 (0.83%)

Table 6. Comparison between regret and total cost of operation for the clusters

The most important concussion is that fatigue matters, and in some cases such as the second cluster it matters quite a lot. While there are some scenarios where the fatigue does not affect too much, there are others (those included in cluster 2) in which the addition of fatigue makes transitions more rare and the total cost of operation changes. Therefore, when a model that does not consider this fatigue cost is used, the result can be off from the optimal.

It is quite curious to think about the reasons behind the regret in scenario 2 being the highest of all, while in fact scenario 4 has more start ups, which are the main cause of fatigue. The reason for this apparent paradox is the kind of start up that is happening. In scenario 4 the solver is opting for a hot start up with the baseline form without fatigue and a hot start up with the A form for the with fatigue (the three different start ups considered are called baseline, A and B). In the fourth scenario there are 4 start ups, but all of them are warm except the first one. The first is a hot start up that follows the same curve in both cases with and without fatigue, the warm start ups do not follow the same curves but these forms have more similar costs so the total regret is still higher for the second scenario.

With more renewable generation going to be introduced in the system, it is very possible that the generators are forced to start up and shut down more often than in the scenarios studied (which are from 2014 and therefore the renewable generation level is not that high). This is a situation that would, with all probability, bring up the regret of not considering the fatigue.

2.6 Sensitivity analysis to fuel costs

This section explains the sensitivity analysis to the fuel prices that has been carried out for the cost minimization model.

There are two parts of the analysis:

1. A sensitivity analysis that varies the fuel cost of 5 particular demand scenarios from 50 to 75 €/MWh. This should give the reader a general view of the effect of an increase in the fuel prices on the cost minimization of the operation of the CCGTs.

2. A sensitivity analysis of one of those particular scenarios that varies the fuel cost 5€/MWh from 50 to 75. This is designed to have a more detailed look at how the increase happens, giving more importance to when the changes happen instead of what they are.

2.6.1 Part 1: general view of an increase in the fuel costs

In order to carry out a general analysis of what happens to the operation of the CCGT in case of an increase in the fuel costs, 5 different demand scenarios from the ones in Section 2.5.2 have been selected and run at a fuel cost of 50 and 75 €/MWh.

The scenarios selected where:

- The base case scenario: #1
- The scenario with the fewest start ups: #2
- The scenario with the least demand: #6
- The scenario with the highest start ups:#9

- The scenario with the most demand: #10

As for the input data, any change in the fuel costs affects the linear variables costs (after all the definition of the linear variable costs is the costs incurred when using fuel, therefore a higher fuel price is obviously linearly affecting this cost) and the transition costs, that are formed by a component of fuel cost and a component of fatigue cost (in the cases that consider fatigue).

Let us begin with the exposition of the results, commencing with the costs:

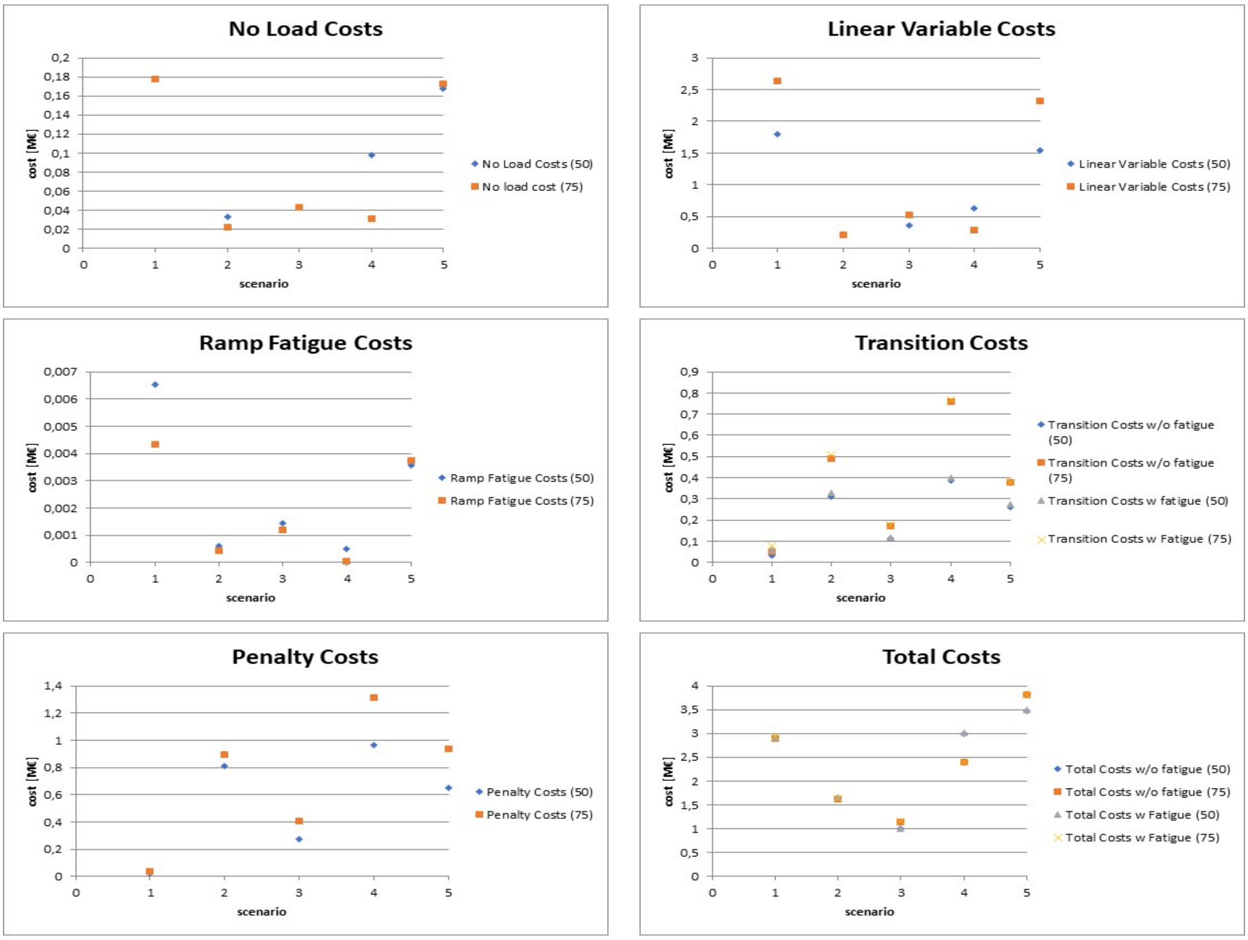

Figure 13. Comparison between the costs in each scenario for the different values of fuel prices

Figure 13 shows the comparison between the different costs at 50 and 75€/MWh for each of the scenarios mentioned. There is a lot of information that can be gathered from here.

- From the no load and linear variable costs can be deduced that a higher fuel cost can signify that the turbine is left shut down for more time. This is deduced from the higher no load costs in the cases in which the fuel price is 50€/MWh which also leads to lower (or very similar as in scenario 2) linear variable costs, while in the rest of the scenarios where the no load costs are maintained the linear variable costs are higher in the case of 75€/MWh.

- From the transition costs graph can be deduced that a higher fuel cost also implies higher transition costs, be it because the transition costs are higher or because the higher linear variable costs make it be worth it for the CCGT owner to shut down and restart up the plant more often than before.

- For the penalty costs, it is evident that the higher the fuel cost the higher the penalty too, therefore it can be assumed that the CCGT spends more time off than in other cases.

But this has some other implications, for example that the lineal correlation to demand that used to exist for the linear variable costs in the base case with 36€/MWh (see Figure 7) of fuel price is lost with this increase in price. Therefore not all scenarios are affected in the same way by this increase.

The same tends to happen with the correlation that used to exist between transition costs and the number of start ups, while in the case of 36€/MWh it was pretty linear (see Figure 8), the same does not happen in these two cases, where there tend to be more start ups in some cases while in others the number barely changes.

Finally, it is important to analyse the regret and the effect that the change in fuel costs has on it. Figure 14 has the values of the regret at the base case, the 50 and the 75€/MWh prices.

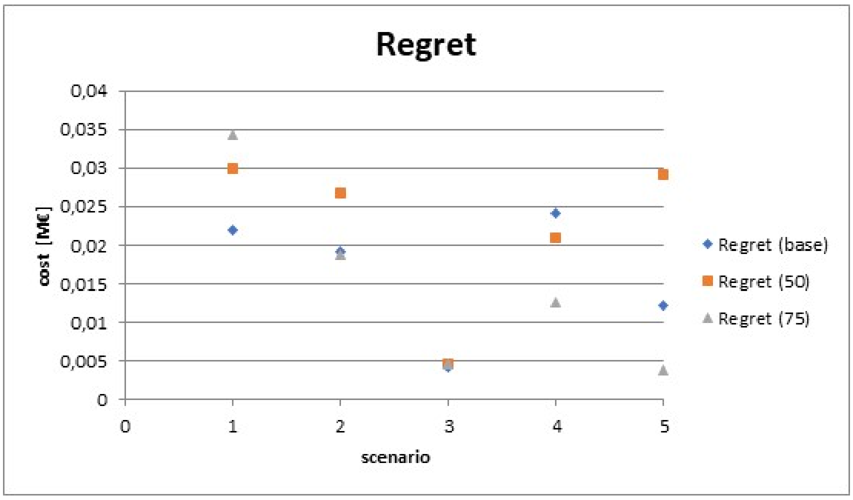

Figure 14. Regret for each scenario at the different fuel costs

From this data can be assumed that the regret does not relate in any way with the changes in prices, sometimes a higher price means it goes up but sometimes it means the complete opposite. In any case, it still remains relevant when compared to the total costs of each scenario (around 1%).

2.6.2 Part 2: in-depth analysis of a single demand scenario

In order to get more details about how these changes explained in Section 2.6.1 happen we have analysed a single scenario, scenario 2, with more values of fuel cost: Ranging from 50 to 75€/MWh in 5€/MWh leaps.

Scenario 2 has been chosen because it seems like most of the conclusions mentioned in Section 2.6.1 can be seen: no load costs fall, linear variable costs are maintained similar, penalty costs rise, transition costs are higher, etc.

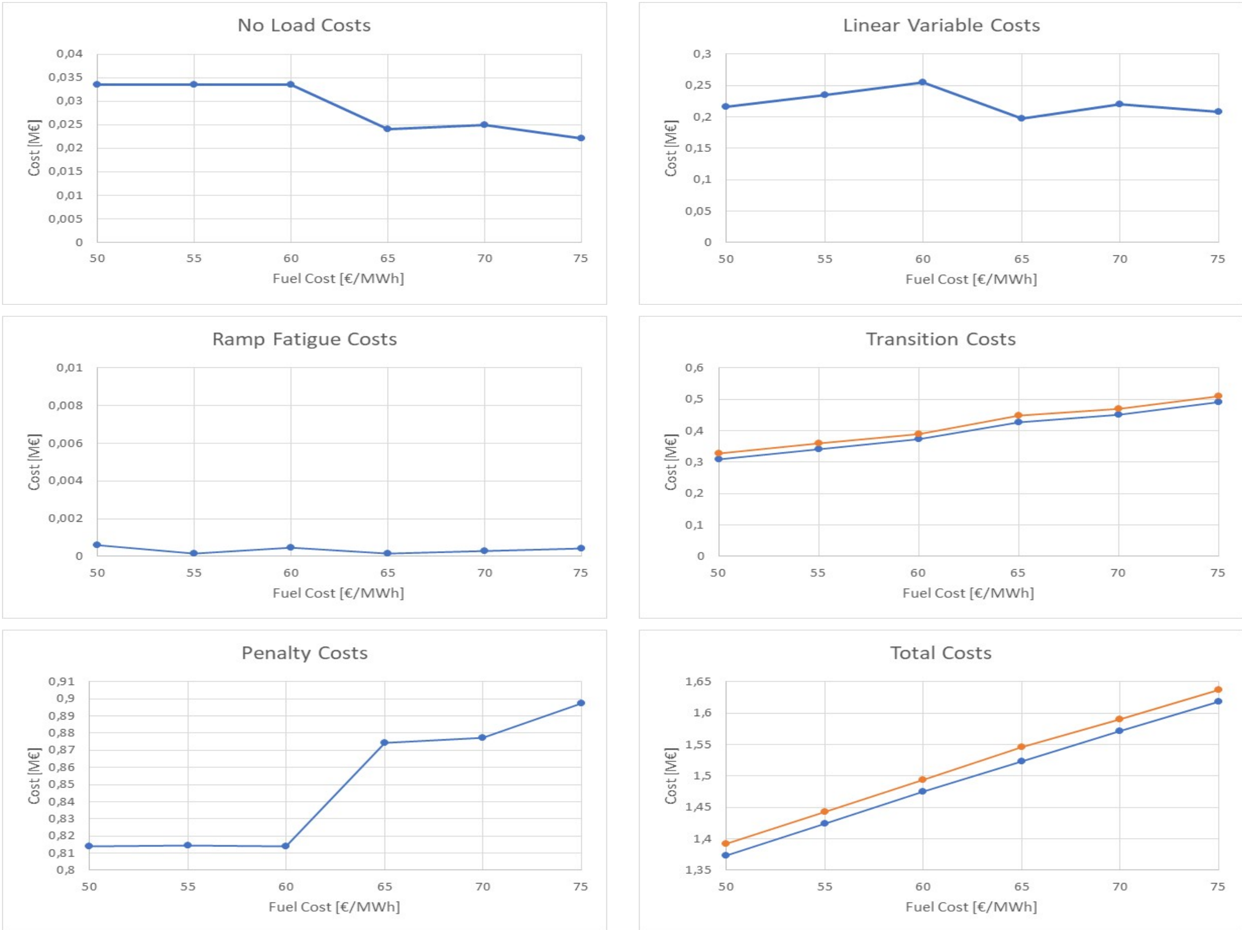

Figure 15. Costs of scenario 2 at each value of fuel price (in orange considers fatigue)

The graphs in Figure 15 show how the different costs behave when smaller rises in fuel price take place.

The no load costs show the trend that was already talked about in Section 2.6.1: they are kept the same until it is not optimal to keep committing resources into producing electricity, then the no load costs drop, but at the same time the penalty costs rise. This can be further viewed in Figure 16.

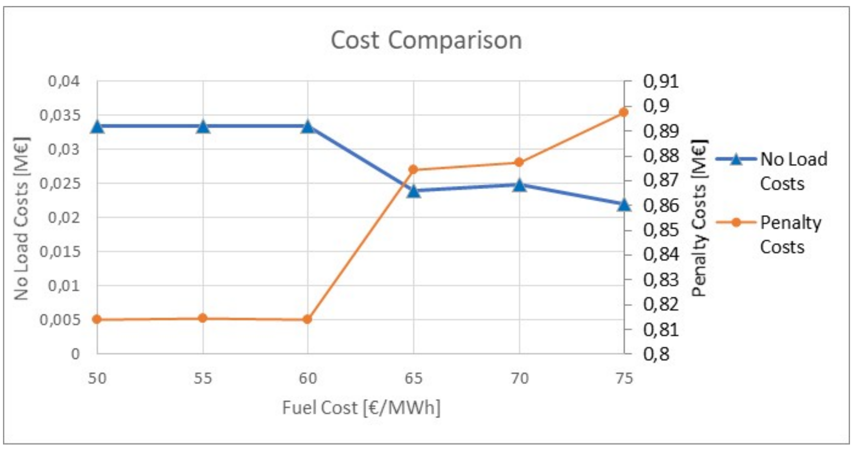

Figure 16. Comparison between the no load and penalty costs

Also, the upwards trend of the transition costs can also be seen in Figure 15, it is caused by a combination of the rising transition costs with the rising fuel prices and a higher number of transitions happening.

The next point that is worth seeing is the importance of the penalty costs within the total cost. While in the base case (at 36€/MWh, see Figure 5) the penalty costs were almost 0 here can be seen that even from 50€/MWh they are already very high. This can be seen in the cost composition, in Figure 17.

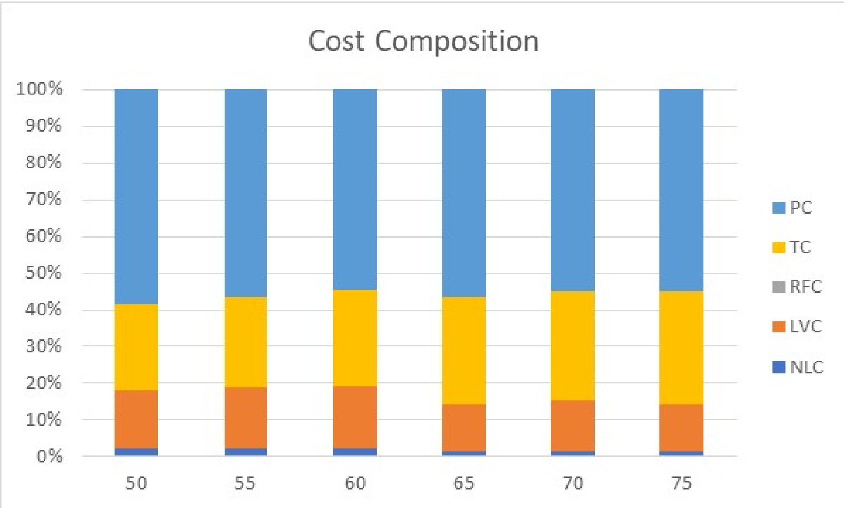

Figure 17. Cost composition of scenario 2 at each fuel price

Finally, it is important to talk about the regret, as mentioned in Section 2.6.1, the regret does not really respond to the changes in fuel prices in any linear way. This can be seen in Figure 18. At a fuel price of 65€/MWh it seems to spike up, this is only caused due to the particularly high step in transition costs, costs that influence the regret the most. In any case, we are still talking about around 1% of the total cost.

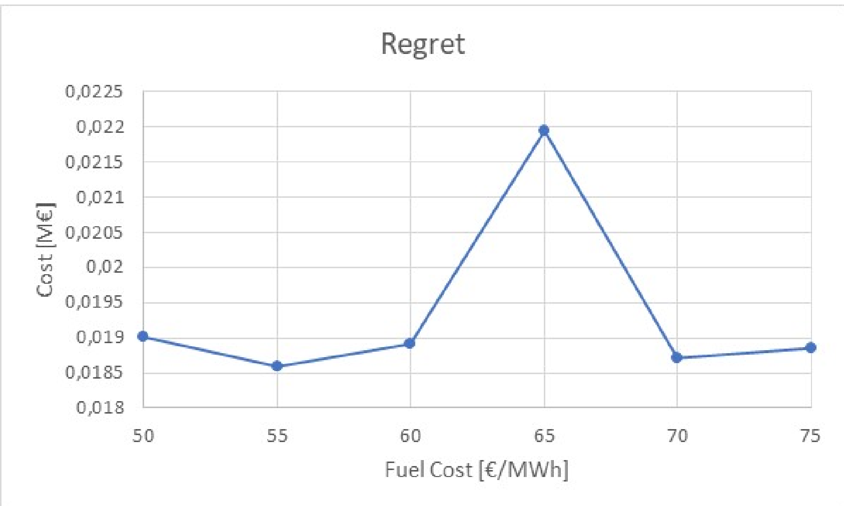

Figure 18. Regret of scenario 2 at each fuel price

2.7 Sensitivity analysis to the O&M prices

The third input that has been used in this sensitivity analysis is the O&M cost. This is introduced in the model through a base maintenance cost that then affects the transition and ramp fatigue costs. This is a cost that is associated to fatigue only, therefore any change to this parameter will not affect the solution of the first phase, which is the "no fatigue" solution.

The base case scenario that has been used for all the cases in this paper is a maintenance cost of 500000€. For this analysis it has been changed from 200000 up to 1M€in steps of 100000€.

The scenario used for this analysis is the base case scenario, scenario #1, because it is a general scenario that has start ups, shut downs and high and low demands within the week.

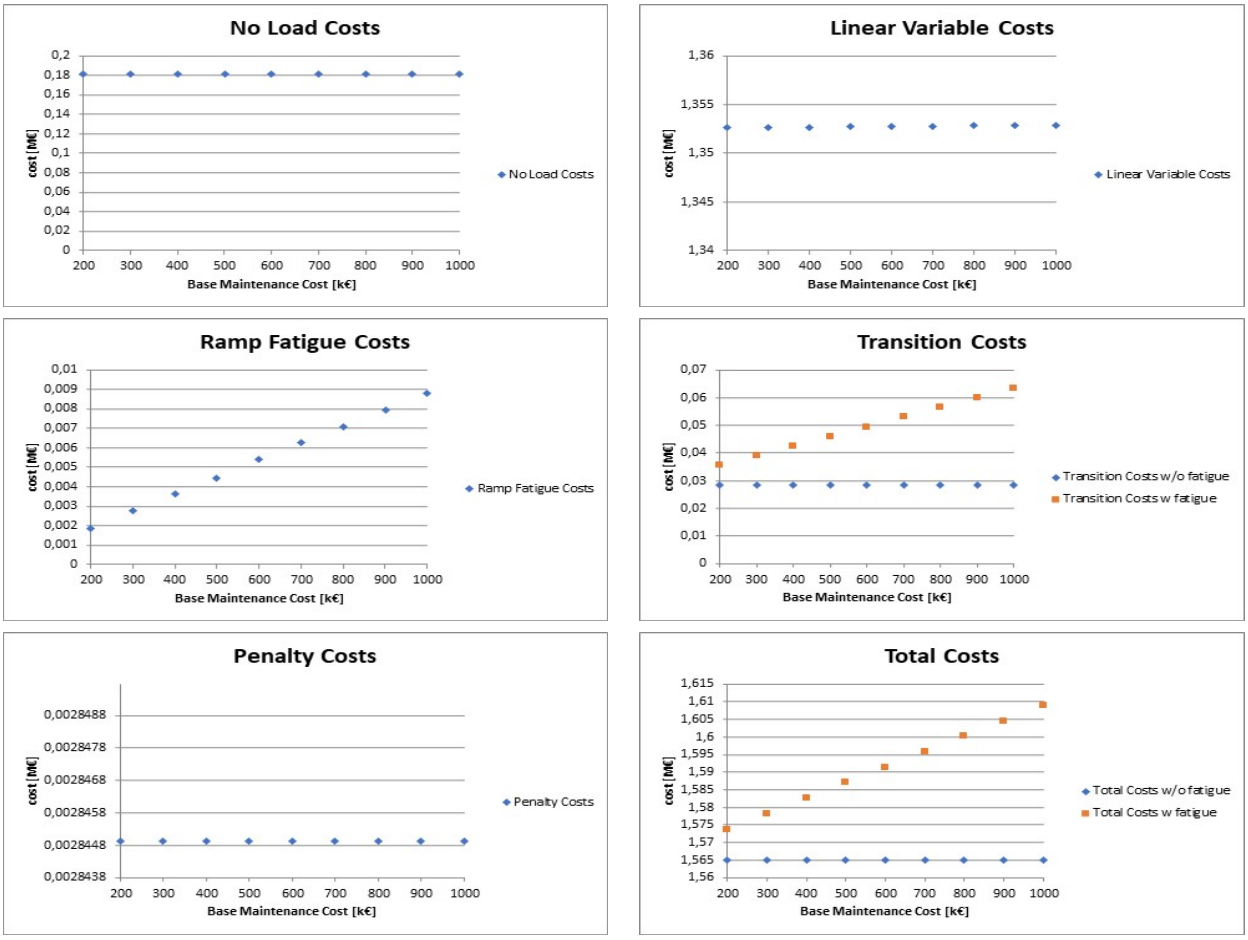

Figure 19. Costs of scenario 1 at each value of maintenance cost

Figure 19 contains the different costs of the CCGT at the selected values of maintenance cost. The main conclusion that can be obtained from here is that maintenance cost affects lineally the costs of the CCGT operation since fatigue is calculated as a percentage value.

As was to be expected there are only two costs affected by this changes in maintenance prices: the ones related to fatigue. Therefore, the maintenance cost is something that old models dismissed, but that this new model allows to consider. This can be further seen when looking at the regret in Figure 20. As the maintenance cost grows so does the regret of not considering it, therefore a plant with more expensive maintenance and components would benefit more from this new models that consider the fatigue.

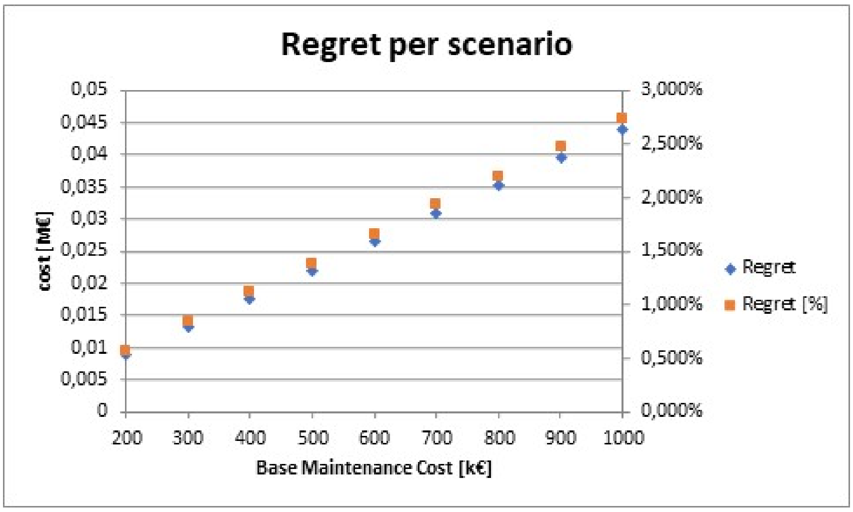

Figure 20. Regret at each maintenance cost

Chapter 3

Profit maximization self unit commitment model with fatigue considerations

In this chapter the profit maximization model that considers fatigue, which represents an original contribution of this thesis, will be developed. It is in many ways a similar model to the cost minimization model already presented, but the objective is completely different. The aim of this model is obtaining the bids and commitments that are better for the maximization of the profits for the owner of the CCGT.

The model has been created from the cost minimization model already explained in Chapter 2. Most of the equations, in fact, apply to both models, with one of the equations from the cost minimization disappearing and some tweaks to other existing equations, which will be explained as follows.

Since the objective is maximizing the profits, there is a second part that must be considered other than just the price for the energy and energy produced: the operating reserves.

Operating reserves are the capacity that a plant is able to provide if needed in a certain time. [7][8] There are three kinds of reserves:

- Frequency containment reserves (primary control) are used to compensate the slight and momentary changes in the loads connected to the system, they are done automatically by the plants at a signal from the system operator.
- Frequency restoration reserves (secondary reserves) are capacity available given by plants that are producing energy. This capacity is used to compensate bigger changes in the conditions of the system such as technical problems. They are necessary to guarantee that there are no threats to the imbalance of the whole system.
- Replacement reserves (tertiary control) are capacity that can replace the secondary reserves in case it is used. Plants that can be started up rather quickly can provide this reserve.

Primary reserves are provided automatically by the plants. They are considered an obligation and are not remunerated so they will not appear in this model.

A plant that can change its power output a quantity of X upwards and Y downwards in 15 minutes from a certain point in time will have X upwards and Y downwards secondary reserve capacity. In Spain as in most of the liberalized countries there is a secondary reserve market, where plant owners can bid day-ahead. The prices in this market are usually lower than the prices in the normal day-ahead market, after all what is offered here is only capacity that in case it is used will be paid at the marginal price of the day-ahead market. Secondary reserves will be modelled in this profit maximization approach, as a means to complement the revenues.

For the purpose of this model, secondary reserves are a way of earning money for free. As long as the reserve capacity offered is not required in real-time operation it is an income for the plant that does not have a cost other than a slight loss in efficiency, and if it were to be used that should be registered in a real-time operation model and is not possible to detect it in this day-ahead planning model.

The tertiary reserve that can be used to provide backup in case secondary reserve needs to be used also has its own market, with even lower prices and use rates. It has not been modelled although its inclusion would be done in a similar fashion to the secondary reserve.

In order to facilitate the inclusion of the reserves there is a second change that has been applied to the model: the time steps, that for the cost minimization problem were 10 minutes long, have been changed into 15 minutes time steps. This comes along with changes in how the start up and shut down curves are defined as well as some limits such as maximum and minimum duration of modes.

In the following sections the changes in the indices, parameters, variables and equations of Section 2 will be laid out. This includes new additions and a mention of the equations that are not necessary any more.

3.1 Index changes

All of the indices from the cost minimization model are kept and remain the same as explained in Section 3.1 except for the time steps.

The time steps now have a duration of 15 minutes instead of 10 minutes. The reasoning behind this change is the introduction of reserves. Since the secondary reserve is given in 15 minutes and the tertiary reserve in 30 minutes it is much more useful to change the time step into 15 minutes rather than keeping the 10 minute long time steps.

For the different modes of operation the new paradigm of longer time steps will need some different definitions to associated parameters such as durations or power curves.

3.2 Parameter changes

There are three changes to the parameters when comparing to the ones in cost minimization model explained in Section 2.2.

The first change is about the market price input. While in the cost minimization model it was purely there for an ex-post calculation, in this model it is the main input. In fact, for this model to work it is not only necessary an input for the day-ahead market price but also the prices of the upwards and downwards reserve markets.

These parameters will appear in the equations in Section 3.4 as $Price_t$, $PResUp_t$ and $PResDn_t$.

The second change is internal to some parameters that are affected by the change in the time steps from 10 minutes to 15 minutes: this change affects the ramp up rates RU_x, RD_x, RU_{xy} and RD_{xy} (the change is not directly in the rate since it is input as a maximum MW/h differential, but on the conversion to MW/time steps), the minimum up and down times of modes TU_x and TD_x and the fixed and maximum duration parameters DUR_x^{FIX} and DUR_x^{MAX}.

The final change is the disappearance of two parameters that are no longer needed: the Demand (now it is a decision variable, the power production) and the penalty cost (since there is no demand to be over or under it is not necessary to have a cost associated to the deviations).

3.3 Variable changes

Following the same reasoning behind the changes in the parameters, there are a few necessary changes in the variables.

Along with the power output there is a new need for two extra variables that contain the capacity set aside at each moment to be used as secondary reserve. These variables will be called in Section 3.4 $Res_{(dn)xt}$ and $Res_{(up)xt}$.

The total power outputs are used to calculate an hourly optimal bid which would then be sent to the market. The reserves work similarly: from the values obtained, an hourly optimal reserve bid can be calculated.

Usually, a bid consists of a certain power or capacity and a price, in this case, since the model works with a deterministic scenario with a defined price the bid only consists on the amount of energy or capacity to be offered at that price.

3.4 Equation changes

The profit maximization model shares a lot of the equations with the cost minimization model in Section 2,but at the same time, the differences between both models are very large.

The most important difference is non other than the objective of the model. Since this model aims to maximize the profits of the plant and not minimize the costs the objective function must be different. Still, since the definition of profit is revenues minus costs, the term of the costs must still appear in the objective function, that in the end is the following:

$$\sum_{t\in T}\sum_{x\in\mu}(Price_t \cdot e_{xt} + PResUp_t \cdot Res_{(up)xt} + PResDn_t \cdot Res_{(dn)xt}) - \\ (\sum_{t\in T}\sum_{x\in\mu}(C_x^{NL}u_{xt} + C_x^{LV}e_{xt} + C_x^{fat}\Delta p_{xt}) + \sum_{y\in M_{xy}^F} C_{xy}^{T}v_{xyt})) \tag{22}$$

There are also some other new equations and minor changes to other existing ones.

The ramping limits is the next part that changes. To the equations present in Subsection 2.4.5 there are two new ones that must be added:

$$RU_x u_{xt} \geq Res_{(up)xt} \qquad \forall t, x \in \mu_x^{UP} \tag{23}$$

$$RD_x u_{xt} \geq Res_{(dn)xt} \qquad \forall t, x \in \mu_x^{UP} \tag{24}$$

These new equations mean that the reserves can only be given at the modes of operation when at least one turbine is on, and that they can only reach the maximum ramp up rate.

These equations are the main reason why the time steps have been changed into 15-minute long time steps, because this way the reserve that the CCGT can give in 15 minutes is limited by the ramp up rate in 1 time step.

Including the reserves implies a second change to the equations. The generation limits now must consider them.

$$u_{xt} - \sum_{\mu^F_{xy} \$ \mu_y^{SD}} v_{xy(t+1)} \geq \frac{p_{xt} + Res_{(up)xt}}{\overline{P_x} - \underline{P_x}} \qquad \forall t, x \tag{25}$$

$$0 \leq p_{xt} - Res_{(dn)xt} \qquad \forall t, x \tag{26}$$

The maximum generation limit must now include a term of the upwards reserve. If the plant has a technical maximum output of 400MW and the owner selects 50MW to be left for reserves then the maximum generation is 350MW. The same happens with the downwards reserve and the technical minimum. If the CCGT needs to have a downwards reserve of 30MW and the technical minimum is 125MW then it must be producing at least 155MW for it all to be feasible.

3.5 Expected results and validation case study

With this model the results to be expected are the following:

- If the prices are low then the costs may be higher than the revenues if any energy is produced, therefore the optimization model will not want to produce any energy because it would be losing money, 0 earnings with 0 costs is better than negative profits.

- If the prices of energy are high enough then the optimization model will choose that the plant produces energy since there is profit to be made.

- In case energy is being produced the optimization model will have to decide whether or not it is profitable to have some capacity saved for reserves or it is better to use all available capacity for production. If the price of energy minus the costs of producing that energy is higher than the revenue obtained for upward reserves then the optimization model will opt for using the capacity for power production and will not save any capacity for reserves.

- In case the plant is producing it will mostly always be producing above its technical minimum, therefore there will always be a capacity for downwards reserve.

- Any combination of the above mentioned possibilities will result from changing energy and reserve prices.

A validation case study has been designed to test the model. Five scenarios with their particularities have been run. They have the same cost information as for the cost minimization case study described in 2, so the only difference among scenarios is in the inputs of day-ahead price and prices for reserves (the same price has been set for upwards and downwards reserves although they can differ in real life scenarios).

The price data used as input has been built to test the workings of the model and does not reflect reality, in fact, since the model uses 15-minute time steps the prices should be maintained for 4 time steps (since they are hourly prices), but this has not been considered, since it is only a validation case study. The prices have been designed as linear or piece-wise linear sets of data, since it is easier to understand how the plant would work this way.

The price scenarios that have been built and included in the model are reflected in Table 21.

As can be seen the first scenario has a growing day-ahead price and a decreasing price of reserves, the second scenario is closer to what reality would be, with a reserve price that is quite low and a changing day-ahead price scenario.

Scenarios 3, 4 and 5 have the same day-ahead prices but different reserve prices: 4, 20 and 36 €/MWh. These scenarios have been built to see the effects of the higher or lower reserve prices on the optimal CCGT production.

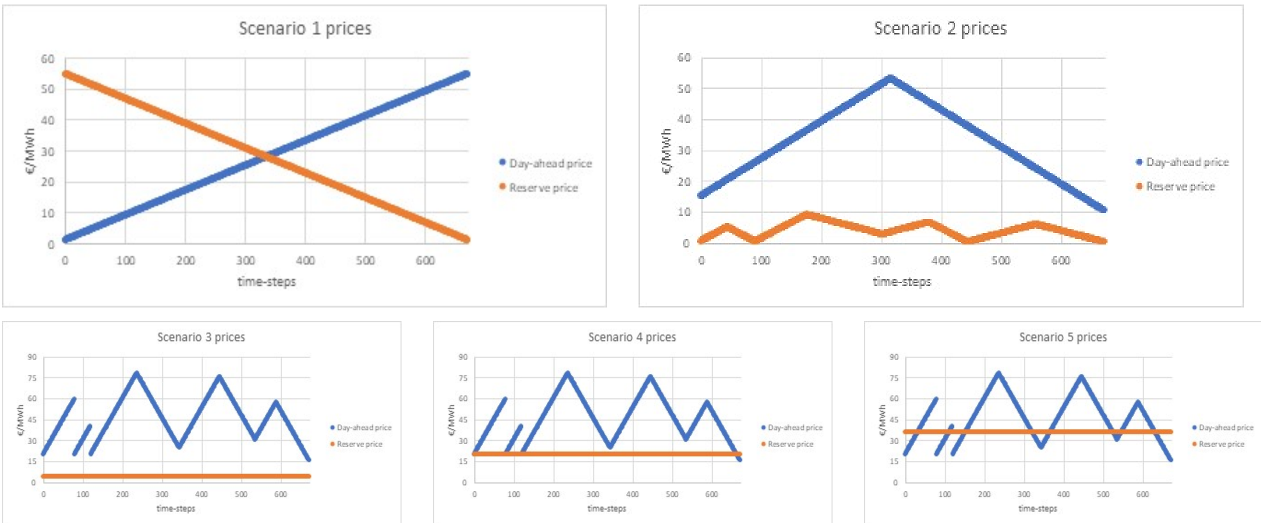

Figure 21. Price input for the scenarios analysed

First the results from the optimization of scenarios 1 and 2 will be discussed. In Table 22 the commitments and power produced in each scenario are displayed.

The first thing that is noticeable is the similarity between the commitments whether or not fatigue is considered for both scenarios. They are indeed pretty much equal, with the main difference being that in some cases, the start ups that do not consider fatigue are undertaken one or two time steps later, and have a higher slope. An initial reasoning for that is that fatigue penalizes more the start up curves that are faster. In any case, this should be farther analysed in a future sensitivity analysis.

Figure 22. Commitment and production outputs for scenarios 1 and 2

The first scenario has the plant shut down until the day-ahead price reaches close to 25€/MWh, even at reserve prices of up to 55€/MW. Then, until the day-ahead price does not reach about 40€/MWh the plant will be producing at the technical minimum with both the gas and steam turbines on (225MW) and will be earning money from the upwards reserve of up to 175MW. Then, once the reserve prices fall down in value and with the ever-growing day-ahead price the plant will switch to working at the technical maximum and earning money from the downwards reserve.

While at first glance the second scenario does too have a growing day-ahead price and should therefore be started up at around the same price as in scenario 1, the absence of the extra income from a high reserve price that exists in scenario 1 makes the optimization model skip the moment when the plant is at the technical minimum with the two turbines working and go directly to the technical maximum of 400MW for as long as the price is high enough.

Further comparison of the effect of the reserve price on the commitment and production of the plant can be obtained comparing scenarios 3, 4 and 5. Table 23 contains the commitment and production for each of the scenarios.

The commitment graphs show that with the same values of day-ahead prices, big changes in reserve prices matter in the operation of the CCGT. The instances in which the plant will be off with higher reserve prices are much smaller, and even non-existent if they are high enough. It is interesting to see that the optimal use of the plant uses only three states: off, on at the technical minimum with both turbines working and on at maximum power production. The relation between the day-ahead and reserve prices and the costs of the fuel and maintenance is the deciding factor between each of the three states.

In order for easier reading of the data, Table 24 has the comparison between the production, upwards reserve and downwards reserve of the 3 scenarios.

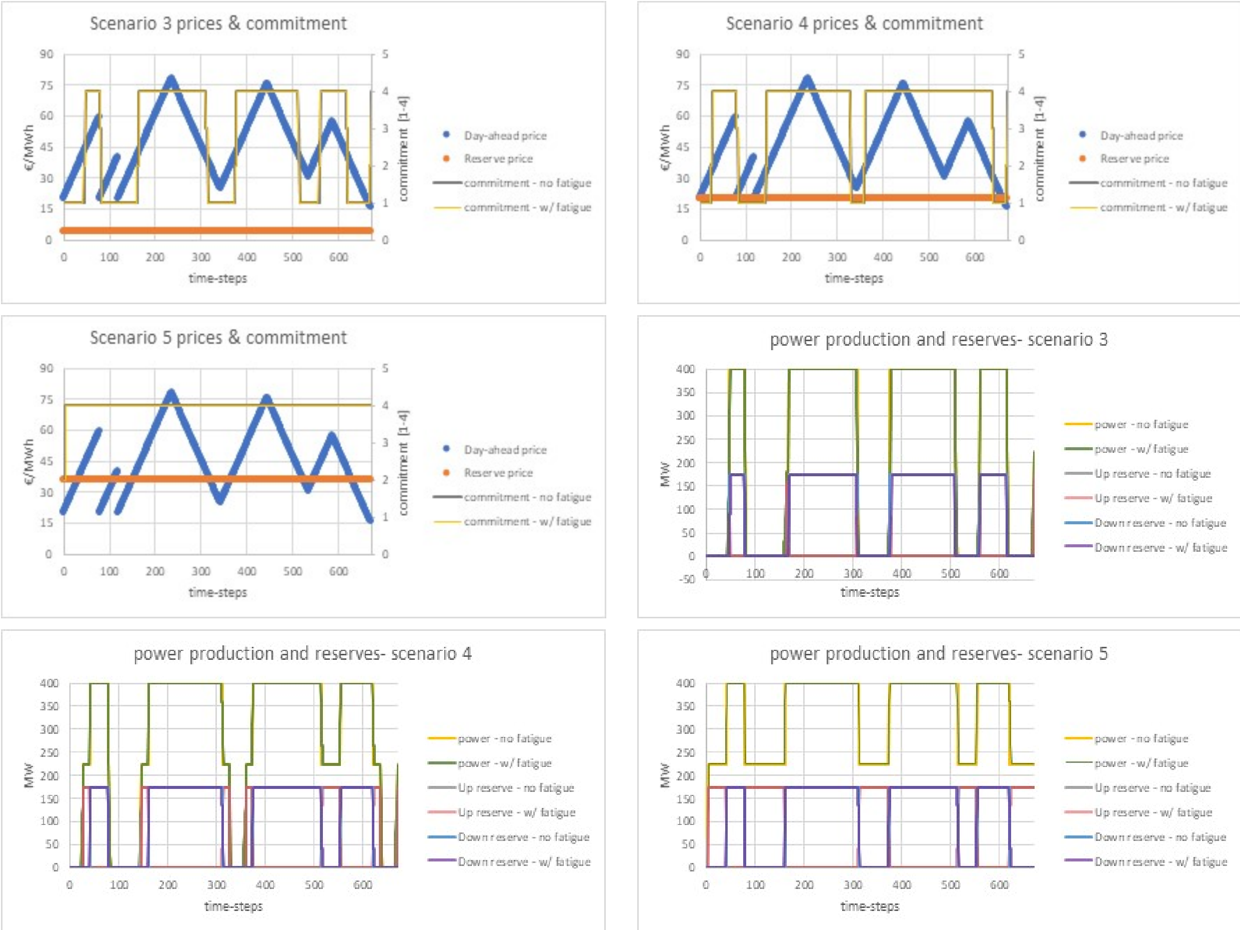

Figure 23. Commitment and production outputs for scenarios 3, 4 and 5

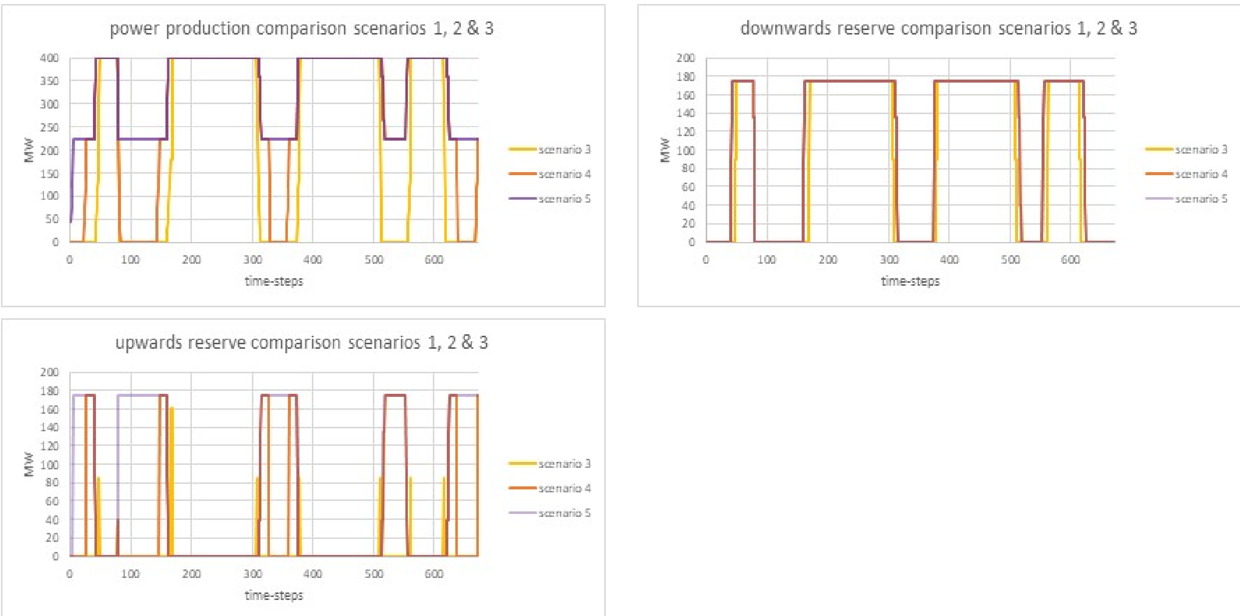

Figure 24. Comparisons between production and reserves in each of the 3 scenarios

To conclude it is important to analyse the regret. Each of the scenarios has been analysed with and without considering the fatigue, the difference between the profits obtained by the scenarios analysed with fatigue and the ones obtained without considering it is the regret. This regret along with the total profits can be found in Table 7.

	Total profits (no fatigue) [k€]	Total profits (considering fatigue) [k€]	Regret [k€]
sc1	116.51	132.56	16.05 (12.11%)
sc2	70.75	74.28	3.53 (4.75%)
sc3	46.35	49.48	3.13 (6.33%)
sc4	75.80	79.25	3.45 (4.35%)
sc5	1217.68	1227.09	9.41 (0.77%)

Table 7. Comparison between regret and total profit in each scenario

The conclusion that can be obtained analysing these results is that the profits are highly dependent on the fatigue. Using the tools that are available today that do not consider this "extra" cost is costing quite a lot of money to the plant owners that they would be able to get otherwise.

Chapter 4

Stochastic cost minimization model

In this chapter the cost minimization model will be changed to introduce stochasticity. In the real world there is no deterministic data about the future, so in order for the model to be useful it must be able to adapt to the any possible scenario that can happen. This chapter introduces the ways in which the cost minimization model can be adapted to optimize the commitment of the plant given a set of possible demand curves as inputs.

With this in mind the decision making process needs to change. Now the optimization will not be of any particular scenario, but the optimization will give a set of variables that cannot change depending on the scenario and a second set of variables that can change from a scenario to another.

The variables that cannot change from one scenario to another are the ones that must be programmed with time: the commitments and transition decisions. These variables cannot change from a moment to another, they take time, so they must be fixed whatever scenario ends up happening.

On the other hand, other variables such as the power production can cbe changed very easily, so they can adapt to the particular scenario that is happening in real time.

In order for this model to work though, the model explained in Chapter 2 must be used first. The possible scenarios must be solved as if they were deterministic, and the results obtained from their solutions must be used as input for the stochastic model.

In the following sections the changes that are necessary to adapt the cost minimization model in Chapter 2 to include the stochasticity are shown.

4.1 Stochasticity-related indices

This cannot be considered a strict change from the cost minimization model, but to clarify it is important to say that 10-minute time steps have been used.

Then a new index is necessary: ω, which will contain the different scenarios, so that they are all evaluated by the same model.

4.2 Stochasticity-related parameters

There are only two changes in the parameters from the cost minimization model shown in Chapter 2, being the first of them the demand. This time there is not a single deterministic demand scenario that must be introduced in the model, instead there are multiple demand scenarios that are uncertain. These parameters must all be introduced, in order to do that the parameter "Dem_t" is swaped for the parameter "Dem_t^ω".

The second change is that, as explained in the introduction to this chapter, the results obtained from minimizing the costs of each scenario as if it were deterministic are considered as an input. To do this we have used the variable Tot^ω_{cost}. This is needed to compute the regret associated to the demand stochasticity.

4.3 Stochasticity-related variables

The variables is where most of the differences between the deterministic and stochastic cost minimization models are found. There are two types of variables in the stochastic model: those that do not change with each scenario (transition and commitment decisions) and those that change with the scenario (all the rest of the variables). The ones that do change with the scenario need a new variables which is the same as in the deterministic model but now stores a different value for each of the scenarios: p^ω_{xt}, Δp^ω_{xt}, $\hat{p}^\omega_{xt}$, e^ω_{xt}, $Dev^\omega_{(dn)t}$ and $Dev^\omega_{(up)t}$.

Then there are two variables that are used to compare the results of the scenarios solved with the deterministic model and the stochastic model, they will therefore contain the regret: α^ω and α^{TOT}. α^ω is used to compare each of the deterministic scenarios with the best alternative with the fixed commitments. α^{TOT} is then used to sum the effects of all the α^ω. It is the variable that is minimized by this model.

4.4 Stochasticity-related equations

The most important equation in any optimization process is the objective function. This is the equation that will be minimized or maximized, depending on the model. In this case the model aims to minimize the regret of choosing the general commitment and transition variables that will have to be used in every scenario. This regret is called α, and therefore the most important new equations that are necessary for the optimization are the ones that define this α.

$$\alpha^{TOT} = \max \alpha^\omega \tag{27}$$

$$\alpha^\omega = \Big(\sum_{t\in T}\sum_{x\in\mu}(C_x^{NL}u_{xt} + C_x^{LV}e^\omega_{xt} + C_x^{fat}\Delta p^w_{xt}) + \sum_{y\in M^F_{xy}} C^T_{xy}v_{xyt} + \sum_t C^{pen}(Dem^\omega_t - \hat{p}^\omega_{xt})\Big) - Tot^\omega_{cost} \qquad \forall\omega \tag{28}$$

While the introduction of the definition of α is the first step towards making this model work, there is a second set of changes that needs to happen. All of the equations need to be reformulated, changing in them the following variables and parameters:

$p_{xt} \rightarrow p^\omega_{xt}$
$\Delta p_{xt} \rightarrow \Delta p^\omega_{xt}$
$\hat{p}_{xt} \rightarrow \hat{p}^\omega_{xt}$
$e_{xt} \rightarrow e^\omega_{xt}$
$Dev_{(dn)t} \rightarrow Dev^\omega_{(dn)t}$

$$Dev_{(up)t} \quad \rightarrow \quad Dev^{\omega}_{(up)t}$$
$$Dem_t \quad \rightarrow \quad Dem^{\omega}_t$$

And along with this, all of the equations where any variable depends on the stochastic scenario ω need to be evaluated for all the stochastic scenarios ($\forall\omega$).

4.5 Validation Case Study

For the purpose of trying the model, a small validation case study has been made. A series of 3 50-time steps hand-made scenarios has been built and the program has been run for them. Since this is a cost minimization approach model they are demand scenarios. The three demand scenarios built are shown in Figure 25.

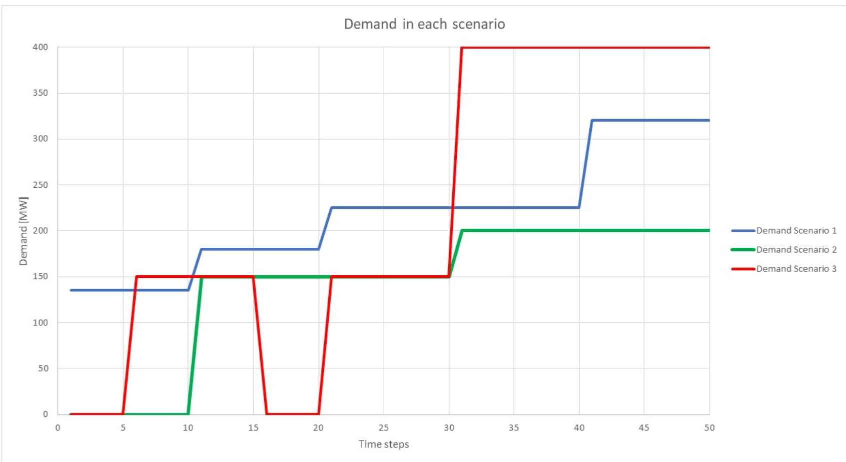

Figure 25. Demand of each stochastic scenario

The first step to solving this cost minimization is solving each of the scenarios as if they were deterministic. Figure 26 contains the commitment of each of the scenarios assuming they are deterministic. This is what I have called optimal commitment for each of the scenarios.

In all three scenarios the demand is low at the beginning but high at the end, but particularly in scenario 3 the demand falls to 0 in the middle part, so in that scenario it is optimal to shut down the turbines. This is what the commitments in Figure 26 shows.

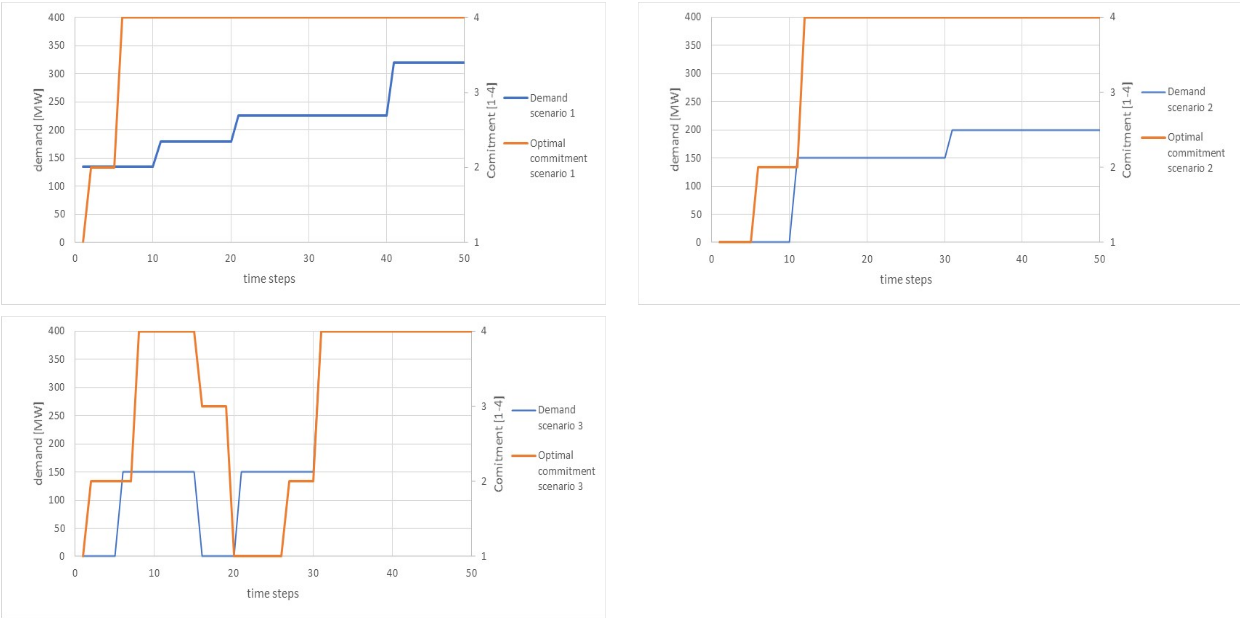

Figure 26. Comparisons between production and reserves in each of the 3 scenarios

Once that information is obtained, the results in terms of costs can be used to solve the stochastic approach. The optimization model gives the optimal commitment decisions that minimize the maximum regret of choosing one commitment over the other.

Figure contains the commitments of each of the scenarios as if they were deterministic and the optimal general commitment, the one that minimizes the regret.

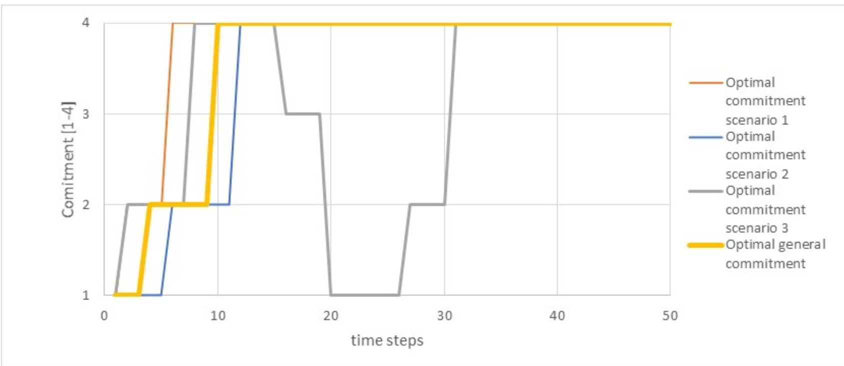

Figure 27. Stochastic optimal commitments and comparison with the deterministic ones

As expected it starts off and ends up on. In the middle part is where the optimization model decides that it is better to leave the turbine on and accept the cost of having it on for a while and lose money if scenario 3 were to happen rather than shut down the turbine and assume the non served energy costs (penalty costs) in case that scenarios 1 or 2 were to happen.

This validation case study shows that the model seems to work, but further sensitivity analysis should be made in order to reach more conclusions.

Chapter 5

Stochastic profit maximization model

IN this chapter the same process of building an stochastic version of the cost minimization model that was employed in Chapter 4 will be applied to the profit maximization model.

The objectives of introducing stochasticity in the profit maximization model remain the same as they were when introducing it into the cost minimization model: making it be able to adapt to the different possible future scenarios that may arise, arriving at an optimal decision for the commitment and transition variables.

The following sections contain the changes that need to be introduced to the profit maximization model in Chapter 3 to make it stochastic.

5.1 Stochasticity-related indices

As happened in section 4.1, the indices that are necessary remain the same as in the deterministic profit maximization model but adding ω, the index that is necessary to save the information that differs from one scenario to the next.

Here it is also important to clarify that the time steps length is 15 minutes, as in the profit maximization model in Chapter 3, so that the reserves can be modelled easily.

5.2 Stochasticity-related parameters

The same kind of changes that applied to section 4.2 will be happening to the profit maximization model: the inputs will now need to be from a series of scenarios instead of a single one and the profit calculated for each of the scenarios using the model in Chapter 3 and assuming they are deterministic needs to be included in the model.

Since the profit maximization model has more inputs than the cost minimization (the energy price and the two reserve prices) there are three input parameters that need to change from simple "$Price_t$", "$PResUp_t$" and "$PResDn_t$" to the same parameters but also depending on the scenario: "$Price_t^\omega$", "$PResUp_t^\omega$" and "$PResDn_t^\omega$".

As for the parameter that includes the profits resulting from running the deterministic scenarios with the profit maximization model in Chapter 3, they are introduced with the parameter Tot_{prof}^ω.

5.3 Stochasticity-related variables

Once again, this change is very similar to the one necessary when introducing stochasticity to the cost minimization model, as explained in Section 4.3.

On the one hand there are variables that will now change for each scenario, which will need the index ω to work: p^{ω}_{xt}, Δp^{ω}_{xt}, $\hat{p}^{\omega}_{xt}$, e^{ω}_{xt}, $Dev^{\omega}_{(dn)t}$ and $Dev^{\omega}_{(up)t}$.

On the other hand, there are the new variables that allow the optimization model to decide which general commitment decision is better and which one is worse: the variables α^{ω} and α^{TOT} will contain the regret, in terms of profit, of choosing one commitment or another when compared with the optimal commitment obtained from the same scenario studied as deterministic and the total regret of choosing the generally optimal commitment respectively.

5.4 Stochasticity-related equations

Finally, the changes in the equations are also the same as the changes that were needed to change the deterministic cost minimization model in Chapter 2 to the stochastic version in Chapter 4.

The first change is the introduction of the definition of the parameters α^{ω} and α^{TOT}.

$$\alpha^{TOT} = \max \alpha^{\omega} \tag{29}$$

$$\alpha^{\omega} = Tot^{\omega}_{prof} - (\sum_{t\in T}\sum_{x\in\mu}(Price^{\omega}_t \cdot e^{\omega}_{xt} + PResUp^{\omega}_t \cdot Res^{\omega}_{(up)xt} + PResDn^{\omega}_t \cdot Res_{(dn)xt})^{\omega} \\ -(\sum_{t\in T}\sum_{x\in\mu}(C^{NL}_x u_{xt} + C^{LV}_x e^{\omega}_{xt} + C^{fat}_x \Delta p^{\omega}_{xt}) + \sum_{y\in M^F_{xy}} C^T_{xy} v_{xyt}))) \quad \forall\omega \tag{30}$$

The total regret is still defined as the sum of the regrets of each of the parts and the regret of each part is calculated as the subtraction of the maximum profit obtained with the general commitments to the total profit of the scenario if it were deterministic.

Since the total regret will always be positive, the optimization model will want to minimize the variable α^{TOT}.

Finally, it is also necessary to change the variables in each of the equations for their versions dependent on the stochastic scenario ω.

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PART II

SUSTAINABLE DEVELOPMENT GOALS

Chapter 1

Introduction to the SDGs

The sustainable development goals (SDGs for short) are 17 global goals set by the UN that have been accepted by governments all over the world and, if achieved, would make the world a better place in its broadest definition.

The SDGs include objectives that reduce inequality between people, that improve life standards and protect the biodiversity. They are designed to touch every area where there are improvements to be made by the human species.

Figure 28 contains the main titles and logos that have been given to each of the 17 sustainable development goals.

Figure 28. Sustainable Development Goals

Although the goals are too important on their own to be classified there is an argument to classify them in goals that aim to reduce inequalities (no poverty, no hunger, good health, quality education, gender equality, clean water and sanitation, reduction of inequalities), goals that relate to climate and biodiversity (clean energy, climate action, sustainable cities, life below water, life on land), goals related to economic growth (decent work and economic growth, industry, innovation and infrastructure) and goals that rely on the individual and collective responsibility (responsible consumption and production, peace, justice and strong institutions and partnership for the goals).

All in all, these objectives have been set with the idea that a move in this direction must help solve the most important issues in the planet right now. It is not just and reasonable that while 1% of the population has 82% of the world's wealth there are over 700 million people living in extreme poverty. It is unthinkable that, with more than 3 billion people on the planet depending on marine and coastal biodiversity, nothing was being done to keep the oceans clean, and therefore over 10000 tons of plastic a year were getting to the oceans.

In this context, aiming at a better future for all, in the frame of the 70th edition of the United Nations general assembly on the 25th September 2015 the sustainable development goals were agreed upon by all countries in the world within the 2030 sustainable development agenda.

Chapter 2

Relation between this project and the SDGs

This project presents a new approach to the operation of CCGTs, combined cycle gas turbines. Therefore the main areas of interest of the project are energy and industry.

From the 17 SDGs there are a few related to energy and industry, mainly #7: affordable and clean energy, #9: industry, innovation and infrastructure and #12: responsible consumption and production.

The complete formulation of goal #7 is "Ensure access to affordable, reliable, sustainable and modern energy". The world is already making an effort to move in this direction, there are some encouraging signs of energy becoming more sustainable and available. While access to energy is not a problem in Spain, my project can relate to the sustainable part of the SDG. In a world were there are more and more renewable energy sources being introduced in the system and other polluting technologies falling out of favour and even being closed there is a problem that comes with the need of security of supply of the electric system. In this context is where the future of CCGTs is clear, until storage technologies are developed they will need to occupy the role of firm capacity, since they are the technology that is better able to adapt to the changing productions of renewable sources.

The official formulation of goal #9 is "Build resilient infrastructure, promote sustainable industrialization and foster innovation". This goal aims at grouping together inclusive and sustainable industrialization with innovation and infrastructure in order to unleash dynamic and competitive economic forces to generate employment and income. In this context, this project can help the industry of energy generation from gas, that has not changed much in the last 15 years, to have a better understanding of their costs. Introducing this new variable into their decision making process can help revitalize the industry increasing the profits or the competitiveness against other technologies.

As for the goal #12, its full formulation says "Ensure sustainable consumption and production patterns". In the energy industry the way in which you make energy production sustainable is through the introduction of renewable energy sources. But without firm capacity the energy transition is not feasible. giving the firm capacity to make the transition possible will be the main role of the CCGTs, and therefore this project also aligns with goal #12.