UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master’s Thesis

COMPARISON OF DIFFERENT MODELING APPROACHES OF COMBINED-CYCLE GAS TURBINES AND REGULATORY REVISION OF THE THIRD PARTY ACCESS TO THE GAS NETWORK

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Madrid, July 2019

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Abstract

Gas has become the first non-renewable option for electricity production in many countries around the world. Three reasons have made it possible for gas units: lower environmental impact during production than coal plants, no social rejection like nuclear plants and greater flexibility and quicker operation than them both. Gas are expected to play a major role in the electricity sector in the coming years.

Under these expected circumstances, there are two fields related to gas that gain special relevance. In one hand, the owner of the different gas units need to guarantee access to the gas infrastructure in order to have gas when needed and avoid the undesirable situation of not being able to produce when the electricity market is providing signals to do so.

The European Union is seeking to harmonise its internal energy market passing regulations to its Member States. Regarding Third Party Access, the European Commission has created a network code on harmonised transmission tariff structures for gas to improve tariff transparency and coherency by harmonising basic principles and definitions used in tariff calculation by Member States.

Considering the Iberian Peninsula countries, in Spain Third Party Access to the gas infrastructure is regulated by Real Decreto 984/2015 and Real Decreto 335/2018 while in Portugal Decreto-Lei 30/2006 is in charge of organising the different gas services.

Combined-cycle gas turbines consist of gas turbines, a heat recovery steam generator and steam turbines. That provides multiple operating configurations which leads to a complex optimization problem if CCGT are included in a unit-commitment problem. Typically CCGT are included in these formulations using a configuration-based model in which the CCGT can operate in certain states with different technical characteristics. However, in practice, CCGT are most of the time in three states: off, working with one gas turbine and one steam turbine or working with two gas turbines and one steam turbines. This leads to he possibility of just modeling those three states, creating a simplified formulation. A comparison between the complete configuration-based aprroach and the simplified formulation has been done in this Master Thesis, obtaining equivalent results between them.

Finally, Plexos software has been used to try model CCGT operation in a similar way. Plexos allow to model the individual gas turbines and steam turbines as different Generation objects and linking them together through the Generator Heat Input membership. An alternative is to model a single equivalent generator using a complex heat rate function. However, neither of the two approches is fully equivalent to any of the two proposed formulations because in the formulation proposed, the different modes can include both gas and steam turbines.

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Chapter 1

Introduction

In the past 20 years, the popularity of gas for electricity generation has increased over other options such as nuclear or coal. There are several reasons behind this past evolution and some others to expect that gas-fired power plants (GFPP), like combined-cycle gas turbines (CCGT), will remain being an important part of the electricity mix around the world.

Gas has been the choice over coal because of their environmental benefits while social concern has left nuclear power out of the game in many countries. In the near future, while renewable will trend, there will be a need for firm capacity to solve renewable's reliability issues and gas units have the needed requirements to play this role. Furthermore, GFPP provide more flexibility in their operation, have a greater efficiency than other fossil fuel-fired units, tipically cost less and are quicker in operation than their alternatives.

In order to be the best non-renewable option for electricity generation, gas should have an efficient supply chain to favour all the benefits previously stated. The supply chain is composed of three main activities: production, transport and distribution for consumption [7].

The natural gas supply chain is shown in Figure 1.1. It is imposible to economically transport the natural gas in the conditions it is extracted: ambient temperature and gas state. It would be necessary a gas temperature between 200°C and 300°C to easily transport it. Instead of doing that, there are two different feasible options. Natural gas can be send through high pressure pipelines (gas form) of by ship (liquid form). For the gas exported by ship, it is necessary to have a liquefaction plant in the exporting country, where it is cooled down until it becomes liquid and a regasification plant where liquefied natural gas (LNG) is heated up and transferred to the transmission pipelines in the form of gas [7].

Despite the huge infrastructure developed around the world, almost 70% of the gas is consumed in the same country where it is produced. Of the remaining 30%, two thirds are exported through pipelines and one third through ships [6], as shown in Table 1.1.

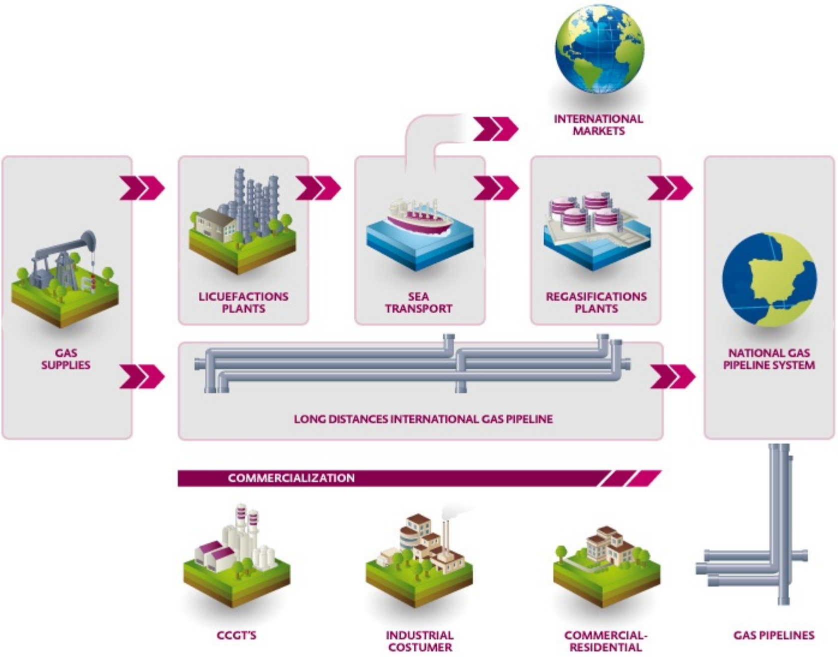


Figure 1.1: Natural gas Supply Chain [1].

Table 1.1: Global gas consumption and exports [6].

Type of trade/consumption	**In bcm**	**%**
Total world consumption	3670.4	100
Consumption in producing countries	2536.3	69.10
Import by pipeline	740.7	20.18
Import by LNG (ship)	393.4	10.71

Natural gas has different final uses: electric power generation, industrial and residencial consumption. Focusing in Europe, total consumption in 2017 was 548 bcm of which around 140 bcm were used for power generation (around 26% of total consumption).

There are seven countries leading gas consumption in Europe which are shown in Table 1.2, which offers the amount of gas used for power generation, the total installed capacity of GFPP, the average utilisation of those plants and the country total gas consumption [8]. Depending on each country energy mix, installed power, typical gas uses and country conditions, it can be more or less dependent on gas for power generation. Germany is the country with overall highest gas consumption in Europe (92.0 bcm) [9]. However, they are not as dependent on gas for power generation as other European countries. For instance, Italy and Great Britain, which rank second and third in total consumption, have the two highest figures for electricity generated from GFPP and are two of the three countries with more gas capacity installed.

Spain's figures differ from the other countries. Despite being the second country with highest gas generation capacity, its load factor is so small (slightly below 22%) that it is the country with less electricity generated with gas as primary source of those in the comparison. That fact together with the relatively small use for other purposes (residential and industrial) that Spain makes of gas results in Spain ranking seventh in total gas consumption in Europe.

Table 1.2: Total gas consumption and electricity generation from gas in main european countries.

Country	Gas for power (TWh)	Installed capacity (MW)	% capacity utilization	Total consumption by country (bcm)
Great Britain	143.6	31124	52.7	79.6
Italy	126.2	44283	32.6	75.2
Turkey	108.2	26637	46.4	53.6
Germany	82.9	30582	30.9	92.0
Netherlands	73.6	18433	45.6	46.4
Spain	31.2	32158	21.7	31.0
France	40.9	11851	39.4	42.9

The way the gas is purchased by companies in Europe has traditionally been by bilateral agreements between companies. However, in the last few years there has been an incresingly interest by the European Union to create a competitive European Gas Market, where consumers and producers can buy and sell gas. That means countries must establish entry and exit points where gas could be freely trade only limited by the size of the gas infrastructure. With this objective, the Agency for the Cooperation of Energy Regulators (ACER) launched the European Gas Target Model (GTM) offering guidelines for the effective implementation of the common market [10].

For achieving a well-functioning and transparent gas wholesale market, it is fundamental to have both, a liquid spot market and a liquid forward/futures market. In that situation, market participants can have access to gas where and when they need it and hedge against possible price volatility in the market, ensuring a long-term contract.

A final issue that the Gas Target Model plans to achieve is improving the role of gas in complementing renewable generation. They expect that there will be an increasing need for flexible response from gas-fired power plants to complement the uncertain renewable generation that will be installed in the following years. In that sense, ACER proposes to review gas network access tariffs that could distort gas market signals which indicate when it is efficient for gas plants to produce.

As the promotor of the single gas market in Europe, the European Union has been very active in developing Directives, Regulation and Network Codes for the Member States related to the internal gas market. The main legislative package, The Third Energy Package, which is current law, introduced two Directives (it sets out a goal that all EU countries must achieve but it is up to them to devise their own laws on how to reach these goals) and three Regulations (law that must be applied entirely across EU). However, only one Directive and one Regulation were related to the gas sector. They are:

- Directive 2009/73/EC concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC.
- Regulation (EC) No 715/2009 on conditions for access to the natural gas transmission networks and repealing Regulation (EC) No 1775/2005.

The European Commission has developed Network Codes to effectively implement Regulations. Its objective is to manage gas flows between the different countries given the increasing number of trades and interconnection between countries. The current network codes regarding electricity are:

- Commission Regulation establishing a Network Code on interoperability and data exchange rules (703/2015/EU).
- Commission Regulation establishing a Network Code on Gas Balancing of Transmission Networks (312/2014/EU).
- Commission Regulation (EU) 2017/459 establishing a network code on capacity allocation nechanism in gas transmission systems and repealing Regulation (EU) No 984/2013.
- Commission Decision on conditions for access to the natural gas transmission networks [2012/490/EU].
- Commission Decision (EU) 2015/715/EU amending Annex I to Regulation (EC) 715/2009 on conditiond for access to the natural gas transmission networks.
- Commission Regulation (EU) 2017/460 of 16 March 2017 establishing a network code on harmonised transmission tariff structures for gas.

The Netherlands and the United Kingdom have the most mature gas hubs in Europe where they have played a major role establishing a price reference for other gas trades. Other countries like Germany, France or Italy have very advanced hubs which is a result of creating internal gas markets years ago. However, countries like Spain and Denmark, which are considered emerging hubs, created their markets few years ago and are increasingly gaining importance but remain almost illiquid. Figure 1.2 shows the level of maturity of the different European gas markets. As commented previously, the Netherlands (Title Transfer Facility, TTF) and the United Kingdom (National Balancing Point, NBP) have established hubs. They are the ones with a higher development of forward markets, used for hedging [2].

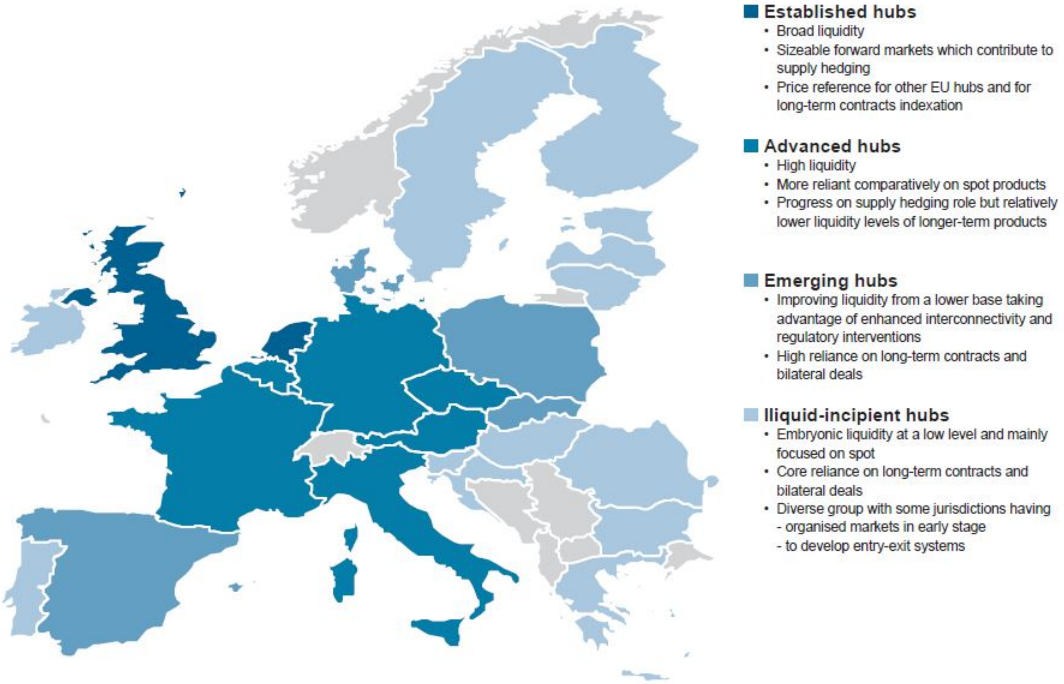
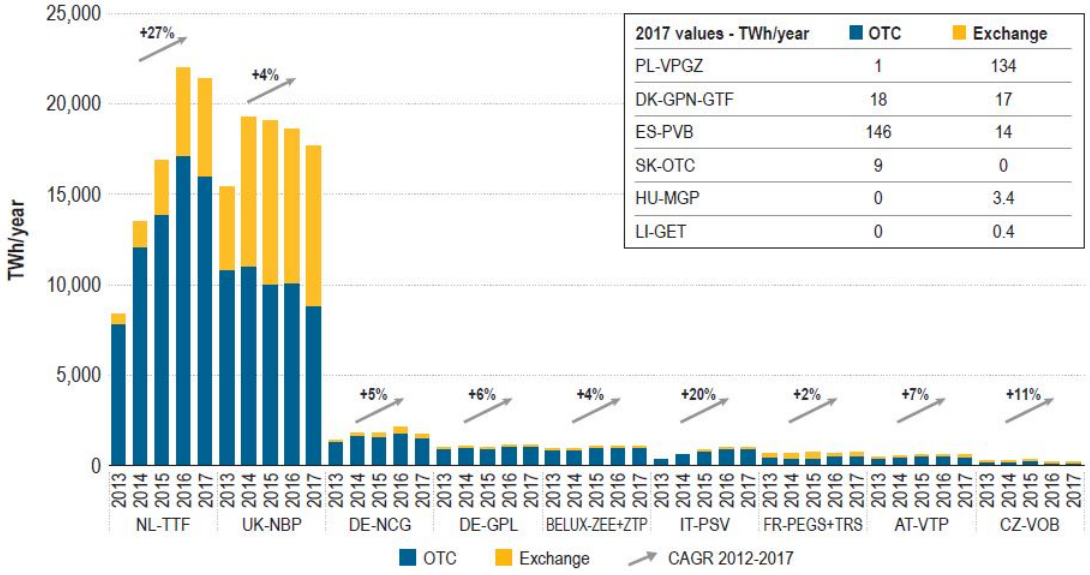


Figure 1.2: Gas hubs liquidity in European countries [2].

Besides liquidity, which still is very different between countries, European markets showed in 2017 increasing levels of convergence (similar sourcing and market prices). In general, the spread in sourcing prices decreased to below 3,5 €/MWh. Northwestern countries showed the highest convergence in prices due to similar market fundamentals, ease of access for upstream suppliers, increase in hub trading and low cost for transportation capacity). In Central Europe, price integration has improved in recent years while Mediterranean countries still lack for sufficient interconnection with the rest of Europe, having lower price convergence [2].

Different gas products are traded everyday in the different European markets. The volume traded in 2017 was around 3% lower than in 2016 but the growth rate in the last fives years is positive for all the hubs.

Figure 1.3 shows the evolution of the traded gas in the period 2013-2017 for the main European hubs. TTF (Netherlands) and NBP (UK) are the biggest markets by huge difference. It is important to note that every year more gas is traded on Exchanges (market settlement) instead of on Over-the-Counter (OTC) (bilateral agreement between two parties).



2017 values - TWh/year	OTC	Exchange
PL-VPGZ	1	134
DK-GPN-GTF	18	17
ES-PVB	146	14
SK-OTC	9	0
HU-MGP	0	3.4
LI-GET	0	0.4

Figure 1.3: Gas traded volumes in the main hubs [2].

Everyday different gas products are traded and they are categorised by their duration (time between the trade and the start of delivery). The different categories are:

- Short duration: from hourly to multi-day durations. Traded in spot markets close to physical delivery.
- Medium duration: from monthly to quarterly periods. Traded in forward markets.
- Long duration: from semi-annually to yearly periods. Traded in forward markets.

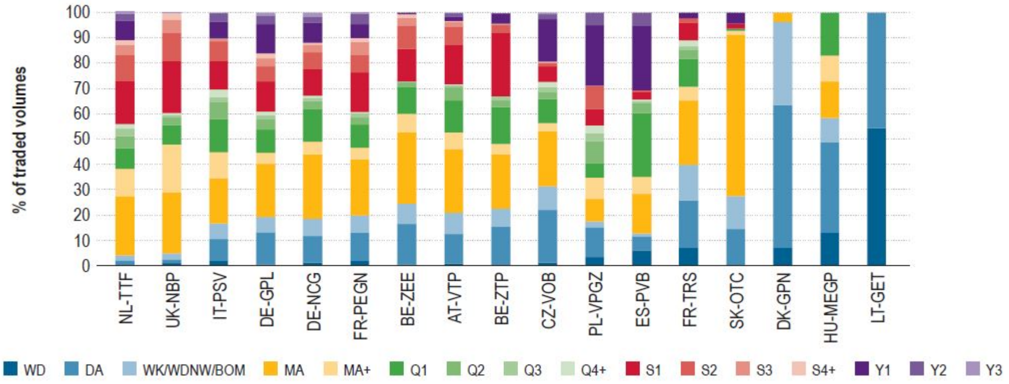


Figure 1.4: Breakdown of volumes per gas product [2].

The gas product mix varies from market to market. Some markets could be very liquid in long duration products while other emerging markets basically trade short duration products. The composition by product of every market is shown in Figure 1.4. The majority of the traded volumes correspond to medium duration contracts.

Beside buying the gas product, gas owners have to acquire the right to transport it through the different gas pipelines in Europe. They have to book capacity in the network and there are different products to do so. Figure 1.5 shows the entry and exit capacity in the gas pipelines that has been contracted and the maximum technical capacity available in the system for the years 2016 and 2017. It wants to point out how the implementation of the Capacity Allocation Mechanism Network Code has modified the way capacity is contracted, leading to higher volumes in the products offered in the Capacity Auctions (yearly, quarterly, monthly, daily and within-day).

It can be seen that total capacity contracted has declined in the period considered despite total gas consumption in Europe rose in the same period. That is explained by the fact that capacity contracts duration has decreased and short term contracts reflect better actual market needs. This way, overcapacity bookings are avoided.

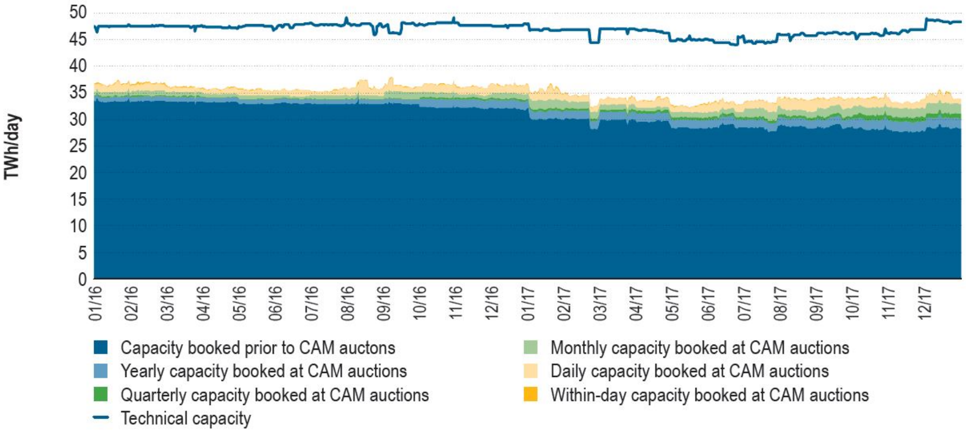


Figure 1.5: Booked capacity in the different auctions [2].

To sum up, natural gas will play a major role in energy supply in the following years mainly backed up by the need of gas for power generation. Since most of the gas consumption in Europe is done with imported gas, the availability of an appropiate gas infraestructure together with guaranteed access of third parties to the grid is crucial to maintain sufficient level of competition in the sector as it is one of the main objectives of the European Union.

1.1 Objectives

This Final Thesis pursues the following objectives:

- Understand the basic ideas of Gas law in Europe, considering the main Regulations and Directives issued by the European Commission, with special emphasis on the Third Party Access regulations in the main European countries in order to understand how it could affect the operation of the different gas units and the further affections to electricity markets.
- Perform a revision of the State-of-the-Art models and formulations of combined cycle gas turbines using configuration-based approaches.
- Improvement and implementation of two different formulations of combined cycle gas turbines, understanding advantages and disadvantages of each model.
- Developement of a case study to compare the capabilities of each combined cycle gas turbine formulation in the minimization of the production costs in the unit-commitment problem.
- Understand how State-of-the-Art software like Plexos can model or not the combined-cycle gas turbines proposed models with the same level of detail and identify advantages and disadvantages of the software.

1.2 Resources

To develop this Final Thesis, the following resources have been used:

- General Algebraic Modeling System (GAMS): It is a high-level modeling system for mathematical optimization. It has been used to develop the combined cycle gas turbine models and obtain the solution of the unit-commitment problem.
- PLEXOS: It is a simulation platform designed to analyze the energy market. Current functionalities cover electric power, gas, heat and water and it is broadly used by market participants, system planners, investors and regulators.

1.3 Chronogram of activities

The complete development of this Final Thesis included the following activities which are scheduled in the Gantt diagram of Figure 1.6.

1. Definition of objectives and Thesis' structure.
2. Development of the two Combined Cycle gas turbines models in GAMS.
3. Execution of the Case Study.
4. Revision of European Gas legislation.
5. Revision of Spanish Gas Third Party Access legislation.
6. Revision of Gas Third Party Access in other European countries.
7. Writing of Annex A.
8. Study of alternative Combined Cycle Gas Turbines formulations.
9. Modeling in Plexos.
10. Writing of Final document.

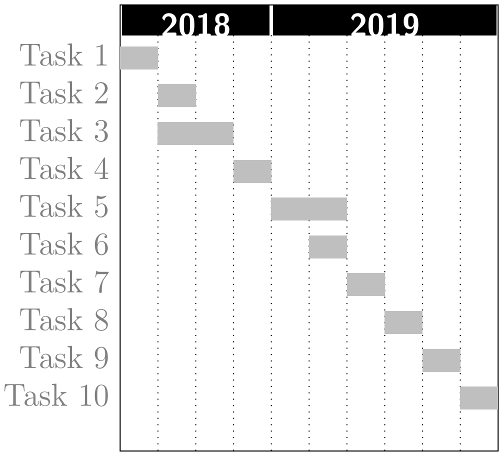


Figure 1.6: Chronogram of Activities

1.4 Master Thesis' structure

Following the Introduction in Chapter 1, Chapter 2 will cover the regulatory review of the Third Party Access regulation by the European Commission and in the main European countries. After it, and going deeper in the modeling part of the Final Thesis, in Chapter 3 different State of the Art formulations for Combined Cycle gas turbines will be analysed and Chapter 4 will present the two approaches that has been modelled in GAMS. A case study comparing both formulations will be done in Chapter 5 and the same problem will be modeled in Chapter 6 using Plexos software. Finally, in Chapter 7, conclusions are offered.

Chapter 2

Regulatory revision of gas Third Party Access

2.1 European Union

The European Union is seeking to harmonise its internal energy market passing regulations to its Member States. Regarding Third Party Access, the European Commission has created a network code on harmonised transmission tariff structures for gas to improve tariff transparency and coherency by harmonising basic principles and definitions used in tariff calculation by Member States [11].

Back in 2009, Regulation No 715/2009 introduced the concept of entry-exit points and transmission costs are no longer associated to one specific gas route as entry and exit capacity can be contracted separately. Network users can have gas transported from any entry point to any exit point. Determining transmission tariffs based on this entry-exit methodology needs to be based on an reference price using specific cost drivers.

Additionally, double charging to and from storage facilities should be avoided. A discount for the use of storage facilities should be set acknowledging its contribution to system flexibility and security of supply. Other discounts should be considered for entry points from LNG facilities and entry points from (and exit points to) infrastructure developed with the purpose of ending the isolation of Member States, as this promotes security of supply.

Transmission services revenues shall be recovered by capacity-based transmission tariffs. However, each national authority could approve that part of the revenues are recovered through commodity-based transmission tariffs. Two different charges could be set: a flow-based charge levied to cover costs caused by the quantity of gas flow and calculated using forecasted or historical flows and/or a complementary revenue charge to manage revenue under or over recovery through the years.

The Network Code also includes guidelines for non-transmission services. It establishes that the cost recovery should be cost-reflective, non-discriminatory, objective and transparent and that it should be charged to the beneficiaries of the service, to avoid cross-subsidisation.

For the harmonisation of transmission tariffs, a reference price is calculated and it should be applied to all entry and exit points in a given system. The reference price methodology aims to enable network users to reproduce the calculation of reference prices and their accurate forecast, ensure that volume risk related to transport in a system is not assigned to final customers and ensure that reference prices do not distort cross-border trade.

The methodology followed is called “capacity weighted distance” and it includes:

- The part of the transmission services revenues to be recovered from capacity-based transmission tariffs.
- The forecasted contracted capacity at each entry point (or cluster of entry points if they are grouped) and at each exit point (or cluster of exit points).
- The shortest distance of pipelines routes between entry and exit points.
- Combination of entry points and exit points.
- The entry-exit split shall be 50/50, meaning total costs should be divided equally between the entry and exit points.

The process is as follows. First, the weighted average distance for each entry point and exit point is calculated. For any entry point, its average distance is calculated as the sum of the products of the capacity at each exit point and the distance between the entry point and each exit point considered, divided by the sum of capacities at each exit point, as shown in Equation 2.1.

$$AD_{En} = \frac{\sum_{allEx} CAP_{Ex} * D_{En,Ex}}{\sum_{allEx} CAP_{Ex}} \tag{2.1}$$

where:

- AD_{En} is the weighted average distance for any entry point or cluster of entry points
- CAP_{Ex} is the forecasted contracted capacity at an exit point or cluster of exit points.
- $D_{En,Ex}$ is the distance between each pair of entry and exit points.

The average distance for each exit point is calculated as the sum of the products of the capacity at each entry point and the distance between the exit point and each entry point considered, divided by the sum of capacities at each entry point, as shown in Equation 2.2.

$$AD_{Ex} = \frac{\sum_{allEn} CAP_{En} * D_{En,Ex}}{\sum_{allEn} CAP_{En}} \tag{2.2}$$

where:

- AD_{Ex} is the weighted average distance for any exit point or cluster of exit points.
- CAP_{En} is the forecasted contracted capacity at an entry point or cluster of entry points.

In second place, the weight of cost for each entry point and each exit point is calculated using Equations 2.3 and 2.2.

$$W_{c,En} = \frac{CAP_{En} * AD_{En}}{\sum_{allEn} CAP_{En} * AD_{En}} \tag{2.3}$$

$$W_{c,Ex} = \frac{CAP_{Ex} * AD_{Ex}}{\sum_{allEx} CAP_{Ex} * AD_{Ex}} \tag{2.4}$$

where:

- $W_{c,En}$ is the weight of cost for a given entry point.
- $W_{c,Ex}$ is the weight of cost for a given exit point.

In third place, and considering the part of the transmission services revenues that are recovered through capacity-based transmission tariffs, the total quantity to be recovered at each entry and exit point can be computed using Equations 2.5 and 2.6.

$$R_{En} = W_{c,En} * R_{\sum En} \tag{2.5}$$

$$R_{Ex} = W_{c,Ex} * R_{\sum Ex} \tag{2.6}$$

where:

- R_{En} are the transmission cost to be recovered from capacity-based transmission tariffs at an entry point.
- R_{Ex} are the transmission cost to be recovered from capacity-based transmission tariffs at an exit point.

- $R_{\sum En}$ are the transmission cost to be recovered from capacity-based transmission tariffs at all entry point.
- $R_{\sum Ex}$ are the transmission cost to be recovered from capacity-based transmission tariffs at all exit point.

Finally, if the revenues to be achieved at each entry and exit point are divided by the forecasted contracted capacity at each of them, the reference prices are obtained with Equations 2.7 and 2.8.

$$T_{En} = \frac{R_{En}}{CAP_{En}} \tag{2.7}$$

$$T_{Ex} = \frac{R_{Ex}}{CAP_{Ex}} \tag{2.8}$$

where:

- T_{En} is the reference price at a given entry point.
- T_{Ex} is the reference price at a given exit point.

As commented previously, a discount of at least 50% should be applied to capacity-based transmission tariffs at entry and exit points to storage facilities.

2.2 Spain

In Spain, the gas sector has been in constant development during the last 20 years and that has required an intensive effort by the competent authorities to develop a regulatory framework for the different gas activities.

Real Decreto 949/2001 [12], which regulates the third party access to the different gas infrastructures and stablishes an economic system for the natural gas sector, wanted to guarantee a fair return for the investments done in the gas sector, design a tariff system in order for each user to pay for the costs they have incurred in and regulate the third party access to guarantee non-discriminatory access.

The different gas facilities that are under third party access according to Real Decreto 949/2001 are: regasification plants, underground storage plants, gas transmission and distribution pipelines, international connections and in general, any facility needed to supply gas to any user with access right. The different users had to send a formal request to the owners of the facilities with the usage schedule they require. In the case of transport facilities, they need to indicate the entry and exit points.

However, Real Decreto 984/2015 [13] made some changes to the previous to comply with the different EU Regulations and Directives developed in the previous years. The main changes were made in how the capacity is contracted and the duration of the contracts. To achieve this, the System Operator should open an online platform were agents can apply for the different capacity products of the facilities included in the third party access regime and they will be assigned to the different agents through market mechanisms. For this purpose, the owners of the infrastructure should announce their availability. Regarding the duration of the contracts, different products should be offered:

- Yearly product: it gives the right of use every day of the year. Capacity can be offered for the following 15 years.
- Quaterly capacity: capacity contracted for all days in the quarter. Quarters start on the 1^{st} of October, January, April and July.
- Monthly capacity: Right of use every day in a given month, starting on the 1^{st} of each month.
- Daily product: Right of use during a day of gas (a day of gas goes from 6am of day D to 6am of day D+1).
- Intraday product: Right of use from the hour when capacity is contracted to the end of the day of gas.

Additionally to these changes, Real Decreto 984/2015 led to the entry into force of Real Decreto 335/2018 [14] which modifies different "Reales Decretos" that regulates the natural gas sector. It modifies Real Decreto 949/2001 to include the new third party access services recognised in Real Decreto 984/2015. The consolidated document considers the services in Table 2.1 which are detailed below.

Table 2.1: Structure of access tariffs to gas services in Spain

Service	Fixed (€/kWh/day)	Variable (€/kWh)	Fixed per operation (€)
Regasification toll	X	X	
Ship unloading toll		X	X
Ship loading toll		X	X
Tanker loading toll	X	X	
Entrance to balancing point	X		
Conduction term	X	X	
Storage in balancing point	X		
Underground storage	X	X	
LNG storage	X		
Exit of balancing point through regasification	X	X	

Liquefied natural gas toll

Regasification toll

This toll gives access to the facilities needed for the regasification of the liquefied natural gas. It includes a fixed term to pay for the daily contracted capacity and a variable term to pay for the daily regasified gas.

$$P_r = T_{fr} * Q_r + T_{vr} * C_r \tag{2.9}$$

- P_r: amount of regasification toll during billing period (€).
- T_{fr}: fixed term of the regasification toll in €/kWh/day.
- Q_r: daily contracted capacity (kWh/day)
- T_{vr}: variable term in €/kWh.
- C_r: kWh of gas regasified if the billing period.

Unloading vessels tariff (ship unloading toll)

Right of use of the installations necessary for off-loading LNG from a carrier to a regasification plant. The charged amount could differ in the different regasification plants. It includes a fixed term per operation and a variable term which depends in the quantity in kWh unloaded.

$$P_d = T_{fd} + T_{vd} * V_r \tag{2.10}$$

- P_d: amount billed per operation (€).
- T_{fd}: fixed term per operation (€).
- T_{vd}: variable term in €/kWh.
- V_r: quantity of LNG unloaded in kWh.

Loading vessels tariff (ship loading toll)

This toll gives access to use the neccesary installations to charge LNG into vessels from a regasification plant. As in the unloading vessels tariff, this toll could differ in each regasification plant. It includes a fixed term per operation and a variable term which depends in the quantity in kWh loaded.

$$P_c = T_{fg} + T_{vg} * V_c \tag{2.11}$$

- P_c: amount billed per operation (€).
- T_{fg}: fixed term per operation (€).
- T_{vg}: variable term in €/kWh.
- V_c: quantity of LNG loaded in the operation, in kWh.

There are 4 types of tolls depending on the loaded quantity and type of operation: less than 5000 m^3 pero operation, between 5000 m^3 and 15000 m^3, more than 15000 m^3 and gas cooling (to achieve loading conditions). Similarly, there are four types of services depending on the duration: short term service which requieres contracting 1 vessel loading, 30-days service with at least 3 vessel loadings, 90-days service with at least 5 loadings and 365-days service contracting at least 12 loadings. If the services are contracted but not used, a penalty is imposed through the fixed term.

Tanker loading toll

This toll allows to use the different installations needed to charge LNG in tank vehicles. It includes a fixed term applicable to the daily capacity contracted and a variable term related to the loaded quantity.

$$P_c = T_{fc} * Q_m + T_{vc} * V_c \tag{2.12}$$

- P_c: monthly amount billed (€).
- T_{fc}: fixed term in €/kWh/day.
- Q_m: Daily contracted capacity (kWh/day).
- T_{vc}: variable term in €/kWh.
- V_c: quantity of LNG loaded per period, in kWh.

Transport and distribution toll

The transport and distribution toll is composed of two terms: a term of entrance to the virtual balancing point (reserve of capacity) and an exit or conduction term that will vary depending on the exit conditions (gas usage).

Entrance to the virtual balancing point from the transport network

This toll entitles the owner to use the transport network from its entrance point to the virtual balancing point. There could be different values depending on the entrance point and there is a fixed term that considers the daily contracted capacity.

$$P_r = T_{fr} * Q_r \tag{2.13}$$

- P_r: monthly amount billed (€).
- T_{fr}: fixed term (€/kWh/day).
- Q_r: Daily contracted capacity (kWh/day).

Entrance to the virtual balancing point from the distribution grid

This toll entitles the owner to use the distribution network from its entrance point to the virtual balancing point. There could be different values depending on the entrance point and there is a fixed term that considers the daily contracted capacity.

$$P_d = T_{fd} * Q_d \tag{2.14}$$

- P_d: amount billed (€).
- T_{fd}: fixed term (€/kWh/day).
- Q_d: Daily contracted capacity (kWh/day).

Conduction term (gas usage)

This toll is computed at the point at which the gas leaves the transmission and distribution network. The gas usage term will depend on the pressure at which the final consumption is connected to. As CCGT are the relevant consumers in this Thesis, it will only be relevant to consider the transmission network and the highest pressures (60 bar). This term is computed using the following formula:

$$T_c = \sum_{i=1}^{3} \left[\sum_{j=1}^{n} (T_{f,ij} * Q_j + T_{v,ij} * C_j) \right] \tag{2.15}$$

- T_c: Monthly billing in gas usage term.
- $T_{f,ij}$: Fixed term in €/kWh/day for consumer j subject to its consumed volume i.
- Q_j: Daily gas flow of customer j subject to billing. In kWh/day.
- $T_{v,ij}$: Variable term for consumer j subject to its gas consumed i in €/kWh.
- C_j: kWh of gas consumed by user j.
- n: Number of consumers connected to the transmission network at 60 bar.

They daily flow subject to billing in that month depends on the actual maximum flow used that month. If it above the 105% of the contracted capacity, a penalty needs to be paid. If it is between the 85% and 105% of the contracted capacity, the charge will be for the maximum capacity used that month. Finally, if the maximum used capacity is below 85%, the user will pay for the 85% of his contracted capacity.

Additionally, each consumer would be assigned a different toll level according to its annual consumption.

Other services

The system operator in Spain provides some other third party access services that could be useful for different agents:

Storage in the virtual balancing point

This toll gives permission to use the installations needed to store gas in the virtual balancing point. It includes a fixed term accounting for the daily contracted capacity.

$$P_a = T_{fp} * Q_p \tag{2.16}$$

- P_a: monthly amount billed (€).
- T_{fp}: fixed term (€/kWh/day).
- Q_p: Daily storage contracted capacity (kWh/day).

Underground storage

This toll allows the agent to use the different underground storage installations and inject and extract gas from it. It includes three fixed terms related to the contracted capacity, the injection and extraction of gas.

$$P_s = T_{fs} * Q_{fs} + T_{fi} * Q_{fi} + T_{fe} * Q_{fe} \tag{2.17}$$

- P_s: monthly amount billed (€).
- T_{fs}: storage fixed term (€/kWh).
- Q_{fs}: storage contracted capacity (kWh).
- T_{fi}: injection fixed term (€/kWh/day).
- Q_{fi}: injection contracted capacity (kWh/day).
- T_{fe}: extraction fixed term (€/kWh/day).
- Q_{fe}: extraction contracted capacity (kWh(day).

LNG storage

This toll allows to use the needed installations to store LNG in the regasification plants. It includes a fixed term related to the contracted capacity.

$$P_g = T_{fg} * Q_g \tag{2.18}$$

- P_g: monthly amount billed (€).
- T_{fg}: fixed storage term (€/kWh/day).
- Q_g: storage contracted capacity (kWh/day).

Exit of the virtual balancing point through regasification plants

This toll gives access to use the needed installations to transport gas from the virtual balancing point to its transformation to LNG in the tanks of a regasification plant. It includes a fixed term, related to the daily contracted capacity and a variable term applicable to the quantity of gas transferred to the tank.

$$P_l = T_{fl} * Q_l + T_{vl} * C_l \tag{2.19}$$

- P_l: monthly amount billed (€).
- T_{fl}: fixed term (€/kWh/day).
- Q_l: daily contracted capacity (kWh/day).
- T_{vl}: variable term (€/kWh).
- C_l: transported gas quantity (kWh).

All this services are provided through the Spanish geography. Enagás provides a map with all the infrastructure the made available to customers, which can be seen in Figure 2.1.

Figure 2.1: Enagas infrastrucure map in Spain [3]

2.3 Portugal

The Portuguese Natural Gas System is organized following the Decreto-Lei nº 30/2006 which was developed to transpose the European Directive 2003/55 concerning common rules for the internal market in natural gas. It pursues the establishment of general rules applicable to the activities of reception, storage and regasification of LNG, underground storage and transport and distribution of natural gas.

The Energy Regulator in Portugal ("Entidade Reguladora dos Serviços Energéticos", ERSE) considers 4 activities subjecto to Third Party Access and the acquisition of gas as first step. There 4 agents in charge of those activities: LNG Terminal Operator, Underground Storage Operator, Transmission Network Operator and Distribution Network Operator that must receive a fair compensation for their services. The activities they provide are [15]:

- Import of gas: it reaches Portugal mainland through gas pipelines (gas from Algeria) and as LNG, unloading at the Sines Terminal (coming from Nigeria).
- Reception, storage and regasification: the three activities take place at the Sines Terminal, in the Southern Atlantic coast.
- Underground storage: this activity is strongly related to the maintenance of country reserves, to guarantee the supply of natural gas and overcome a possible over

demand. There is one underground storage facility in Portugal, located in Carriço, where 4 salt cavities are located.

- Transmission: transport of natural gas through high pressure pipelines $\leq$ 20 bar to supply the distribution network or large customers. The network has a total length of 1300 km and two interconnections with Spain (in the east and the north). It mainly covers the coastal area of Portugal.
- Distribution: distribution of gas through medium and low pressure networks

ERSE has the responsability to develop and approve the Tariffs Code which establishes the tariff calculation methodology for the different regulated services. For each service, it is necessary to define the main physical variables that more effectively reflect the cost incurred in the provision of the service. For the different service offered in the Portuguese gas infrastructure, Table 2.2 shows the different components of the tariff present in each of them [16],[17].

Table 2.2: Structure of access tariffs to gas services in Portugal.

Service	Energy (€/kWh)	Capacity (€/kW)	Fixed Term (€)
Overall Use of the System	X		
Transmission Network	X	X	
Use of LNG Terminal	X	X	X*
Underground Storage	X	X	

*Only for loading of tanker trucks with LNG

Global Use of the System

The Global Use of System tariff should recover the cost incurred in the operation of the system (by TSO), costs related to the regulator activity, past tariffs deviations, costs arising from energy and environmental policies or measures with general economic interest. It is recovered through an energy-based tariff for every customer.

LNG Terminal Tariff

The tariff for LNG terminal use is composed of three different activities which are charged independently according to the use made of the infrastructure.

- LNG unloading at sea port: It has one energy price in €/kWh.
- LNG storage: it is applied through a daily price of stored energy in €/kWh/day.
- Regasification and emission to the transmission system: it has there different prices.

  - Used regasification capacity in €/kWh/day.
  - Energy regasified, commodity charge, in €/kWh
  - LNG truck loading price, in € per loading operation.

Underground Gas Storage Tariff

The Undergroud Gas Storage tariff comprises three prices: gas injection, gas emissions to the transmission network and gas storage. The gas injection and emission tariff is a commodity charge in €/kWh while the gas storage price is a daily price dependind on the quantity of gas stored in €/kWh/day.

Transmission Access Tariff

To charge for the use of the transmission network, an Entry/Exit system is applied in Portugal. In each entry point of the transmission network, the entry prices of the transmission tariff are applied to gas nominations. Depending on the entry point, there could be different entry prices. Similarly, in each exit point, the transmission tariff is applied to gas nominations and exit prices could also vary between exit points. For customers connected to the transmission network (like CCGT plants), the exit prices of the transmission tariff are charged through the Use of the System tariff.

The Transmission Network tariff is charged monthly and it is composed of the following concepts:

- Used capacity charged in each entry point, applied to the maximum daily energy nominated by a market player in the previous 12 months, in €/(kWh/day)/month
- Used capacity charged in each exit point, applied to the maximum daily energy nominated by a market player in the previous 12 months, in €/(kWh/day)/month
- Off-peak energy charge in exit point in €/kWh.
- Peak energy charge in exit point in €/kWh.

Figure 2.2 shows the transmission network through the coast, the regasification terminal in Sines and the gas storage unit in Carriço.

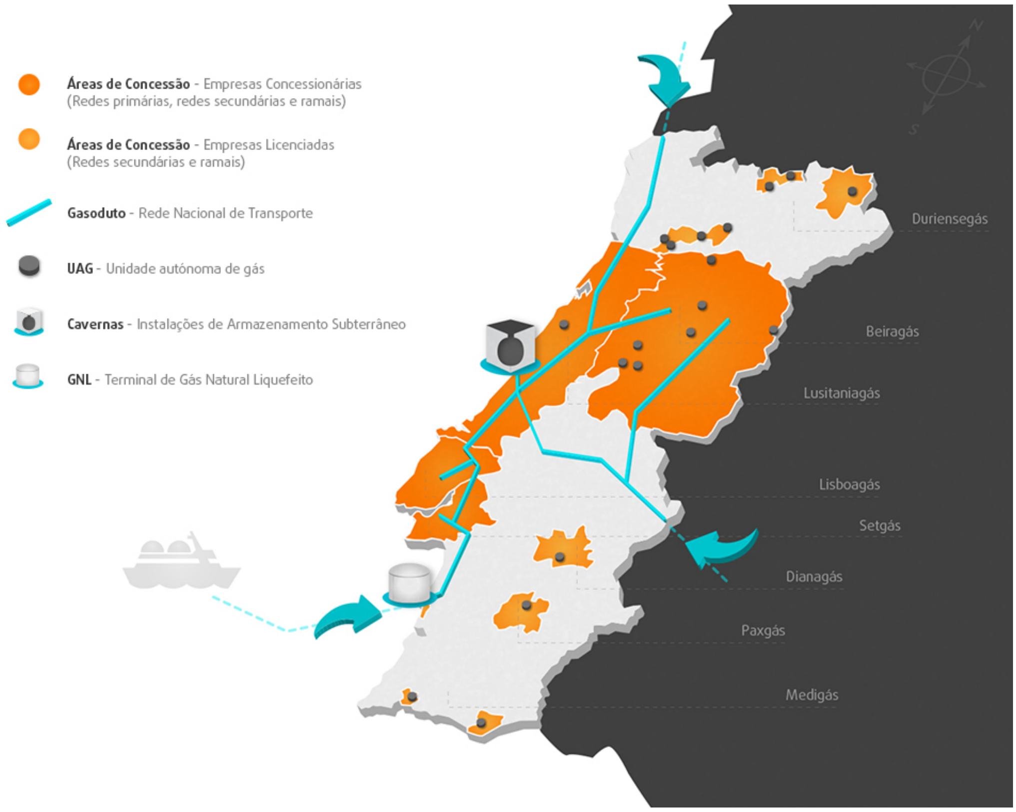


Figure 2.2: Gas infrastrucure map in Portugal [4].

Chapter 3

Combined Cycle Formulations' State of the Art

The different benefits that Combined-cycle Gas Turbines (CCGT) power bring to the electric system (flexibility, efficiency and environmental issues) caused the building of many of these kind of power plants around the world. Basically, a CCGT consists of gas combustion turbines (GT), heat recovery steam generator (HRSG) and steam turbines (ST). These three elements provides multiple operating configurations for the plant that creates a complex optimization problem for the Short-Term planning unit-commitment. The addition of CCGT to the commitment problem carried out by system operator has increased the computational requirements of the problem and this has lead to the necessity to develop more efficient CCGT formulations.

There are three possible CCGT representations as stated in [5]. From simpler to higher complexity, they are:

- Aggregate modeling: CCGT is considered as a pseudo unit treated as a regular thermal unit. The different configurations are ignored and equivalent operating conditions and costs are used. It is a simple model with low computational requirements. It has had broad use between different Independent System Operators (ISO) in the US.
- Component modeling: each one of the physical components of the CCGT is modelled considering their technical characterictics. This representation has been used for security analysis. However, it is not a suitable representation of CCGTs for unit-commitment problems.
- Configuration-based modelling: it uses multiple and mutually exclusive modes depending on the number of GT and ST available. Each mode has its own technical characteristics and only certain transitions between modes are allowed. This representation has been recognised as the most suitable for CCGT scheduling and some system operators are starting to use this model. However, the main drawback is

that it includes more binary variables and constraints to the optimization problem, making it the more complex formulation and some kind of simplification is required to be included in unit-commitment problems.

In [5] a CCGT configuration-based model is proposed. It represents the feasible combinations between some states. In each state there are a number of gas turbines and steam turbines, as represented in Figure 3.1. In this case, the CCGT has 2 GT and a single ST. There are a total of 5 states where Mode 0 representes the state in which the CCGT is offline. In the example given in Figure 3.1, there are some transitions disallowed. For instance, if the CCGT is in mode 4 (2 GT + 1 ST), the system is not allowed to disconnect or turn off at the same time a gas turbine and a steam turbine (moving to mode 1). Despite the mathematical formulation will allow it, there are technical constraints to consider in the model.

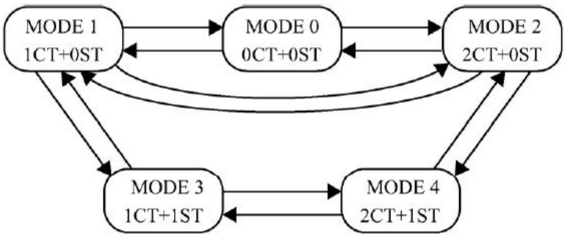


Figure 3.1: Modes transition in a configuration-based model [5].

Going in depth into the mathematical formulation, the objective function aims to minimize the total operating costs (production and transition costs). This objective function is given by Equation 3.1:

$$min \sum_{t \epsilon T} \sum_{g \epsilon G} \sum_{x' \epsilon M_g} [C_g^{NL,x'} u_{g,t}^{x'} + C_g^{LV,x'} (\underline{P}_g^{x'} u_{g,t}^{x'} + p_{g,t}^{x'}) + \sum_{y \epsilon M_g^{F,x'}} C_g^{T,x'y} v_{g,t}^{x'y}] \tag{3.1}$$

The objective is to minimize the cost for each period t, for each generator g and for all modes x' (all feasible modes but all-off mode), considering all existant modes (M_g). The production costs are divided between no-load costs ($C_g^{NL,x'}$) in which the plant incurrs for being connected in a certain state x' ($u_{g,t}^{x'}$) and linear production costs ($C_g^{LV,x'}$) that depend on the sumation of the technical minimum power ($\underline{P}_g^{x'}$) and the power above technical minimum ($p_{g,t}^{x'}$). Finally, there transicion costs ($C_g^{T,x'y}$) in which the unit incurrs when moving from state x' to state y ($v_{g,t}^{x'y}$).

The objective function is subject to certain constraints. There should be constraints to ensure the transition between modes, the state coupling and the minimum up and down times.

$$\sum_{x \epsilon M_g} u_{g,t}^{x} = 1 \ \forall g, t \tag{3.2}$$

Equation 3.2 is included to guarantee that modes are mutually exclusive. For every unit considered and for each period of operation, only one state can be active ($u_{gt}^{x} = 1$).

However, Equation 3.2 is not enough to guarantee the correct transitioning between modes of a certain unit. Equation 3.3 add the necessary constraint to allow the system move from a state to another.

$$u_{g,t}^{x'} - u_{g,t-1}^{x'} = \sum_{y \epsilon M_g^{F,x'}} v_{g,t}^{yx'} - \sum_{y \epsilon M_g^{F,x'}} v_{g,t}^{x'y} \ \forall g, x', t \tag{3.3}$$

From time period to time period, each unit can do four actions in each mode (x'): remain out of the mode, remain being in the mode, entering the mode, leaving the mode. Table 3.1 represents all possible transitions and how they are allowed by Equation 3.3. $u_{g,t}^{x'}$ and $u_{g,t-1}^{x'}$ represent if a certain mode x' is ON at period t and t-1, respectively while $\sum v_{g,t}^{yx'}$ represents if there has been any transition to mode x' and $\sum v_{g,t}^{x'y}$ if there has been any transition from mode x' to any other mode. If the unit enters mode x', $\sum v_{g,t}^{yx'} = 1$ while if it leaves x', $\sum v_{g,t}^{x'y} = 1$

Table 3.1: Possible mode transitions for each unit

Action	$u_{g,t}^{x'}$	$u_{g,t-1}^{x'}$	$\sum v_{g,t}^{yx'}$	$\sum v_{g,t}^{x'y}$	LHS	RHS
Remain out the mode	0	0	0	0	0	0
Remain in the mode	1	1	0	0	0	0
Enter the mode	1	0	1	0	1	1
Leave the mode	0	1	0	1	-1	-1

Under those conditions, Equation 3.3 allows the four possible actions since the Left Hand Side (LHS) and Right Hand Side (RHS) of the equation have the same value.

Due to technical aspects of the gas turbine or the steam turbine, they cannot be turned on, off or change the working mode when desired. Instead, each mode has a minimum required time to remain in the mode and a minimum time not to enter again the mode once it has been left.

$$\sum_{i=t-TU_g^x+1}^{t} \sum_{y \epsilon M_g^{F,x}} v_{g,i}^{yx} \leq u_{g,t}^{x} \ \forall g, x, t \epsilon [TU_g^x, T] \tag{3.4}$$

Equation 3.4 is set in order to guarantee the minumum time requiered to remain in a certain mode. If the system has moved to mode x from mode y, meaning $v_{g,i}^{yx} = 1$ and $u_{g,t}^{x} = 1$ at a certain period t, until TU_g^x periods have not passed, and the LHS of Equation 3.4 is 0, system will not be allowed to leave mode x.

$$\sum_{i=t-TD^x_g+1}^{t} \sum_{x\epsilon M^{F,y}_g} v^{xy}_{g,i} \leq 1 - u^x_{g,t} \ \forall g, x, t\epsilon[TD^x_g, T] \tag{3.5}$$

Equation 3.5 can be interpreted similarly. If the system has left mode x ($v^{xy}_{g,i} = 1$ and $u^x_{g,t} = 0$), the system cannot come back to mode x until TD^x_g periods have passed.

Finally, it is important to add three constraints to control the power output of the CCGT. For each mode, there should be a minimum and maximum power output. Additionally, there should be a cap on ramp-rates to guarantee that the difference in power delivered between consecutive period is technically feasible. The three equations modelling this are Equation 3.6 to 3.8.

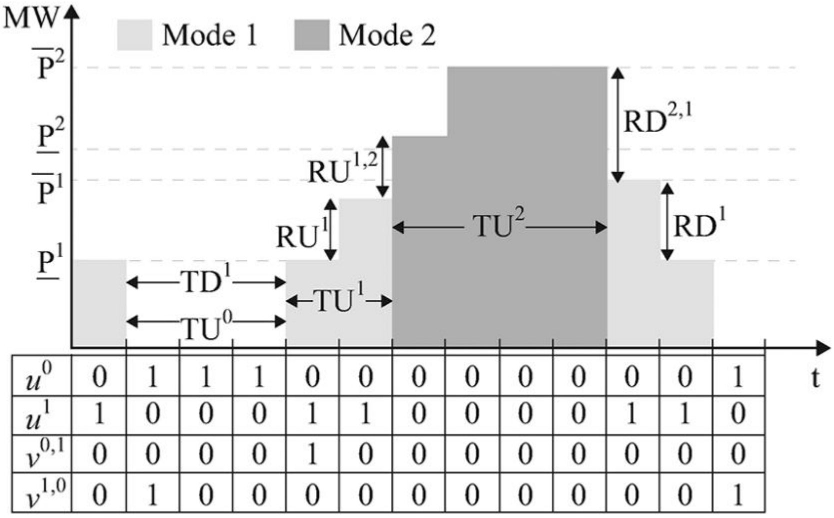
$$p^{x'}_{g,t} \leq (\overline{P}^{x'}_g - \underline{P}^{x'}_g) u^{x'}_{g,t} \ \forall g, x', t \tag{3.6}$$

$$p^{x'}_{g,t-1} - p^{x'}_{g,t} - \sum_{y'\epsilon M^{F,x}_g} p^{y'}_{g,t} \leq RD^{x'}_g u^{x'}_{g,t-1} - \sum_{y\epsilon M^{F,x'}_g} (RD^{x'}_g + \underline{P}^{x'}_g - \underline{P}^{y'}_g - RD^{x'y}_g) v^{x'y}_{g,t} \ \forall g, x', t \tag{3.7}$$

$$p^{x'}_{g,t} - p^{x'}_{g,t-1} - \sum_{y'\epsilon M^{F,x}_g} p^{y'}_{g,t-1} \leq RU^{x'}_g u^{x'}_{g,t} - \sum_{y\epsilon M^{F,x'}_g} (RU^{x'}_g + \underline{P}^{x'}_g - \underline{P}^{y'}_g - RU^{yx'}_g) v^{x'y}_{g,t} \ \forall g, x', t \tag{3.8}$$

Equation 3.6 constraints the maximum power output. The power over the minimum output should be lower than the difference between the maximum and minimum output for a given mode. Equation 3.7 establishes a limit for the maximum allowed decrease of power of the unit between periods. The constraint also limits the variation of power if a mode change ocurrs. Similarly, Equation 3.8 set a contraint to limit the maximum power increase the unit can withstand.

The minimum downtime, minimum uptime, maximum power, ramp-down and ramp-up are represented graphically in Figure 3.2. Binary variables status are represented in the bottom of the figure. For the 13 periods under consideration, only three modes are considered. In the first period, the unit is at mode 1 minimum output and it inmediantely transitioned to mode 0. The unit have to remain in mode 0 until the minimum downtime of mode 1 and the minimum uptime of mode 0 are reached. Once it happens, the unit moves again to mode 1 and it starts increasing power, limited by the ramp-up constraint of mode 1. Once the minimum uptime of mode 1 passes and ramp-up limit between mode 1 and 2 allows it, the unit moves to mode 2. While in mode 2, it delivers the maximum power availaible in the mode during three periods and once the minimum uptime in the mode passes, the unit goes back to mode 1 but limited by the ramp-down constraints.



u^0	0	1	1	1	0	0	0	0	0	0	0	0	1
u^1	1	0	0	0	1	1	0	0	0	0	1	1	0
$v^{0,1}$	0	0	0	0	1	0	0	0	0	0	0	0	0
$v^{1,0}$	0	1	0	0	0	0	0	0	0	0	0	0	1

Figure 3.2: Representation of minimum time up and down, reserve constraints and minimum and maximum power output in each mode [5].

Other references contain additional features that could be added to the formulation. For instance, in [18] a comparison between component and mode models for CCGTs is made. It considers a CCGT with multiple GTs and STs what makes the scheduling of CCGTs a more complicated problem to solve than the scheduling of typical thermal plants. In the modes model, each mode has its own characterics and operating parameters while for the component model, each GT and ST is modeled individually. Although it has been explicitly considered during this Chapter, GTs can operate independently while STs cannot and they need a GT to provide exhaust gases.

In the mode model formulation, it is similar to what is presented in [5] but instead of considering mode transition costs, the formulation accounts for the fuel spent when transitioning, which has a cost. Additionally, to account for the cost of producing, it includes a piecewise linear fuel-power curve. However, the individual component formulation conceives the formulation from a totally different approach. Each GT and ST is considered as a single unit with its own characteristics.

Each GT in the component model needs to have a fuel-MW curve to obtain the power produced as a function of the fuel imput. Then, for each MW generated in the GT, there is a quantity of steam produced by the heat recovery steam generator. Therefore, a MW-steam curve is needed. Finally, the ST needs a steam-MW curve to obtain the power produce as a function of the steam available. Only the fuel consumed is added in the objective function, since for generating power with the ST, no extra-cost are incurred in.

Transition and State Coupling constraints represent the major difference between both modeling approaches. In the component model there is a need to set several constraints. For instance, for groups with multiple GTs and one or two STs, some contraints are:

maximum number of GTs that can be started up/shut down simultaneously, minimum number of GTs that must to be on for running all STs, maximum number of GTs that can be on without operating any STs or a required number of GTs that must be on for a minimum of hours before starting the first STs. Extra constraints could be added if the groups with 2 ST have one of high pressure and another of low pressure: minimum and maximum number of GTs that must be on for operating the high pressure turbine/low pressure turbine, high pressure turbine must be operated for a minimum number of hours before starting the low pressure and high pressure and low pressure turbine cannot be started at the same period. Despite the level of detail of these constraints, most of them are especified through the allowed transitions in the configuration-based approach.

Comparing both approaches, [18] states that the approximations made in the operating costs in the modes formulations could lead to suboptimal solutions. Despite being formulated differently, the transition costs between modes in the mode model are equivalent to summing up the corresponding start up and shut down costs of the units involved in the transition. In general, the component model is a more accurate model leading to a better representation of the physical behaviour of the different components and their associated costs.

The importance of developing a practical formulation to be implemented in market operation is treate in [19]. In this case in the unit-commitment carried out by the Midcontinent Independent System Operator (MISO). Modeling Combined-cycle units efficiently and effectively is becoming of greater importance. In the previous approach followed by the system operator to include combined-cycle units in the unit-commitment problem, those units could be offered at aggregated or individual level and the market participants choose what to bid. In this scheme, only the aggregated or individual offer could be used during the 24 hours of a given day. If the aggregated offer is used for any hour of the day, it was used for all hours in the day. This approach reduced the flexibility that CCGTs could have provided and MISO decided to modify it.

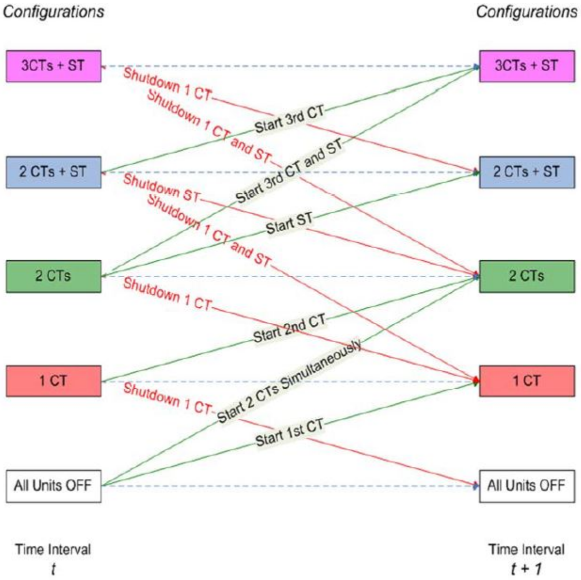


Figure 3.3: Hourly allowed transitions for CCGTs.

Figure 3.3 shows an example of the allowed intra-day transitions allowed by MISO after modyfing the CCGTs bidding scheme to a configuration-based model. The market participants must provide the allowed transitions between modes and the market clearing engine will choose which configuration to commit. For each mode, the market participant must define the energy offer price curve, the minimum load cost (cost of producing at minimum output) and up and down times. They are required to provided the maximum power ramps between hours and the maximum number of start-ups allowed in a day.

A new approach for CCGT modeling appears in [20]. They propose a hybrid model that take the benefits of configuration and individual models. The proposed model will reflect CCGT physical features more accurately. The proposed methodology includes a complete configuration model and an aggregate configuration model. In the complete, 2 GT and 1 ST turbines are considered but it accepts the two GT to be different between them. That leads to 7 different modes (all off, GT1, GT2, GT1 + GT2, GT1 + ST, GT2 + ST and GT1 + GT2 + ST) while in the aggregated, the GT are identical and there are only 5 modes (all off, 1GT, 2GT, 1GT + 1ST, 2GT + 1ST). It uses binary matrices to relate units with their commitment state in each mode and start-up and shut-down of unit with the transition between modes variable.

The model includes another feature: time-dependent start-up cost. The start-up is higher when the unit has been off for longer. Three different start-up types are considered: hot, intermediate and cold. However, start-up costs could be included on the unit's start-up costs or in the transition costs between units. Finally,they are included in the unit's start-up costs. One example of the benefits of this approach is the case of multiple start-ups, where each unit could have a different start-up type depending on the time they have been off.

Chapter 4

Comparison of formulations for modeling CCGT's working modes

Combined-cycle gas turbines can be modeled in different ways, as explained in Chapter 3. One of the objectives of this Final Thesis is to compare to different approaches to modeling CCGTs. The first model includes the Equations presented in [5] but additional equations have been added and others have been modified to include new features and to solve the unit-commitment problem. For instance, two new equations introduced were the power balance equation for each period and the limitation on the number of modes switches within periods. Despite the configuration-based approach followed in the first model allows to model CCGTs in a very detailed manner, in real operation, CCGTs operate most of the time in three states: off, working with a single gas turbine and a steam turbine and working with two gas turbines and a steam turbine. The mode with one unit of each will be called $1x1$, while when operating with two gas turbines and one steam turbine, it will be working on $2x1$ mode. From this point, it arises the possibility to model only those three modes, controlling the startup of the $1x1$ and $2x1$ mode through binary variables. This is done in the second modeling approach which has been developed trying to imitate the behaviour of the first model.

4.1 Complete formulation

This model allows the CCGT to work in 5 different modes as it is shown in Figure 3.1. The allowed transitions between modes can be controlled and modified as desired, the output at each mode is limited by a minimum and maximum power, there are two binary variables to account for the current state and mode swithching and there are power ramp limits within each mode and between modes. Both power producing and mode transitions have a cost that is minimized.

4.1.1 Nomenclature

Indexes and Sets

g $\in G$	Generating units, from 1 to G
x,y $\in M_g$	Working modes, from 0 to M_g
x',y' $\in M_g$	Working modes in M_g different to 0
$M_g^{F,x}$	Feasible transitions between modes x and y with x $\neq$ y
k $\in K$	Hourly periods from 1 to T hours

Parameters

$C_g^{LV,x}$	Linear variable cost of each mode [€/MWh]
$C_g^{NL,x}$	No-load cost of each mode [€/h]
$C_g^{T,xy}$	Transition cost between modes [€]
$\overline{P}_g^x$	Maximum power output of each mode [MW]
$\underline{P}_g^x$	Minimum power output of each mode [MW]
RD_g^x	Ramp-down rate of each mode [MW/h]
RU_g^x	Ramp-up rate of each mode [MW/h]
$RD_g^{x,y}$	Ramp-down rate between two modes [MW/h]
$RU_g^{x,y}$	Ramp-up rate between two modes [MW/h]
TD_g^x	Minimum downtime of each mode [h]
TU_g^x	Minimum uptime of each mode [h]
D_k	Hourly demand [MWh]
IS_g^x	Initial state of each group in each mode 1 = ON, 0 = OFF
Pin_g^x	Initial power output of each group in each mode [MWh]

Positive variables

$p_{g,k}^x$	Power output of each mode above minimum output [MWh]
$t_{g,k}$	Absolut power output of each group [MWh]
NSE_k	Non-served energy [MWh]

Binary variables

$u_{g,k}^x$	Commitment of each mode. 1 = ON, 0 = OFF
$v_{g,k}^{x,y}$	Transition between modes. 1 if transition from x to y

4.1.2 Mathematical model

Objective function:

$$min \sum_{k\in K}\sum_{g\in G}\sum_{x\in M_g}\left[C_g^{NL,x}u_{g,k}^x + C_g^{LV,x}p_{g,k}^x + \sum_{y\in M_g^{F,x}} C_g^{T,x,y}v_{g,k}^{x,y}\right] + \sum_k NSE_k * NSEC \quad (4.1)$$

Equation 4.1 represents the function that is minimized. The sumation includes all periods k, all groups g and all allowed modes x in each group. Then, no-load and linear variable are minimized together with the costs asociated with transitions between mode x and the modes to which x is allowed to transit to, represented by y. A term of non-served energy is included to guarantee that the problem remains feasible if demand to be covered is higher than available power.

Power balance constraint:

$$D_k = \sum_g t_{g,k} + NSE_k \;\forall k \quad (4.2)$$

Equation 4.2 is a basic equation that is included to guarantee that demand is covered in each period k using the different available units or non-served energy in the case of power unavailabilities. It is a new Equation that was not included in [5] and it is added in order to solve the unit-commitment problem. The sum of all absolut powers by each unit plus the non-served energy must equals the demand.

Transition between modes constraint:

$$u_{g,k}^x - \left(u_{g,k-1}^x\right)_{k>1} - \left(IS_g^x\right)_{k=1} = \sum_{y\in M_g^{F,x}} v_{g,k}^{y,x} - \sum_{y\in M_g^{F,x}} v_{g,k}^{x,y} \;\forall g,x,k \quad (4.3)$$

Equation 4.3 allows the effective transition between modes as it was explained in Table 3.1. However, the initial state status has been included in order to allow to indicate the initial state of the units in the problem. This is an important issue, since unit-commitment problems can produce really different results if the previous status of the units is not introduced.

Minimum uptime constraint:

$$\sum_{i=t-TU_g^x+1}^{t}\sum_{y\in M_g^{F,x}} v_{g,i}^{y,x} \le u_{g,t}^x \;\forall g,x,t\in[TU_g^x,T] \quad (4.4)$$

Equation 4.4 introduced a restriction on the capacity of the units to switch from one mode to another. What the *LHS* of the equation does is to sum how many times there has been a change from mode x to mode y in the strictly previous spam of hourly periods equaling the minimum uptime parameter value. This value has to be lower or equal than the current status of mode x (being 1 if on). That means that if there has been a mode switch to mode x in the last periods, the $LHS = 1$ meaning that the RHS needs to be 1 until sufficient time has passed and the LHS is again 0.

Minimum downtime constraint:

$$\sum_{i=t-TD_g^x+1}^{t} \sum_{y \in M_g^{F,x}} v_{g,i}^{x,y} \leq 1 - u_{g,t}^x \; \forall g, x, t \in [TD_g^x, T] \tag{4.5}$$

Equation 4.5 is formulated in a similar way as Equation 4.4 but its purpose is to avoid coming back to a mode that has been on recently. Until sufficient periods have not passed (TD), the unit is not allowed to return to a mode.

Power output limits constraints:

$$p_{g,k}^x \leq (\overline{P}_g^x - \underline{P}_g^x) u_{g,k}^x \; \forall g, x, k \tag{4.6}$$

Equation 4.6 restricts the power output of each mode by a minimum and maximum cap. If the unit is not committed ($u = 0$), the power delivered is 0 and if it is committed, the power output over technical minimum could be as maximum the difference between the maximum and the minimum available output.

Ramp-down limits constraint:

$$\begin{aligned} \left(Pin_g^{x'}\right)_{k=1} + \left(p_{g,k-1}^{x'}\right)_{k>1} - p_{g,k}^{x'} - \sum_{y \in M_g^{F,xn}} p_{g,k}^y \leq RD_g^{x'} u_{g,k-1}^{x'} \\ - \sum_{y \in M_g^{F,x'}} (RD_g^{x'} + \underline{P}_g^{x'} - \underline{P}_g^y - RD_g^{x',y}) v_{g,k}^{x',y} \; \forall g, x', k \end{aligned} \tag{4.7}$$

Equation 4.7 tries to limit the variation of power of the unit between periods, acounting for possible mode switches. In this sense, if the unit remains in the same active mode between two periods, the maximum power decrease alllowed for the unit would be RD_g^x. However, if there is a mode change from x to y ($v_{g,k}^{x',y} = 1$), the equation is more complex and apart from the rampdown between modes ($RD_g^{x',y}$), it has to account for the change in minimum available output of the different modes since $p_{g,k}^{x'}$ accounts for the power over minimum output.

Ramp-up limits constraint:

$$p^{x'}_{g,k} - p^{x'}_{g,k-1} - \sum_{y\in M_g^{F,x'}} p^{y}_{g,k-1} - (Pin^{x'}_g + \sum_{y\in M_g^{F,x'}} Pin^{y}_g)_{k=1} \leq RU^{x'}_g u^{x'}_{g,k}$$
$$- \sum_{y\in M_g^{F,x'}} (RU^{x'}_g + \underline{P}^{x'}_g - \underline{P}^{y}_g - RU^{y,x'}_g) v^{y,x'}_{g,k} \ \forall g, x', k \tag{4.8}$$

In a similar way as in Equation 4.7, the maximum increase of power is restricted by 4.8 and the same parameters are included to guarantee that a single equation allows to limit the maximum variation of power independently a mode change ocurred or not.

Absolut power equation:

$$t_{g,k} = \sum_{x} p^{x}_{g,k} + \underline{P}_{g,x} * u^{x}_{g,k} \ \forall g, k \tag{4.9}$$

Despite most of the equations use the power above minimum output ($p^{x}_{g,k}$), it is necessary to include a variable that accounts for the total power delivered by each unit, independently of the mode, summing all of them. Equation 4.9 adds this by adding the power delivered by all modes of a certain unit.

Limit on transition between modes constraint:

$$\sum_{x} \sum_{y\in M_g^{F,x}} v^{y,x}_{g,k} \leq 1 \ \forall g, k \tag{4.10}$$

Equation 4.10 is added to limit the maximum number of transitions from a certain mode in each hourly period. It can be 0 or 1.

Limit on connected modes constraint:

$$\sum_{x} u^{x}_{g,k} = 1 \ \forall g, k \tag{4.11}$$

For each group, the maximum number of connected modes is 1 according to Equation 4.11.

4.2 Simplified formulation

The simplified formulation limits the number of gas turbines to 2 and the number of steam turbines to 1. Additionally, there are only three possible states whose startup is controlled through binary variables. Those states are represented in Figure 4.1. It is a simplified representation of the configuration-based approach represented in Figure 3.1, where modes 1 and 2 have been eliminated to comply with the idea of the simplified formulation.

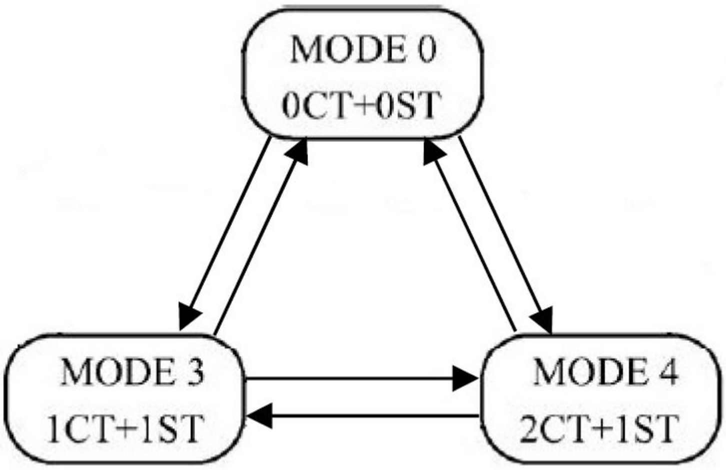


Figure 4.1: Modes transition in the simplified model

In this formulation, the number of groups double. The same unit will have a group g to account for the power delivered when working in the 1x1 mode and another group g that will be active when the unit is generating in the 2x1 mode. When working in the 2x1 configuration, both groups need to be active but the power delivered will be accounted solely in the 1x1 group.

4.2.1 Nomenclature

Indexes and Sets	
g	Generation units, from 1 to G units
k	Hourly periods, from 1 to T hours

Parameters	
C_g^{LV}	Linear variable cost [€/MWh]
C_g^{NL}	Non-load cost of each group [€/h]
$\overline{P}_g$	Maximum power output of each group [MW]
$\underline{P}_g$	Minimum power output of each group [MW]
RD_g	Ramp-down rate of each group [MW/h]

RU_g	Ramp-up rate of each group [MW/h]
SDC_g	Shutdown costs [€]
SUC_g	Startup costs [€]
$es2x1_g$	Group type: 1x1 o 2x1
$gts2x1_{g,gg}$	Logic relation between 1x1 groups with 2x1 groups
TU_g	Minimum up time after startup process [h]
TD_g	Minimum down time after shutdown process [h]
IS_g	Initial State 1 = ON, 0 = OFF
Pin_g	Initial power output [MW]
D_k	Hourly demand [MW]
$NSEC$	Non-served energy cost [€/MWh]

Positive variables

$p_{g,k}$	Power output above minimum output [MWh]
$t_{g,k}$	Absolut power output, indicated in 1x1 groups [MWh]
NSE_k	Non-served energy [MWh]

Binary variables

$v_{g,k}$	Commitment status of each group g in period k
$y_{g,k}$	Startup decision
$z_{g,k}$	Shutdown decision
$x_{g,k}$	Direct startup to mode 2x1
$w_{g,k}$	Direct shutdown from mode 2x1

4.2.2 Mathematical model

Objective function:

$$\begin{multline} min \sum_{g \forall es2x1_g=1} \sum_{k} C_g^{NL} v_{g,k} + C_g^{LV} p_{g,k} + SUC_g y_{g,k} + SDC_g z_{g,k} \\ + \sum_{g \forall es2x1_g=2} \sum_{k} (C_g^{NL} - \sum_{gg/gts2x1_{gg,g}} C_{gg}^{NL}) v_{g,k} + C_g^{LV} p_{g,k} + SUC_g y_{g,k} + SDC_g z_{g,k} \\ + \sum_{k} NSE_k * NSEC \tag{4.12} \end{multline}$$

The objective function in Equation 4.12 minimizes the no-load cost, the linear variable cost and the startup and shutdown costs. The first part of the equation does it for the groups modelling 1x1 units ($es2x1_g = 1$) and then for 2x1 units ($es2x1_g = 2$). For those last groups, the no-load cost is the difference between the no-load cost for 2x1 group and the no-load cost of the 1x1 group.

Hourly power balance constraint:

$$D_k = \sum_g t_{g,k} + NSE_k \ \forall k \tag{4.13}$$

Equation 4.13 is added to oblige the different generation groups to produce power to meet the demand. If not enough generation capacity is available, the optimazation problem can still be solved using non-served energy, to meet total demand.

Minimum up time constraint:

$$\sum_{k-TU_g+1}^{k} y_{g,k} \leq v_{g,k} \ \forall g, k \in [TU_g, T] \tag{4.14}$$

Equation 4.14 limits the shutdown of a certain group during a given number of hours following a startup of the same group. The unit is only allowed to be on off state ($v_{g,k} = 0$) if there has not been any startup in the previous TU_g hours.

Minimum down time constraint:

$$\sum_{k-TD_g+1}^{k} z_{g,k} \leq 1 - v_{g,k} \ \forall g, k \in [TD_g, T] \tag{4.15}$$

Equivalently to the minimum up time constraint, Equation 4.15 limits the startup of a unit if it has been recently turned off. If there has been a shutdown in the previous TD_g, the unit is not allowed to be connected and $v_{g,k}$ must remain 0.

Shutdown of 1x1 group at technical minimum constraint:

$$p_{g,k} \leq (\overline{P}_g - \underline{P}_g) * (v_{g,k} - z_{g,k+1}) \ \forall g, k, es2x1_g = 1 \tag{4.16}$$

Equation 4.16 requieres the 1x1 groups to shutdown at technical minimum. If the unit is going to shutdown in the following period ($z_{g,k+1} = 1$), the power above the minimum output must be 0.

Startup of 1x1 group at technical minimum constraint:

$$p_{g,k} \leq (\overline{P}_g - \underline{P}_g) * (v_{g,k} - y_{g,k}) \ \forall g, k, es2x1_g = 1 \tag{4.17}$$

Equation 4.17 obliges the different units to startup at technical minimum when commiting. In the commitment period, the status of the binary variable ($y_{g,k} = 1$ and $v_{g,k} = 1$) make the power above minimum output to be 0.

Maximum power output above minimum output constraint:

$$p_{g,k} \leq (\overline{P}_g - \underline{P}_g)(v_{g,k} - \sum_{gg/gts2x1_{gg,g}} v_{gg,k}) \; \forall g,k, es2x1_g = 1 \tag{4.18}$$

$$p_{g,k} \leq (\overline{P}_g - \underline{P}_g) * v_{g,k} \; \forall g,k, es2x1_g = 2 \tag{4.19}$$

Equation 4.18 is only defined for 1x1 units but it has a direct relation with 2x1 units since if the steam turbine is connected, the power output above minimum output would be 0, meaning that the 2x1 group is producing power. Otherwise, the power output is limited by a maximum and minimum level ($\overline{P}_g$ and $\underline{P}_g$). For the case of the 2x1 units, if they are committed their power output above its technical minimum varies within the mentioned limits.

Ramp down constraint:

$$\begin{aligned}(t_{g,k-1})_{k>1} + (Pin_g)_{k=1} - t_{g,k} \leq RD_g + &\sum_{gg/gts2x1_{gg,g}} (v_{gg,k} - y_{gg,k})(RD_{gg} - RD_g) \\ +z_{g,k}(\underline{P}_g - RD_g) + &\sum_{gg/gts2x1_{gg,g}} z_{gg,k}(RD_{gg} - RD_g) \\ +w_{g,k}(&\sum_{gg/gts2x1_{gg,g}} \underline{P}_{gg} - RD_{gg} - \underline{P}_g + RD_g) \; \forall g,k\end{aligned} \tag{4.20}$$

Equation 4.20 tries to model the different possibilities for ramps down, depending on the situation of the group between two periods. It could actually remain working with 1x1 or 2x1 modes, turn off the steam turbine and keep the gas turbine or turn off everything. For each of those behaviours, there is a maximum level of ramp down, as it is explained in Table 4.3.

Table 4.3: Ramp-down allowed for the different transitions between groups.

Action	$v_{gg,k}$	$y_{gg,k}$	$z_{g,k}$	$z_{gg,k}$	$w_{g,k}$	**Ramp down allowed**
Remains in 1x1	0	0	0	0	0	RD_g
Remains in 2x1	1	0	0	0	0	RD_{gg}
From 2x1 to 1x1	0	0	0	1	0	RD_{gg}
From 1x1 to OFF	0	0	1	0	0	$\underline{P}_g$
From 2x1 to OFF	0	0	1	1	1	$\underline{P}_{gg}$
From 1x1 to 2x1	1	1	0	0	0	RD_g

There are total of six possible behaviours subject to ramp-down constraints. Depending if the 2x1 mode is working or not, the maximum ramp will be given by the ramp of the 1x1 mode or the 2x1 mode. If the unit stops producing, the maximum ramp-down will be the minimum output power, meaning that is has to stop from technical minimum. An special case occurs with the ramp-down when starting the 2x1 mode that needs to be considered if the minimun output of the 2x1 group is lower than the maximum output of the 1x1 group alone.

Ramp up constraint:

$$
\begin{aligned}
t_{g,k} - (t_{g,k-1})_{k>1} - (Pin_g)_{k=1} \leq RU_g + \sum_{gg/gts2x1_{gg,g}} v_{gg,k}(RU_{gg} - RU_g) + \\
+ y_{g,k}(\underline{P}_g - RU_g) + x_{g,k}((\sum_{gg/gts2x1_{gg,g}} \underline{P}_{gg} - RU_{gg}) - \underline{P}_g + RU_g) \ \forall g,k
\end{aligned}
\tag{4.21}
$$

Equation 4.21 is used to constraint the upwards power variation of the unit between periods. This limitation exists due to the impossibility of increasing unlimitedly the power output of the units in a short period of time. As it was done for the ramp down constraint, Table 4.4 shows the allowed ramps for the different possible behaviours between periods of the unit.

Table 4.4: Up ramps allowed for the different transitions between groups.

Action	$v_{gg,k}$	$y_{g,k}$	$x_{g,k}$	**Ramp up allowed**
Remains in 1x1	0	0	0	RU_g
Remains in 2x1	1	0	0	RU_{gg}
From 1x1 to 2x1	1	0	0	RU_{gg}
From OFF to 1x1	0	1	0	$\underline{P}_g$
From OFF to 2x1	1	1	1	$\underline{P}_{gg}$
From 2x1 to 1x1	0	0	0	RU_g

Startup to 2x1 mode logic:

$$y_{g,k} + \sum_{gg/gts2x1_{gg,g}} y_{gg,k} - x_{g,k} \leq 1 \ \forall g,k \tag{4.22}$$

$$y_{g,k} - \sum_{gg/gts2x1_{gg,g}} y_{gg,k} + x_{g,k} \leq 1 \ \forall g,k \tag{4.23}$$

$$-y_{g,k} + \sum_{gg/gts2x1_{gg,g}} y_{gg,k} + x_{g,k} \leq 1 \ \forall g,k \tag{4.24}$$

$$-y_{g,k} - \sum_{gg/gts2x1_{gg,g}} y_{gg,k} + x_{g,k} \leq 0 \ \forall g,k \tag{4.25}$$

Table 4.5: Combinations of the binary startup variable to allow the transition from off to 2x1 mode.

Combination	$y_{g,k}$	$y_{gg,k}$	$x_{g,k}$	Eq. 4.22	Eq. 4.23	Eq. 4.24	Eq. 4.25
1	0	0	0	OK	OK	OK	OK
2	0	0	1	OK	OK	OK	X
3	0	1	0	OK	OK	OK	OK
4	0	1	1	OK	OK	X	OK
5	1	0	0	OK	OK	OK	OK
6	1	0	1	OK	X	OK	OK
7	1	1	0	X	OK	OK	OK
8	1	1	1	OK	OK	OK	OK

Equations 4.22 to 4.25 allow the units to move from off status to technical minimum of the 2x1 group. Three binary variable have 8 possible combinations between them. Four equations are needed to allow certain combinations and discard other, depending on if they represent a technically logical transition or not.

Combinations number 2, 4, 6 and 7 do not comply with Equations 4.22 to 4.25. Therefore, the combination of binary variables is not allowed to happen at any hourly period. Combination 2 is not allowed because, the startup from OFF to 2x1 ($x_{g,k}$) cannot happen without the startup of the nx1 group ($y_{g,k}$) and the 2x1 group ($y_{gg,k}$). Combination 4 cannot startup at 2x1 status without the startup of the 1x1; combination 6, without the 2x1 group and in combination 7, if the 1x1 group and the 2x1 group startup at a certain period, it is necessary that $x_{g,k}$ is on.

Shutdown from 2x1 mode logic:

$$z_{g,k} + \sum_{gg/gts2x1_{gg,g}} z_{gg,k} - w_{g,k} \leq 1 \ \forall g, k \tag{4.26}$$

$$z_{g,k} - \sum_{gg/gts2x1_{gg,g}} z_{gg,k} + w_{g,k} \leq 1 \ \forall g, k \tag{4.27}$$

$$-z_{g,k} + \sum_{gg/gts2x1_{gg,g}} z_{gg,k} + w_{g,k} \leq 1 \ \forall g, k \tag{4.28}$$

$$-z_{g,k} - \sum_{gg/gts2x1_{gg,g}} z_{gg,k} + w_{g,k} \leq 0 \ \forall g, k \tag{4.29}$$

Table 4.6: Combinations of the binary shutdown variable to allow the transition from 2x1 mode to off.

Combination	$z_{g,k}$	$z_{gg,k}$	$w_{g,k}$	Eq. 4.26	Eq. 4.27	Eq. 4.28	Eq. 4.29
1	0	0	0	OK	OK	OK	OK
2	0	0	1	OK	OK	OK	X
3	0	1	0	OK	OK	OK	OK
4	0	1	1	OK	OK	X	OK
5	1	0	0	OK	OK	OK	OK
6	1	0	1	OK	X	OK	OK
7	1	1	0	X	OK	OK	OK
8	1	1	1	OK	OK	OK	OK

Shutdown from 2x1 mode follows a similar pattern to the startup previously analysed. Equations 4.26 to 4.29 allow to avoid certain combination of the shutdown binary variables and Table 4.6 represents all combinations, as it was done in the startup to nx1 logic.

2x1 coupling logic constraint:

$$\sum_{gg/gts2x1_{gg,g}} v_{gg,k} \leq v_{g,k} \; \forall g, k, es2x1_g = 1 \tag{4.30}$$

Equation 4.30 is set to guarantee that if the 2x1 group of a given unit is on, it is necessary that the binary variable representing the status of the 1x1 group of the same unit is on, as well. There are four possible combination of binary variables between $v_{g,k}$ and $v_{gg,k}$, that are described in Table 4.7.

Table 4.7: Possible coupling states in the Simplified formulation

Combination	$\boldsymbol{v_{g,k}}$	$\boldsymbol{v_{gg,k}}$	**Working mode**
1	0	0	OFF
2	0	1	Not feasible
3	1	0	1x1
4	1	1	2x1

Inter-period coupling logic constraint:

$$y_{g,k} - v_{g,k} - z_{g,k} + |IS_g|_{k=1} + |v_{g,k-1}|_{k>1} = 0 \; \forall g, k \tag{4.31}$$

Equation 4.31 aims to model the commitment status between periods. If follows the same logic as Equation 4.3 in the Complete Formulation.

Absolut power constraints:

$$t_{g,k} = p_{g,k} + \underline{P}_g v_{g,k} + \sum_{gg/gts2x1_{gg,g}} p_{gg,k} + (\underline{P}_{gg} - \underline{P}_g) v_{gg,k} \; \forall g, k, es2x1_g = 1 \tag{4.32}$$

$$t_{g,k} = 0 \ \forall g, k, es2x1_g = 2 \tag{4.33}$$

The absolut power is assigned to the 1x1 units of each group. That is why the absolut power for the 2x1 mode, Equation 4.33, is cero. Assigning it to the 1x1 units allow to simplyly introduce the power balance and ramp constraints in Equations 4.13, 4.20 and 4.7.

Chapter 5

Case Study

The two formulations proposed in Chapter 4 for modeling from two different aproaches Combined Cycle units are put in practice in this Chapter by considering 5 differents CCGT units to meet a demand curve, illustrated in Figure 5.1 during a 168 hours-period (1 week).

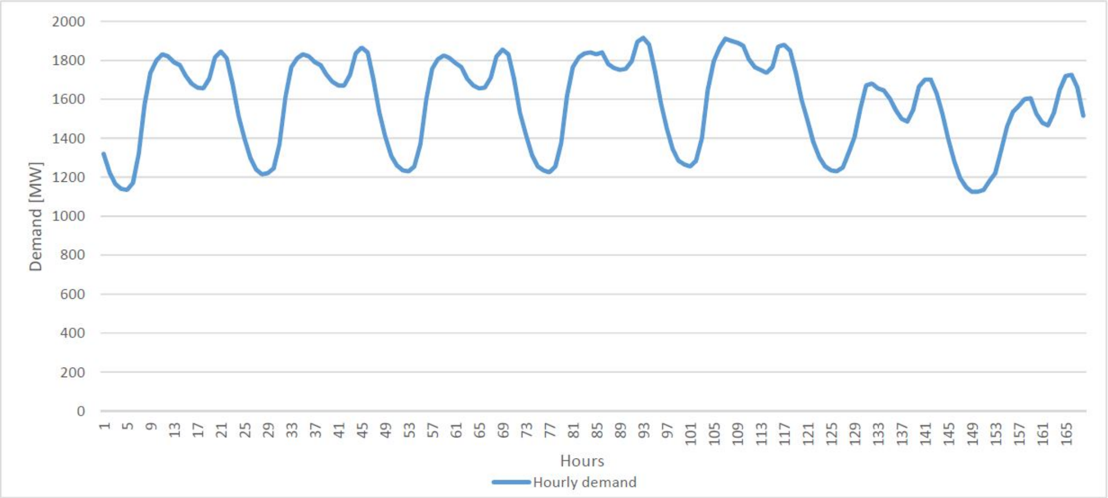


Figure 5.1: Demand curve to be covered with 5 CCGTs.

The demand data represents a typical week in the Spanish system but a reduction factor was applied to allow only 5 CCGTs to cover it. As it can be seen in Figure 5.1, demand values during the week considered range from 1000 MW to 2000 MW. The maximum power output available from the 5 units is 2300 MW. The hourly variations in demand and the overcapacity present in the system will allow the units to change between modes and cover the demand at all hours.

Since the Simplified formulation limits the number of states to three (OFF, 1x1 and 2x1), it is necessary to limit the existing modes in the Complete formulation. The best way to do it is by not allowing any transition to the modes that are going to be eliminated. Additionally, in the Simplified formulation, start to 2x1 mode is allowed. Therefore, it is necessary to modified the allowed transitions from what it was initially considered in [5] and depicted in Figure 3.1.

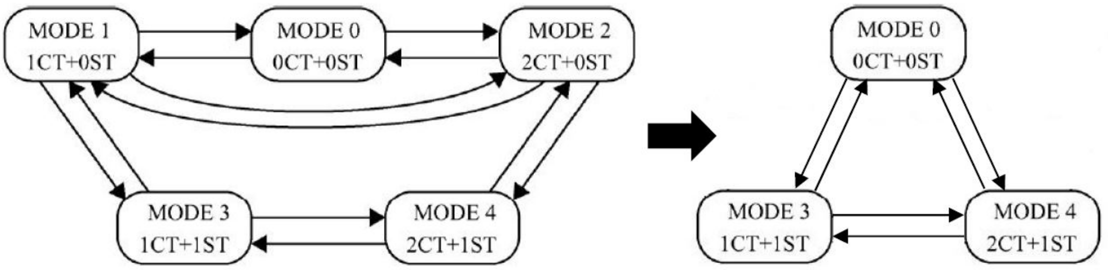


Figure 5.2: Modification in allowed transitions for the Complete formulation.

In the Complete formulation, Mode 1 (1 GT + 0 ST) and Mode 2 (2 GT + 0 ST) are not considered. Thus, they are eliminated, as it can be seen in Figure 5.2. Finally, Mode 3, containing 1 GT + 1 ST is the equivalent to the 1x1 mode in the Simplified formulation while Mode 4 (2 GT + 1 ST) is represented by 2x1 in the second approach.

5.1 Data

5.1.1 Complete formulation

Table 5.1: Technical data for the different modes of each group for the complete formulation

Unit	Mode	C_{LV}	C_{NL}	TD	TU	$\underline{P}$	$\overline{P}$	RD	RU	IS	P_{in}
CCGT1	**OFF**	0	0	3	3	0	0	0	0	0	0
	3	25	3200	1	1	100	250	50	50	1	50
	4	60	10700	3	3	175	400	75	75	0	0
CCGT2	**OFF**	0	0	2	2	0	0	0	0	0	0
	3	35	1000	1	1	50	200	40	40	0	0
	4	70	5000	2	2	100	350	60	60	1	200
CCGT3	OFF	0	0	5	5	0	0	0	0	0	0
	3	15	5000	1	1	100	300	15	15	0	0
	4	40	15000	5	5	200	600	30	30	1	200
CCGT4	**OFF**	0	0	1	1	0	0	0	0	0	0
	3	20	5000	1	1	50	250	75	75	1	20
	4	50	10000	1	1	100	400	100	100	0	0
CCGT5	**OFF**	0	0	2	2	0	0	0	0	0	0
	3	30	10000	1	1	75	250	50	50	1	25
	4	45	12000	2	2	175	550	50	50	0	0

Table 5.2: Transition costs between modes in the Complete formulation.

Group		**CCGT1**			**CCGT2**			**CCGT3**			**CCGT4**			**CCGT5**		
Final state		**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**
Initial state	**OFF**	-	4500	7500	-	2500	5000	-	5000	15000	-	2000	3000	-	3000	6000
	3	2250	-	3000	1250	-	2500	2500	-	10000	1000	-	1000	1500	-	3000
	4	3750	1500	-	2500	1250	-	7500	5000	-	1500	500	-	3000	1500	-

Table 5.3: Allowed transitions between modes in the Complete formulation

Group		**CCGT1**			**CCGT2**			**CCGT3**			**CCGT4**			**CCGT5**		
Final state		**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**
Initial state	**OFF**	-	1	1	-	1	1	-	1	1	-	1	1	-	1	1
	3	1	-	1	1	-	1	1	-	1	1	-	1	1	-	1
	4	1	1	-	1	1	-	1	1	-	1	1	-	1	1	-

Table 5.4: Ramp down limits between modes in the Complete formulation

Group		**CCGT1**			**CCGT2**			**CCGT3**			**CCGT4**			**CCGT5**		
Final state		**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**
Initial state	**OFF**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	100	-	50	50	-	40	100	-	15	50	-	75	75	-	50
	4	175	75	-	100	60	-	200	30	-	100	100	-	175	50	-

Table 5.5: Ramp up limits between modes in the Complete formulation

Group		**CCGT1**			**CCGT2**			**CCGT3**			**CCGT4**			**CCGT5**		
Final state		**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**	**OFF**	**3**	**4**
Initial state	**OFF**	-	100	175	-	50	100	-	100	200	-	50	100	-	75	175
	3	-	-	75	-	-	60	-	-	30	-	-	100	-	-	50
	4	-	50	-	-	40	-	-	15	-	-	75	-	-	50	-

5.1.2 Simplified formulation

Table 5.6: Technical data for the different units of the CCGT groups in the simplified formulation.

Group	**CCGT1**		**CCGT2**		**CCGT3**		**CCGT4**		**CCGT5**	
Unit	**1x1**	**2x1**	**1x1**	**2x1**	**1x1**	**2x1**	**1x1**	**2x1**	**1x1**	**2x1**
$\boldsymbol{C_{NL}}$	3200	10700	1000	5000	5000	15000	5000	10000	10000	12000
$\boldsymbol{C_{LV}}$	25	60	35	70	15	40	20	50	30	45
$\boldsymbol{SDC}$	2250	1500	1250	1250	2500	5000	1000	500	1500	1500
$\boldsymbol{SUC}$	4500	3000	2500	2500	5000	10000	2000	1000	3000	3000
$\boldsymbol{es2x1}$	1	2	1	2	1	2	1	2	1	2
$\boldsymbol{\underline{P}}$	100	175	50	100	100	200	50	100	75	175
$\boldsymbol{\overline{P}}$	250	400	200	350	300	600	250	400	250	550
$\boldsymbol{RD}$	50	75	40	60	15	30	75	100	50	50
$\boldsymbol{RU}$	50	75	40	60	15	30	75	100	50	50
$\boldsymbol{TD}$	3	3	2	2	5	5	1	1	2	2
$\boldsymbol{TU}$	3	3	2	2	5	5	1	1	2	2
$\boldsymbol{IS}$	1	0	1	1	1	1	1	0	1	0
$\boldsymbol{Pin}$	150	0	300	0	400	0	70	0	100	0

Table 5.7: Allowed mode transitions in simplified formulation

		CCGT1		**CCGT2**		**CCGT3**		**CCGT4**		**CCGT5**	
		1x1	**2x1**	**1x1**	**2x1**	**1x1**	**2x1**	**1x1**	**2x1**	**1x1**	**2x1**
CCGT1	**1x1**	-	YES	-	-	-	-	-	-	-	-
	2x1	-	-	-	-	-	-	-	-	-	-
CCGT2	**1x1**	-	-	-	YES	-	-	-	-	-	-
	2x1	-	-	-	-	-	-	-	-	-	-
CCGT3	**1x1**	-	-	-	-	-	YES	-	-	-	-
	2x1	-	-	-	-	-	-	-	-	-	-
CCGT4	**1x1**	-	-	-	-	-	-	-	YES	-	-
	2x1	-	-	-	-	-	-	-	-	-	-
CCGT5	**1x1**	-	-	-	-	-	-	-	-	-	YES
	2x1	-	-	-	-	-	-	-	-	-	-

The main objective of comparing two different formulation is to achieve the same results between them. Then, the technical data of the turbines needs to be the same in both cases. For the complete formulation, Table 5.1 offers the technical data within each mode. For instance, linear variable cost, non-load cost, minimum and maximum power output or the within-mode ramps. It is also necessary to add data for the inter-mode parameters. Table 5.2 provides the costs of transitioning between modes. It can be checked that for any units, the costs of transitioning from mode 0 to mode 4 are the same than summing together the costs of moving from OFF to mode 3 plus moving from 3 to mode 4, as Equation 5.1 represents. In Table 5.3 a “1” represents that transition is allowed for a given Initial and Final State. Finally, Table 5.4 and Table 5.5 offers the ramp down and ramp up limits between modes.

$$CT_{0,4} = CT_{0,3} + CT_{3,4} \tag{5.1}$$

In the case of the simplified, less amount of data needs to be provided, since the equations allows to infer some of them, like the ramps limits between modes, that are not implicitly specified. Table 5.6 provides all the technical data and it also specifies through the $es2x1$ row which groups are 1x1 and 2x1, whose relation is determine by the data available in Table 5.7, where a “YES” means that a 1x1 group is related with a 2x1 group. Each 1x1 can only be related with one 2x1 and to make things easy, the share the name of the unit (CCGTx).

5.2 Results

The results obtained are identical for both formulations in terms of the power provided by each unit at each period and the mode in which they worked. Units made the same transitions in the same periods. The power produced by each unit in each hourly period can be seen in Figure 5.3. Depending on the fixed and variable costs of each unit, some of them work as baseload while others, more flexible, cover the peaks.

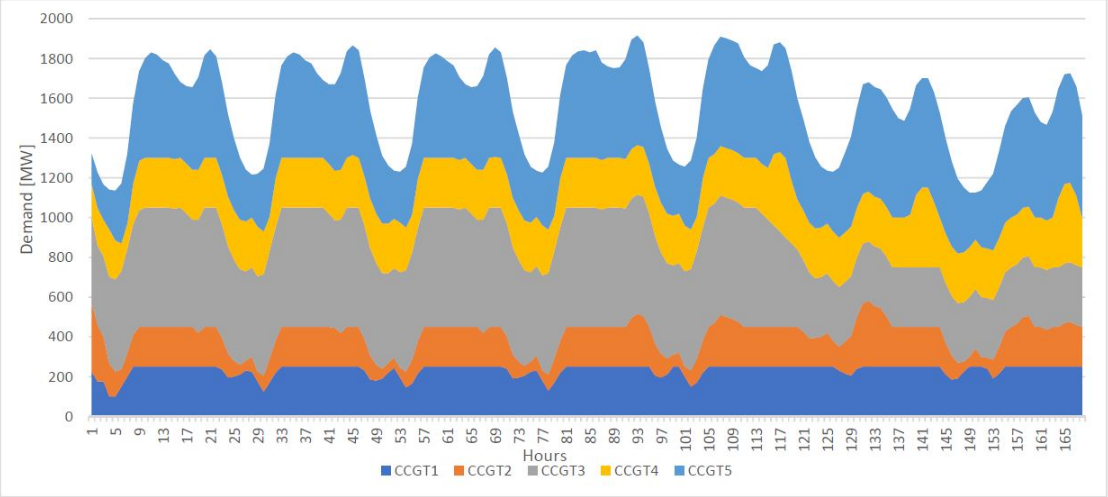


Figure 5.3: Demand coverage with CCGT units for both formulations.

In terms of the transition between modes, since the demand to cover is high in comparison with total available power, units never shutdown but they tipically work with only one gas turbine and one steam turbine, swithching to 2x1 mode when demand peaks. It can be checked in Figure 5.4 that units move to the mode with two gas turbines and one steam turbine when demand is higher. For short periods working at 2x1 mode, the units with lower transition costs are the one that change to that mode. For longer periods, units with lower variable costs at 2x1 mode are the ones transitioning.

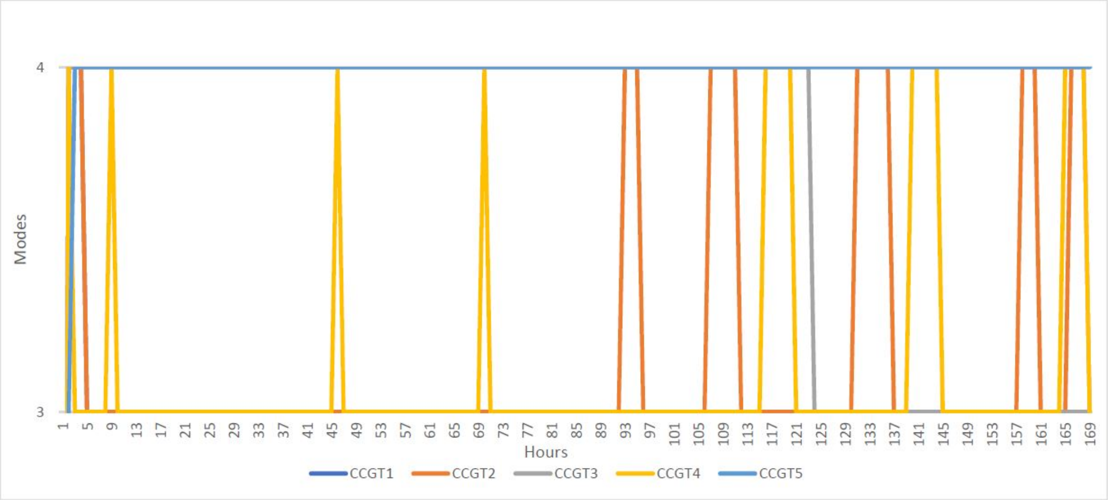


Figure 5.4: Mode switching in the units for both formulations.

An additional aspect in which both formulations need to be compared is the computational requirements and problem size. As described in Chapter 4, the complete formulation has a total of 11 equations and 6 variables, while the simplified formulation has 23 equations and 9 variables. In the simplified formulation, the number of equations increases substantially due to the inclusion of 8 equations to allow the system to move from 2x1 to off and from off to 2x1. In the simplified formulation that is simply done by allowing the transition between states using a parameter.

However, in the simplified formulation, variables are defined for each hourly period and each group while in the complete formulation, they are also defined for each mode of the groups. For that reasons, the total number of variable in the complete formulation is higher. There are 14449 variables and 9240 discrete variables in the complete formulation while in the simplified, the number is reduced to 11929 variables and 8400 discrete variables.

The simplified formulation, though, is bigger considering the number of total equations. It has 28697, almost 1000 more than the complete formulation (27857 equations). The total size of the problem is defined by multiplication of equations by variables, but considering that some of them might not have any relationship, the simplified formulation has a total of 94062 non-zero elements, less that the 119062 of the complete formulation.

Finally, for the case under study, computation times show that the complete formulations reached the optimal solution quicker. It took it 1072 seconds to achieve it while for the simplified formulation, the optimization process took 1395 seconds.

Chapter 6

Introduction to CCGT modeling in Plexos

Plexos is a simulation software used for optimization, field in which it provides very broad modeling capabilities. Plexos have multiple uses in the electricity sector. Among them, determining the optimal size and timing of new investments, assesing the impact of renewable generation sources, calculating market prices and trading strategies, load forecasting, calculating AC network power flows or performing stochastic unit commitment of a portfolio.

The way Plexos store the information about an electric system is by creating a database file that is modified from the Plexos interface, shown in Figure 6.1. There, classes, belonging to different class groups, could be added. For instance, the class group "Production" includes the clases Generation of Fuel that are used to define different generators and fuel types, respectively.

A database includes a single system object, that could represent a energy system. All the objects included later belong to this main object. The main object has different collections to which the rest of the objects belong to: generators, fuel, regions, nodes... When a generator is created, it is included to the generation collection of the main system. A membership is created when an object is added to a collection.

Additionally, each object created could have collections itself that are used to define the relationships between the different objects in the system. For instance, to represent that a generator is located in a certain node, it is necessary to add the node object to the nodes collection of the generator, or viceversa.

The main interface of the Plexos software is shown in Figure 6.1. The top bar is used to manage the different databases and change the configuration of the program. The bar in the left-hand side helps navigate thorugh the different objects included in the database. When an object of the different class groups is selected, it appears in the tab "Objects" in the center of the interface. The properties of the objets can be added, eliminated or modified there and memberships with other objects could be made.

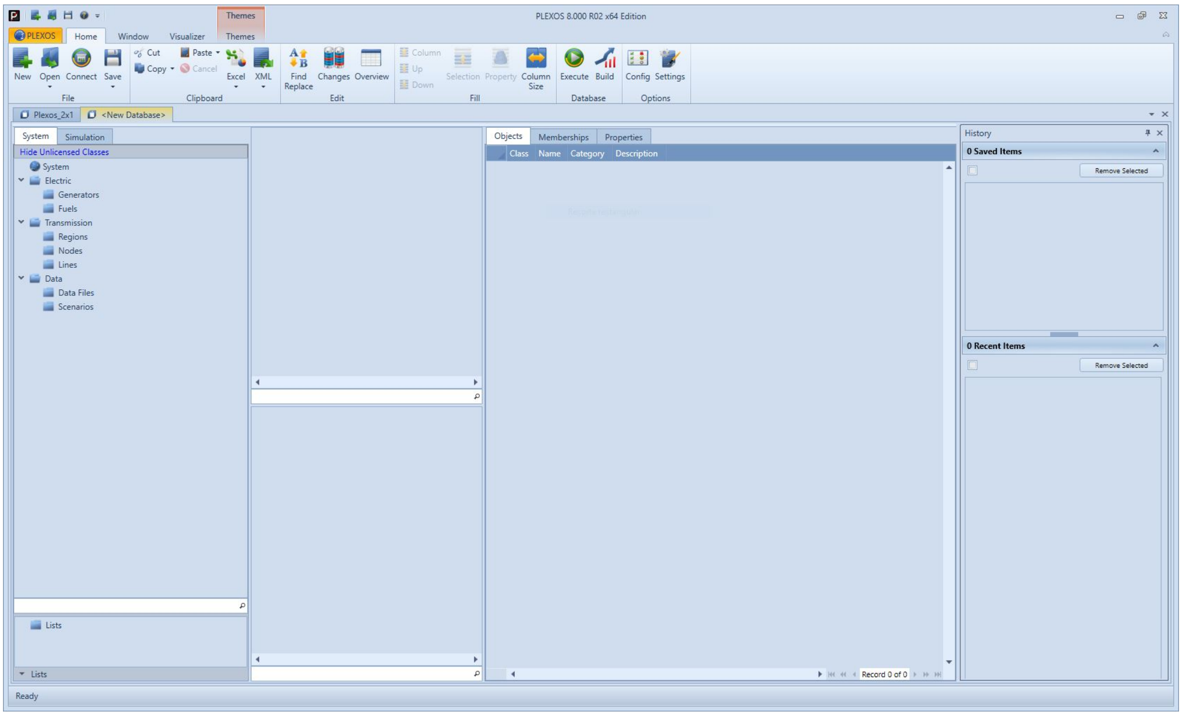


Figure 6.1: Plexos interface when starting the program.

In this case, the problem formulated in Chapter 5 is going to be replicated. For modeling CCGT, Plexos offers two alternatives. The first one is to model the individual gas turbines and steam turbines as different Generation objects and linking them together through the Generator Heat Input membership. The second one is by modeling a single equivalent generator using a complex heat rate function. The best option is to model gas turbines individually where the waste heat output of the gas turbines will be the heat input of the steam turbines.

However, neither of the two approches is fully equivalent to any of the two proposed formulations in Chapter 4. The main issue is that the modes in the Complete or Simplified formulation could have both gas and steam turbines and transitions are allowed between different modes. The Plexos software only allow to model the CCGT as an unique unit or component by component. The most similar way to model this is by creating two Generation objects by CCGT and considering them the 1x1 and 2x1 states.

To imitate the behaviour of the 2x1 formulation proposed in Chapter 4 and the Case Study in Chapter 5, the exactly same units should be included, as represented by Figure 6.2. In this sense, the 1x1 and 2x1 groups of the five CCGT are included. Additionally, it is necessary to add Gas as a fuel and to create a region with an unique node. The node is included to perform the unit-commitment in that node.

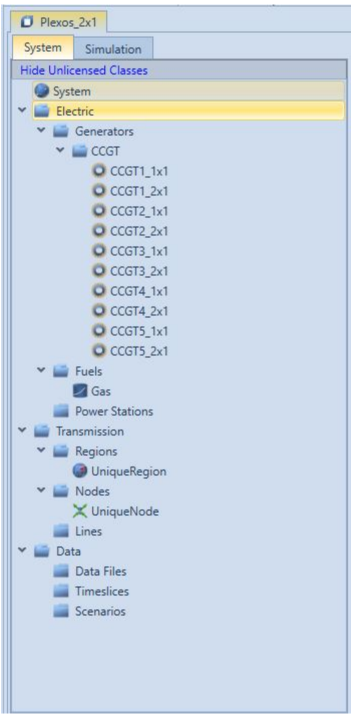
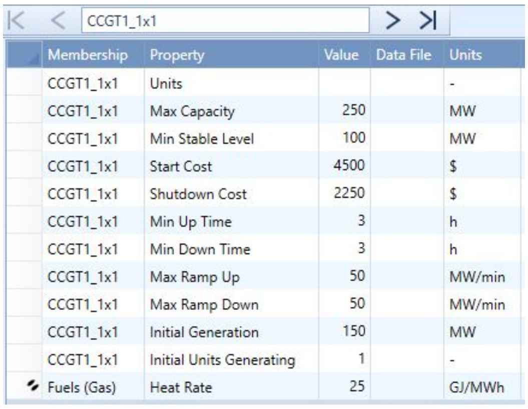


Figure 6.2: Elements added to the current database.

The database needs to be fulfilled with the technical data of the different units. Several paramenters for each unit could be incorporated but to imitate the behaviour of the Simplified Formulation, only the parameters included in the former are introduced, as it is shown by Figure 6.3. In this case, the same technical data that was included for the 1x1 mode of the first CCGT in Table 5.6 is included in the database.

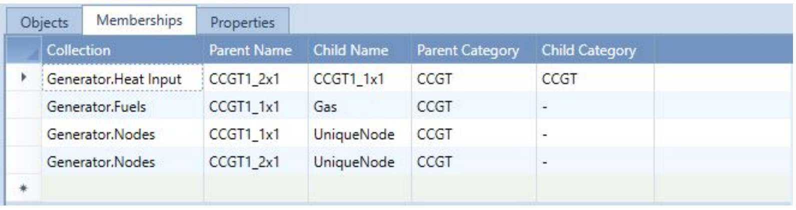
Plexos does not allow to introduce a production cost function but it is necessary to introduce the fuel cost in its class and the heat rate in the different generation units and the generating unit and the fuel need to be linked.



Membership	Property	Value	Data File	Units
CCGT1_1x1	Units			-
CCGT1_1x1	Max Capacity	250		MW
CCGT1_1x1	Min Stable Level	100		MW
CCGT1_1x1	Start Cost	4500		$
CCGT1_1x1	Shutdown Cost	2250		$
CCGT1_1x1	Min Up Time	3		h
CCGT1_1x1	Min Down Time	3		h
CCGT1_1x1	Max Ramp Up	50		MW/min
CCGT1_1x1	Max Ramp Down	50		MW/min
CCGT1_1x1	Initial Generation	150		MW
CCGT1_1x1	Initial Units Generating	1		-
Fuels (Gas)	Heat Rate	25		GJ/MWh

Figure 6.3: Parameters included for each CCGT mode.

Finally, it is necessary to introduce some memberships between the different objects. For the purpose of modeling CCGT, four memberships are required, as represented in Figure 6.4. The first one is the Generator Heat Input membership that links the 1x1 group with the 2x1 group. It is also necessary to indicate the type of fuel the CCGT uses. In this case, it is gas. Finally, both units need to be linked to the node at which they are injectig power, to solve the unit-commitment problem.



Collection	Parent Name	Child Name	Parent Category	Child Category
Generator.Heat Input	CCGT1_2x1	CCGT1_1x1	CCGT	CCGT
Generator.Fuels	CCGT1_1x1	Gas	CCGT	-
Generator.Nodes	CCGT1_1x1	UniqueNode	CCGT	-
Generator.Nodes	CCGT1_2x1	UniqueNode	CCGT	-

Figure 6.4: Relationships between 1x1 and 2x1 modes.

Chapter 7

Conclusions

The main conclusions that can be drawn from this Master Thesis are:

- Gas will play an important role in the electricity industry in the following years thanks to combined-cycle gas turbines that will be used as back-up generation when renewables could not cope with the demand. Gas units provide more flexibility in their operation, have a greater efficiency and are quicker in operation that other conventional units. These characteristicas are highly valuable in the electricity sector and will make gas units become the best non-renewable option for electricity generation.
- There is a direct relationship between the gas and electricity markets though CCGT operation. The conditions in the gas markets affect the production costs of gas units and their bids in the electricity markets. In this sense, gas units need to guarantee a stable gas supply and access to the different gas infrastructure through Third Party Access contracts.
- The European Union has been very active in developing Directive, Regulations and Network Codes concerning the internal gas market. The increasing importance of gas markets in Spain and Portugal has also lead to the harmonisation of the access conditions to gas infrastructure in these countries. The number of services provided has increased in the past years and regulation needed to be adapted to guarantee equalness in the access to those services.
- CCGT are typically modeled using three representations: an aggregate model, in which the CCGT is treated as a pseudo unit with the aggregate characteristics of the different units, a component modeling, in which each of the physical components is modeled independently and a configuration-based model, where the CCGT can transition between certain modes that have different charecteristics. The configuration-based approach is the more suitable one but it can be simplified limiting the number of possible states to three.

- The complete formulation allows to model any possible state of the CCGT while the simplified focus on the three typical states in which CCGT normally operate: off, 1 GT + 1 ST and 2 GT + 1 ST. In the case study that was developed, both formulations were used in an unit-commitment problem, with 5 CCGTs and the exact same results were obtained in terms of power delivered by each unit and the mode in which the unit was working in every period. The complete formulation was faster in achieving the optimal result despite being a bigger optimization problem.
- The Plexos software provides huge modeling possibilities concerning CCGTs. It can model CCGTs using an aggregate model or a component model but it does not include the configuration-based approach. In order to imitate the modeling characteristics used in the proposed formulations in Chapter 4, additional constraints should be added to link the different modes, represented as individual units, with their own technical characteristics.

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Appendix A

GAMS code

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GAMS code of complete formulation

```
OPTIONS LIMROW=0, LIMCOL=0, SOLPRINT=ON;
OPTIONS LP=CPLEX, RMIP=CPLEX, MIP=CPLEX, RMIQCP=CPLEX, MIQCP=CPLEX;
OPTIONS RESLIM=86400, ITERLIM=2000000;
OPTIONS OPTCA=0, OPTCR=0;
OPTIONS bratio=1 ;
OPTIONS THREADS=-1;


$INCLUDE Dat\Sets_nx1.set

sets
xn(x)            todos los x menos el del modo 0
;
*defino xn como todo x menos el modo de funcionamiento 0
xn(x)=yes$(ord(x)<>0);

alias
(x,y)
(xn,yn)
(k,kk)
;


$INCLUDE Dat\Parametros_nx1.param
$INCLUDE Dat\TechData_3_nx1.dat
$INCLUDE Dat\TechData_2_nx1.dat
$INCLUDE Dat\Precio_nx1.dat


$ontext
parameters
NLC(g,x)         coste sin carga
LVC(g,x)         coste variable lineal
CT(g,x,y)        coste transicion entre estados
Toff(g,x)        Tiempo mínimo apagado
Ton(g,x)         Tiempo mínimo encendido
Pmin(g,x)        potencia minima por grupo y modo
Pmax(g,x)        potencia maxima por grupo y modo
MF(g,x,y)        transiciones entre modos posibles para cada grupo
RDu(g,x)         maxima rampa de bajada en un modo
RUu(g,x)         maxima rampa de subida en un modo
RDv(g,x,y)       maxima rampa de bajada durante cambio de modo
RUv(g,x,y)       maxima rampa de subida durante cambio de modo
Precio(k)        Income function for each period
Demanda(k)       Demand
;

$offtext

parameters

t1(k,g)          potencia total
u1(k,x,g)         commitment
ct1
coste(k)         coste por hora
;

variables
FO               valor de la funcion objetivo
;

```

```
positive variables
p(g,x,k)         potencia generada por el grupo en el modo en el periodo
t(g,k)           potencia absoluta
penal(k)         penalización
;

binary variables
u(g,x,k)         variable binaria que vale 1 cuando esta en ese modo y 0 cuan»
do eta en otro
v(g,x,y,k)       variable binaria que vale 1 cuando ha hecho el cambio entre »
el modo "x" y el "y"
;

Scalar Penalizacion /10000/
;


equations
eq01max          Funcion objetivo: maximizar beneficio
eq01min          Funcion objetivo: minimizar costes
dembal           Balence de demanda
eq02(g,k)        solo puede estar funcionando en uno de los modos
eq03(g,x,k)      restriccion para cambios entre modos
eq04(g,x,k)      tiempo minimo encendido
eq05(g,x,k)      tiempo minimo apagado
eq06(g,x,k)      limitacion de potencia
eq07(g,x,k)      limitacion de rampa de bajada
eq08(g,x,k)      limitacion de rampa de subida
eq09(g,k)        potencia de cada grupo en el periodo
eq10(g,k)        limite numero de cambios de modo por grupo y periodo
;

$ontext
eq01max..
      FO=E= sum(k,sum(g,sum(xn,p(g,xn,k)+Pmin(g,xn)*u(g,xn,k)))*Precio(k))
            - sum(k,
                sum(g,
                         sum(xn,
                                 NLC(g,xn)*u(g,xn,k)+LVC(g,xn)*(Pmin(g,xn)*u(»
g,xn,k)+p(g,xn,k))
                                 -sum(y$(MF(g,xn,y)),
                                         CT(g,xn,y)*v(g,xn,y,k)
                                 )
                         )
                 )
         )
;

$offtext

eq01min..
      FO=E= sum(k,
                sum(g,
                         sum(x,
                                 NLC(g,x)*u(g,x,k)+LVC(g,x)*p(g,x,k)
                                 +sum(y$(MF(g,x,y)),
                                         CT(g,x,y)*v(g,x,y,k)
                                 )
                         )
                 )
         )
```

```
        +SUM(k,penal(k))*Penalizacion

;

dembal(k)..
        Precio(k)=E=SUM(g,t(g,k))+penal(k)

;

eq02(g,k)..
        sum(x,u(g,x,k))=E=1
;

eq03(g,x,k)..
        u(g,x,k)-u(g,x,k-1)$(ORD(k)>1)-IS(g,x)$(ORD(k) = 1) =E= sum(y$MF(g,x,y),v(g,y,x,k))-sum(y$MF(g,x,y),v(g,x,y,k))
;

eq04(g,x,k)$(ORD(k) >= Ton(g,x))..
        sum(kk$(ord(kk)>=(ord(k)-Ton(g,x)+1) AND (ORD(kk) <= ORD(k))),
                sum(y$(MF(g,x,y)),
                        v(g,y,x,kk)
                )
        )=L=u(g,x,k)
;

eq05(g,x,k)$(ORD(k) >= Toff(g,x))..
        sum(kk$(ord(kk)>=(ord(k)-Toff(g,x)+1) AND (ORD(kk) <= ORD(k))),
                sum(y$(MF(g,y,x)),
                        v(g,x,y,kk)
                )
        )=L=1-u(g,x,k)
;

eq06(g,x,k)..
        p(g,x,k)=L=(Pmax(g,x)-Pmin(g,x))*u(g,x,k)
;

eq07(g,xn,k)..
        Pin(g,xn)$(ORD(k) = 1)  + p(g,xn,k-1)$(ORD(k) > 1) - p(g,xn,k) - sum(y$MF(g,xn,y),p(g,y,k))
        =L=
        RDu(g,xn)*u(g,xn,k-1)-sum(y$MF(g,xn,y),
                                (RDu(g,xn)+Pmin(g,xn)-Pmin(g,y)-RDv(g,xn,y))*v(g,xn,y,k)
                             )
;

eq08(g,xn,k)..
        p(g,xn,k) - (p(g,xn,k-1) + sum(y$MF(g,y,xn), p(g,y,k-1)))$(ORD(k) > 1) - (Pin(g,xn) + sum(y$MF(g,y,xn), Pin(g,y)))$(ORD(k) = 1)
        =L=
        RUu(g,xn)*u(g,xn,k)-sum(y$MF(g,y,xn), (RUu(g,xn)+Pmin(g,xn)-Pmin(g,y)-RUv(g,y,xn))*v(g,y,xn,k))
;

eq09(g,k)..
        t(g,k)=E=SUM(x,p(g,x,k)+Pmin(g,x)*u(g,x,k))

;

```

```
eq10(g,k)..
         SUM(x,SUM(y$MF(g,x,y),v(g,y,x,k))) =L= 1
;

MODEL model_nx1
/
*eq01max
eq01min
dembal
eq02
eq03
eq04
eq05
eq06
eq07
eq08
eq09
eq10
/
;
model_nx1.OptFile=1;

*SOLVE model_nx1 maximizing FO using MIP;
SOLVE model_nx1 minimizing FO using MIP;


t1(k,g) = t.l(g,k)+0.000000001;
u1(k,x,g) = u.l(g,x,k)+0.000000001;
ct1=sum(k$(ord(k)=3),
                sum(g,
                         sum(xn,

                                 sum(y$(MF(g,xn,y)),
                                         CT(g,xn,y)*v.l(g,xn,y,k)
                                 )
                         )
                 )
         )


;

coste(k) =sum(g,sum(xn,NLC(g,xn)*u.l(g,xn,k)+LVC(g,xn)*p.l(g,xn,k)+sum(y$(MF(»
g,xn,y)),CT(g,xn,y)*v.l(g,xn,y,k))))+ penal.l(k)*Penalizacion

;

display t1
display u.l
display v.l
display ct1
display penal.l
;



FILE     GDXXRWPARAMOUT / gdxxrwparamout.txt /;
PUT      GDXXRWPARAMOUT;
*Pone el parametro parametro1TRAS en la Hoja 1 en el rango C3:AH24
* en vez de rango puede darse solo la celda de inicio, pero en ese caso va a »
borrar todo lo que
```

```
* este debajo y a la derecha de esa celda, con le rango solo borra lo que est»
uviera en el rango
PUT      'par = Precio          rdim=1          rng=Precios!A2:B169'/;
*PUT     'par = Demanda         rdim=1          rng=Precios!A2:B169'/;
PUT      'par = t1              rdim=1          rng=Hoja2!A1:F169'/;
PUT      'par = u1              rdim=1          rng=Hoja3!C3:AB172'/;
PUT      'par = coste           rdim=1          rng=Hoja4!A1:B169'/;

PUTCLOSE GDXXRWPARAMOUT;
EXECUTE_UNLOAD ".\resultados.gdx" Precio, t1, u1, coste;
*genera el archivo resultados.xlsm, y un archivo de log por si fallara
EXECUTE 'gdxxrw.exe log=resultados O=resultados.xlsm input=".\resultados.gdx"»
 EpsOut=0 @gdxxrwparamout.txt'
EXECUTE 'del gdxxrwparamin.txt gdxxrwparamout.txt';
EXECUTE 'del gdxxrwparamin.txt gdxxrwparamout.txt resultados.gdx';

```

GAMS code of simplified formulation

```
OPTIONS LIMROW=0, LIMCOL=0, SOLPRINT=ON;
OPTIONS LP=CPLEX, RMIP=CPLEX, MIP=CPLEX, RMIQCP=CPLEX, MIQCP=CPLEX;
OPTIONS RESLIM=86400, ITERLIM=2000000;
OPTIONS OPTCA=0, OPTCR=0;
OPTIONS bratio=1 ;
OPTIONS THREADS=-1;

$ontext
sets
g                grupos
k                periodos
;
$offtext

$ontext
parameters

NLC           "[k€] Coste sin carga"
LVC           "[k€] Coste variable lineal"
SDC           "[k€] Coste de apagado"
SUC           "[k€] Coste de arranque"
es2x1         "Mode"
Pmin          "[GW] Potencia mínima"
Pmax          "[GW] Potencia máxima"
RD            "[GW] Máxima rampa de bajada"
RU            "[GW] Máxima rampa de subida"
gts2x1      "Relación entre modos"
Toff          "[h] Tiempo mínimo apagado"
Ton           "[h] Tiempo mínimo encendido"
IS            "Estado inicial de las vaiables"
Precio        "[GW] Curva de demanda"

$offtext

* Read the data from the data file
$INCLUDE Dat\Sets_2x1.set
$INCLUDE Dat\Parametros_2x1.param
$INCLUDE Dat\TechData_2x1.dat
$INCLUDE Dat\ModeRel_2x1.dat
$INCLUDE Dat\Precio_2x1.dat

;

alias
(g,gg)
(k,kk)
;
$ontext
parameters

NLC(g)           Non-load cost
LVC(g)           Lineal variable cost
SDC(g)           Shut-down cost
SUC(g)           Start-up cost
es2x1(g)         Mode
Pmin(g)          Minimum power
Pmax(g)          Maximum power
RD(g)            maxima rampa de bajada
RU(g)            maxima rampa de subida
gts2x1(g,g)      Mode relations
Toff(g)          Minimum time off
```

```
Ton(g)           Minimum time on
IS(g)            Initial state of units
Precio(k)        Income function
;
$offtext

parameters

t1(k,g)          potencia total
v1(k,g)          commitment
susd
coste(k)         Coste horario
;

variables
FO               valor de la funcion objetivo
;

Scalar Penalizacion /10000/;

positive variables
p(g,k)           potencia generada por el grupo en el modo en el periodo
t(g,k)           potencia absoluta
penal(k)         penalización
;

binary variables
v(g,k)           Decision de acoplamiento del grupo termico en el periodo k e»
n todos los periodos que funciona
y(g,k)           Decision de arranque     del grupo termico en el periodo k s»
olo en el periodo que arranca
z(g,k)           Decision de parada       del grupo termico en el periodo k s»
olo en periodo que para
x(g,k)           Arranque 2x1 desde 0.
w(g,k)           Parada desde 2x1.
;




equations
eq01             funcion objetivo
dembal(k)        Balance de demanda
eq04(g,k)        tiempo minimo encendido
eq05(g,k)        tiempo minimo apagado
RDDATPAR1(g,k)   Parada grupos 1x1
RDDATPAR2(g,k)   Parada grupos 2x1
RDDATARR1(g,k)   Arranque grupos 1x1
RDDATARR2(g,k)   Arranque grupos 2x1
eq07(g,k)        limitacion de rampa de bajada
eq08(g,k)        limitacion de rampa de subida
R2x1LIMp1(g,k)   restricción para ligar las potencias de los 2x1
R2x1LIMv2(g,k)   restricción para ligar los estados de acoplamiento de los 2x»
1
RCAAP(g,k)       restricción de coherencia arranque acoplamiento parada
potabs1(g,k)     Potencia total generada imputada a grupos 1
potabs2(g,k)     Potencia grupos 2 es cero
arr2x11(g,k)     Lógica arranque 2x1.
arr2x12(g,k)     Lógica arranque 2x1.
arr2x13(g,k)     Lógica arranque 2x1.
arr2x14(g,k)     Lógica arranque 2x1.
```

```
par2x11(g,k)     Lógica parada 2x1
par2x12(g,k)     Lógica parada 2x1
par2x13(g,k)     Lógica parada 2x1
par2x14(g,k)     Lógica parada 2x1
;


eq01..
         FO =E= SUM((g,k)$(es2x1(g)=1),
                            SUC(g) * y(g,k)
                          + NLC(g) * v(g,k)
                          + LVC(g) * p(g,k)
                          + SDC(g) * z(g,k)
                )
                +SUM((g,k)$(es2x1(g)=2),
                            SUC(g) * y(g,k)
                          + (NLC(g)-SUM(gg$gts2x1(gg,g), NLC(gg))) * v(g,k)
                          + LVC(g) * p(g,k)
                          + SDC(g) * z(g,k)
                )
                 +SUM(k,penal(k))*Penalizacion
;

dembal(k)..
        Precio(k)=E=SUM(g,t(g,k))+Penal(k)

;


eq04(g,k)$(ORD(k) >= Ton(g))..
         SUM(kk$((ORD(kk) >= ORD(k)-Ton(g)+1) AND (ORD(kk) <= ORD(k))),
                 y(g,kk)
         )
         =L=
         v(g,k)
;


eq05(g,k)$(ORD(k) >= Toff(g))..
         SUM(kk$((ORD(kk) >= ORD(k)-Toff(g)+1) AND (ORD(kk) <= ORD(k))),
         z(g,kk))
         =L=
         1-v(g,k)
;

RDDATPAR1(g,k)$(es2x1(g) = 1)..
         p(g,k) =L= (Pmax(g) - Pmin(g)) * (v(g,k) - z(g,k + 1))
;

RDDATPAR2(g,k)$(es2x1(g) = 2)..
         p(g,k) =L= (Pmax(g) - Pmin(g)) * (v(g,k))
;

RDDATARR1(g,k)$(es2x1(g) = 1)..
         p(g,k) =L= (Pmax(g)-Pmin(g))*(v(g,k)-y(g,k))
;

RDDATARR2(g,k)$(es2x1(g) = 2)..
         p(g,k) =L= (Pmax(g)-Pmin(g))*(v(g,k))
;

```

```

eq07(g,k)..
         Pin(g)$(ORD(k) = 1) + t(g,k-1)$(ORD(k) > 1) - t(g,k) =L= RD(g) + SUM»
(gg$gts2x1(g,gg),(v(gg,k)-y(gg,k))*(RD(gg)-RD(g))) + z(g,k)*(Pmin(g)-RD(g)) +»
 SUM(gg$gts2x1(g,gg),z(gg,k)*(RD(gg)-RD(g)))  + w(g,k)*(SUM(gg$gts2x1(g,gg),P»
min(gg)-RD(gg))-Pmin(g)+RD(g))
;

eq08(g,k)..
         t(g,k) - t(g,k-1)$(ORD(k) > 1) - Pin(g)$(ORD(k) = 1) =L= RU(g) + SUM»
(gg$gts2x1(g,gg),v(gg,k)*(RU(gg)-RU(g))) + y(g,k)*(Pmin(g)-RU(g)) + x(g,k)*(S»
UM(gg$gts2x1(g,gg),Pmin(gg)-RU(gg))-Pmin(g)+RU(g))
;


R2x1LIMp1(g,k)$(es2x1(g) = 1)..
*           p1   <=    (p1max -p1min)·(v1-v2)
           p(g,k) =L= (Pmax(g)-Pmin(g)) * (v(g,k) - SUM(gg$gts2x1(g,gg), v(gg»
,k)))
;


R2x1LIMv2(g,k)$(es2x1(g) = 1)..
*           v2   <=   v1
            SUM(gg$gts2x1(g,gg), v(gg,k) ) =L= v(g,k)
;


RCAAP(g,k)..
         y(g,k) - v(g,k) - z(g,k) + IS(g)$(ORD(k) = 1) + v(g,k-1)$(ORD(k) > 1»
) =E= 0
;

potabs1(g,k)$(es2x1(g) = 1)..
         t(g,k) =E= p(g,k)+Pmin(g)*v(g,k) + SUM(gg$gts2x1(g,gg),p(gg,k)+(Pmin»
(gg)-Pmin(g))*v(gg,k))
;

potabs2(g,k)$(es2x1(g) = 2)..
         t(g,k) =E= 0
;

arr2x11(g,k)..
         y(g,k) + SUM(gg$gts2x1(g,gg),y(gg,k)) - x(g,k) =L= 1
;

arr2x12(g,k)..
         y(g,k) - SUM(gg$gts2x1(g,gg),y(gg,k)) + x(g,k) =L= 1
;

arr2x13(g,k)..
         -y(g,k) + SUM(gg$gts2x1(g,gg),y(gg,k)) + x(g,k) =L= 1
;

arr2x14(g,k)..
         -y(g,k) - SUM(gg$gts2x1(g,gg),y(gg,k)) + x(g,k) =L= 0
;


par2x11(g,k)..
         z(g,k) + SUM(gg$gts2x1(g,gg),z(gg,k)) - w(g,k) =L= 1
```

```
;

par2x12(g,k)..
         z(g,k) - SUM(gg$gts2x1(g,gg),z(gg,k)) + w(g,k) =L= 1
;

par2x13(g,k)..
         -z(g,k) + SUM(gg$gts2x1(g,gg),z(gg,k)) + w(g,k) =L= 1
;

par2x14(g,k)..
         -z(g,k) - SUM(gg$gts2x1(g,gg),z(gg,k)) + w(g,k) =L= 0
;



MODEL model_2x1
/
eq01
dembal
eq04
eq05
RDDATPAR1
RDDATPAR2
RDDATARR1
RDDATARR2
eq07
eq08
R2x1LIMp1
R2x1LIMv2
RCAAP
potabs1
potabs2
arr2x11
arr2x12
arr2x13
arr2x14
par2x11
par2x12
par2x13
par2x14
/
;

model_2x1.OptFile=1;
SOLVE model_2x1 minimizing FO using MIP;


display p.l
display t.l
display v.l
display y.l
display z.l
display penal.l
;

t1(k,g) = t.l(g,k)+0.00000000001;
v1(k,g) = v.l(g,k)+0.00000000001;
susd=SUM((g,k)$(es2x1(g)=1 AND (ord(k)=3)),
                            SUC(g) * y.l(g,k)
                          + SDC(g) * z.l(g,k)
```

```
                )
                +SUM((g,k)$(es2x1(g)=2 AND (ord(k)=3)),
                            SUC(g) * y.l(g,k)
                          + SDC(g) * z.l(g,k)
                )
;
coste(k)= SUM(g$(es2x1(g)=1),
                            SUC(g) * y.l(g,k)
                          + NLC(g) * v.l(g,k)
                          + LVC(g) * p.l(g,k)
                          + SDC(g) * z.l(g,k)
                )
                +SUM(g$(es2x1(g)=2),
                            SUC(g) * y.l(g,k)
                          + (NLC(g)-SUM(gg$gts2x1(gg,g), NLC(gg))) * v.l(g,k)
                          + LVC(g) * p.l(g,k)
                          + SDC(g) * z.l(g,k)
                )
+penal.l(k)*Penalizacion

;




display susd
;

FILE     GDXXRWPARAMOUT / gdxxrwparamout2x1.txt /;
PUT      GDXXRWPARAMOUT;
*Pone el parametro parametro1TRAS en la Hoja 1 en el rango C3:AH24
* en vez de rango puede darse solo la celda de inicio, pero en ese caso va a »
borrar todo lo que
* este debajo y a la derecha de esa celda, con le rango solo borra lo que est»
uviera en el rango
PUT      'par = Precio        rdim=1          rng=Hoja1!A2:B169'/;
PUT      'par = t1            rdim=1          rng=Hoja2!A1:K169'/;
PUT      'par = v1            rdim=1          rng=Hoja3!A1:K169'/;
PUT      'par = coste         rdim=1          rng=Hoja4!A1:B169'/;

PUTCLOSE GDXXRWPARAMOUT;
EXECUTE_UNLOAD ".\resultados2x1.gdx" Precio, t1, v1, coste;
*genera el archivo resultados.xlsm, y un archivo de log por si fallara
EXECUTE 'gdxxrw.exe log=resultados2x1 O=resultados2x1.xlsm input=".\resultado»
s2x1.gdx" EpsOut=0 @gdxxrwparamout2x1.txt'
EXECUTE 'del gdxxrwparamin2x1.txt gdxxrwparamout2x1.txt';
EXECUTE 'del gdxxrwparamin2x1.txt gdxxrwparamout2x1.txt resultados2x1.gdx';



```