MCCXXII

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Study of the influence of loading history on the residual life of the devices of thermoelectric plants to optimize the management of energetic conversion system

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ABSTRACT

Because of changes in the Italian electricity market, consequence of the liberalization process, new management strategies of power plants and electricity generation systems have been applied, from a basic use towards flexibilization to cover daily and weekly variations. This operation mode leads to higher profits in the short term, but tends to cause lifetime reduction of critical components, due to creep damage and thermo-mechanical fatigue.

This paper evaluates the residual life of critical equipment for steam power plants. The effects of rapid and frequent changes in both temperature and pressure in these components will be evaluated in economic terms too.

CONTENTS

INTRODUCTION

The gradual liberalization of the electricity market in Italy has generated a growing competition among different electricity producers, forcing a growing number of plants originally designed for the production in base load to operate in a cyclic manner according to the daily and weekly demand curves.

However, cycling plants may cause either long-term cost penalties, such as excessive "wear and tear" costs, equipment repair and replacement costs, or decreased unit reliability/availability. Cycling also may lead to short-term cost penalties, which include higher heat rates, increased operations and maintenance costs, increased need for training, and degradation of equipment performance. Balancing technical and total cost tradeoffs has become critical to the operation of fossil-fuel units in cycling modes.

Until now, much of the emphasis on two-shifting has been with thermal stress and fatigue of large plant items operating at high temperature. Two-shifting has been regarded as another facet of normal plant operation, where a unit may be cycled just a few times a year. Nevertheless, two-shifting can bring problems of its own. For example, because of their need to start up “against the clock,” superheaters and reheaters can experience temperature excursions significantly above design.

Other aspects of two-shift operation, particularly on older plants, include the difficulty of operating equipment used to process and supply fuel, general increased wear and tear, and operation of a water treatment plant.

The focus has been placed on the most stressed component inside the boiler of a steam power plant fueled by coal (the high temperature superheater) from an economic point of view. In fact in the study have been reported the results of a comparison between two different modes of management of the same plant, with a detailed analysis on the main cost components (fuel costs, O&M costs, capital costs, etc.) and energy sales in the free market, whose knowledge is necessary for a reliable assessment of economic impact due to flexibility.

CHAPTER 1 THE FLEXIBLE ENERGY MARKET

1.1 CYCLIC OPERATION

Over the past decade, the electricity sector in Italy has been subjected to profound changes in the structure and organization. In particular, some measures have been implemented to end with the monopoly in the generation sector. The process of market liberalization is therefore producing a growing competition between producers and this makes it increasingly important to optimize management strategies and plant control in order to reduce production costs. This optimization must also take into account the stringent environmental laws which restrict the operating margins of power plants.

The operating economy of generation plants is therefore an essential aim for all the electric operators since it is the prerequisite for the survival of the Power Company in the energy market. This objective is achieved through systematic optimization of performances and methods of plant management.

The variability of fuel prices, the new and more efficient technology systems and the daily variability of electricity demand pose complex problems to the plant operator that has to develop operational models aimed to improving the exercise in terms of efficiency, flexibility and reliability.

Essential characteristics for the correct exercise of the power system are in fact the capacity of generating units of satisfying with appropriate dynamic the load changes required by the system (especially the demand of short term that is higher recompensed) and operating at minimum load during the off-peak period. Therefore, each unit should have design features that makes it capable to work either at high loads or at technical minimum and make the nocturne and weekend shutdown with short time for the next restart.

It is usual to classify the loading rate of a combined cycle in accordance with the standard ISO 3977 “Gas Turbine – Procurement”, according to the hours of operation and the number of starts per year, placing the plant in a certain range of cyclic operation, as shown in Table 1.

	Maximum continuous load	Base load	Medium load	Alternate base/peak	Daily cyclic	Peak
Operating hours	8.000 8.600	6.000 8.000	3.000 6.000	2.000 3.000	2.000 4.000	200 800
Service factor	90 – 100	70 – 90	35 – 70	20 – 50	20 – 50	2 – 10
Number starts	3 – 40	20 – 80	10 – 60	40 – 120	250 – 300	60 – 150
Operating hours/Number starts	>200	60 – 400	60 – 400	30 – 60	10 – 18	3 – 8

Table 1.1 Operating modes according to the standard ISO 3977 “Gas Turbine – Procurement”

Operational flexibility of a thermal power plant consists essentially of two concepts:

- The speed of change of the electrical power supplied consistent with the maximum allowable gradient.
- The range of electric power between the technical minimum and full load.

Going from a basic to a flexible usage to cover daily and weekly variations involves the need of verifying the suitability of plants to develop a different role for which they were provided in the design phase and studying types of plant management to reduce problems related to flexibility.

From now it is possible to say that the flexibility will be reflected on: the useful life of components, the control of thermodynamic parameters and emission control.

The flexible behavior usually increases the wear and the fatigue failures. The boilers, in particular the parts at higher temperature, gas turbines, steam turbines and auxiliary components are subjected to higher thermo-mechanical cycles due to an increase in transients frequency and an increase of heating velocity because of the need of respond to grid requests with rapidity. Each cycle damage the components and the accumulated damages end up causing more frequent breakdowns and unplanned out of service. Moreover, the methods used to start and stop the plant influence its reliability and its life expectancy.

This is especially true when the plants have not been designed for cycling operations. The financial costs associated with cycling operation are very high. An analysis of selected older coal-fired plants has found them to be more rugged and cost effective to cycle than the newest combined cycle units. Low fuel prices are another advantage of coal. Making the decision to cycle coal-fired units should be carefully considered, as there are numerous long term effects, component damage and significant costs that need to be carefully calculated.

The true cost of on/off, load cycling and high load operations of 90-120 percent of rated capacity are often not known or not well understood by utility operators. Even when a unit is designed for cycling, there are external effects in the balance of plant design, water chemistry, pulverizer and coal/ash types. To optimize operations and determine the true cost of each operation, cycling of units should be subjected to a thorough analysis of their cycling operations. Utilizing this knowledge, a power plant is able to significantly reduce costs, have more operational flexibility, faster MW response and improved profitability.

1.1.1 Damage mechanisms of cycling

Cycling happens when units are required to be brought on line and shut down as needed. Generally, the units are kept on line for shorter durations. These durations can be of few hours or few days. For example, the units may be brought on line to take care of excess demand during peak hours and shut down overnight. This is regular cycling in the sense that the time and duration of operation is well defined and the schedule is predictable. Sometimes the units are used to take care of the demand when a base loaded unit, generally a coal fired boiler, is down for maintenance or repairs. If the maintenance is regularly scheduled, then the cycling units' operation is also predictable. However, there may be times when the regular base loaded units have to be shut down due to some emergency maintenance or repairs. These types of operations are totally unpredictable both in duration and starting up time.

Another type of cycling can happen because of economic optimization. Power grids buy power daily based on the market price. The power generators may want to start a unit on very short notice if the market price will result in profitable revenue.

Start up time is key for the cycling units. If the start-up is predictable, then units can be started with the given procedure in advance. Obviously, fast starts reduce the start-up cost because of shorter non-production time. Unscheduled start-ups may be tied to the potential of extra income. If the unit starts up quicker, then more revenue can be generated by supplying the power sooner. Thus, while cycling happens because of the power requirements, faster starts are desired to reduce cost or maximize income potential.

Both cycling and faster starting affect the life consumption adversely. Cycling affects life consumption because there are simply more number of cycles imposed than those assumed in the design. Fast starting damages the unit because rapid ramping produces much higher stresses causing faster unit deterioration.

Definitions of cycling have varied from on/off starts, (normally defined as hot, warm, and cold starts) and two-shifting to load cycling and high frequency load variations. Inclusion of all cyclic operations is critical to proper analysis. Many units have only a few starts, but provide a large amount of intra hour load following. However, this can significantly add to a unit's cyclic damage. Hot starts are typically defined to have very high, 700F to 900F, boiler/turbine temperatures and less than 8 to 12 hours off-line.

Warm starts have boiler/turbine temperatures of 250F - 700F and are off-line for 12 to 48 hours. Cold starts are ambient temperature starts, 250F or less, and have 48 to 120 hours off-line. These definitions may vary due to unit size, manufacturer and dispatcher/Independent System Operator (ISO) definitions.

Damage manifests itself in terms of known past and future maintenance and capital replacements, forced outages and deratings from cycling. It can also result from high load operation. Often the damage mechanism is fatigue and corrosion of the boiler tubes. The time to failure from cycling operation in a new plant can be from 5 to 7 years and in older plants nine months to two-years after start of significant cycling.

1.1.2 Calibrating damage to costs

The vast number of unit types, equipment manufacturers, balance of plant types, and operational regimes makes the cycling costs difficult to categorize. However, damage models have been developed that include creep and fatigue and their interaction for each unit type, pressure range and temperatures. These models account for cyclic operation, baseloaded operation, and operation above MCR. The models are calibrated with plant signature data (temperatures and pressures) for key unit components operating during typical load transients. Damage model validation process includes the assessment of key components with finite element analysis and creep/fatigue analysis methods.

By utilizing these models, it is possible to determine the remaining useful component life. Life cycle analyses of key high cycling cost components are statistically calibrated to the failure history of the components. All of the damage is calibrated to actual plant costs. Traditionally, un-calibrated engineering fatigue and creep analyses are rarely useful, and are often misleading in predicting cycling costs.

Critical components where detailed plant signature data is analyzed include:

- Steam drum
- Water wall /evaporator tubing
- First/second pass water wall tubing
- Superheater and reheater tubing and headers
- Economizer inlet
- Start up system components

In addition, analysis is carried out for the turbine/ generator-related components: Valves, cases, generator windings and steam chests.

The maximum temperature ramp rate and the overall range of temperature change experienced by a component during the transient are key indicators of cycling-related creep and fatigue damage. All of the parameters are used to quantify the severity of each unit's load, start up, and shut down transients. Signature data is also used in evaluating and troubleshooting a unit's cycling operations.

Using this information, the operators are able to determine the recommended temperature for the ramp rate limits for the superheater and economizer during all types of start up, and shut down and cooling. With this information the operators are able to minimize damage, maximize the asset's life and reliability while reducing maintenance costs.

Signature data is utilized by plant managers to calibrate its cost control of operations and maintenance program. This real-time code displays temperature ramp rates in key components and alerts the operators of excessive ramp rates. The study proposed here can also be seen in this perspective, to provide a cost in terms of reduced time of replacement and maintenance of the more stressed components.

Damage modeling is combined with historical capital maintenance spending and unit loading over time, to derive cost per unit-specific typical load cycle. Usually it must be given an assessment of the annual cost of management and regular maintenance when varying the managements and therefore the costs not directly related to the plant operation will not be taken into account.

To compare the managements it is necessary to have historical data or hourly simulations of the production, load factors and the behavior in starts, also because there are specific situations in the different months and weeks of the year. It is enough to think in the difference between summer and winter environmental conditions and the problems related to the condensation of steam or to the characteristics of the supply and combustion air.

1.1.3 Cycling costs

Plant costs (management and maintenance) tend to increase when the cyclical or flexible management strategy is introduced. It is possible to assess this increase and the study presented here in the last chapter compares two types of management: one in base load and the other in a more flexible mode, adopting suitable cost conditions and selling prices.

The unit’s specific analysis results depend on the regression analysis of the costs versus cycles and the unit signature data during cyclic operations at all load changes. The increased incremental costs attributed to cycling fall into the following categories:

- Additional maintenance and recurring capital costs associated with overhaul, usually the largest cycling cost elements for units studied to date.
- Cost of higher use of less economical generating units (including the purchase of additional short-term capacity) resulting from higher failure rates.
- Long-term unit efficiency changes because of component degradation, including worn seals and fouled heat exchangers.
- Higher heat rate caused by operating at lower than desired capacity levels and by dynamic load changes during cycling that increase efficiency degradation.
- Cost of startup fuels, auxiliary power, chemicals and additional manpower required for unit startup
- Capital expenditures for new capacity because of the shortened life of the units being cycled.

Measurement of unit heat rate cycling, while at steady state indicates there is significant degradation in unit heat rate when power plants cycle extensively. Poor efficiency is due to low load operation, load following, unit startups and unit shutdowns. The cumulative long term effects of cycling can increase the unit heat rate due to fouled heat exchangers, warn seals and wear/tear on valves and controls. It follows that the resulting increase of cost for a plant designed to operate at base load is significant when it is exercised in a cyclic mode.

In addition, methods used to start and shutdown a plant influence strongly on its reliability and life expectancy. The flexible operation of combined cycles involves therefore additional costs compared to a typical baseload exercise, which are essential to quantify with precision as they may determine strategic choices.

For example, the cost of EFOR ("Equivalent Forced Outage Rate" – the unavailability index that takes into account the accidental off-service hours and the hours of operation in derating accidentally) increase as a function of cycling. These increases are obviously minor for the units that are specifically designed to be flexible, higher for base load units that have been modified to be flexible and even higher for those units that have not been modified. Higher EFOR values mean that to keep plants operating, capital costs and maintenance costs increase. Such costs may not be competitive and with a reduced production capacity the unit may be premature retired.

An accurate knowledge of operation modes during flexible operation and related costs are therefore of great importance in order to optimize this behavior and determine the real cost of each operation.

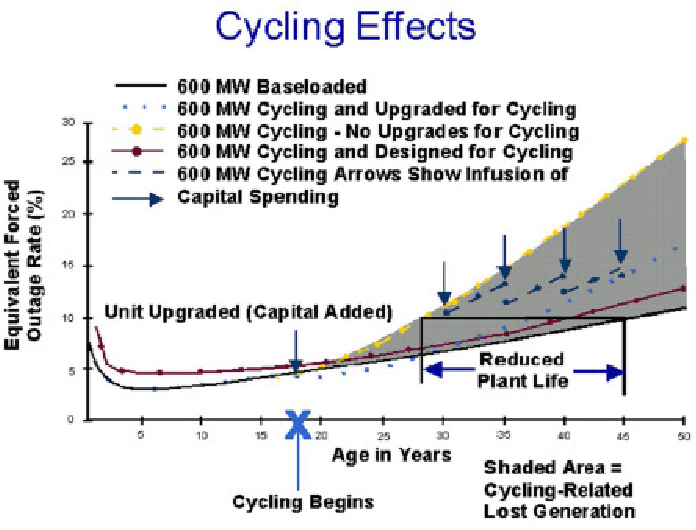

Fig 1.1 Percentage trend of the EFOR over time of plant with different characteristics

1.2 ITALIAN ELECTRICITY MARKET

The decree of the electricity market liberalization (the so-called “Bersani Decree”), dated 19 February 1999, has market the beginning of the Italian market opening under the EU Directive EC 96/92. Following a series of legislative measures that have taken place since then, 31 March 2004 was officially opened in Italy the Power Exchange (initially for producers). With the full liberalization of the electricity market to all citizens, it has been opened a new phase for the Italian electricity users. Today, in fact, despite various difficulties companies and individuals can identify alternative suppliers and negotiate with them significant commercial elements (price, delivery conditions, etc.) in order to achieve real savings, which is extremely useful considering the rising energy costs.

The Power Exchange has been created and is managed as an essential tool for the creation of a competitive electricity market in Italy, to promote the emergence of efficient equilibrium prices that allow producers and wholesalers to sell and buy electricity where there is greater cost-effectiveness, to ensure their operators the transparency and security of the trade. In particular it must promote competition in the business of manufacturing and wholesale through the creation of a marketplace ant to encourage maximum transparency and efficiency of the activity, carried out in natural monopoly, of the dispatching.

1.2.1 Subjects of the electricity system

The main subjects involved in the functioning of the electric system – each with a specific role expressly defined by law – are, in addition to Parliament and Government:

- The Ministry of Economic Development which, among other things, defines the strategic and operational directions for the safety and economy of the national electricity market.
- The Authority for Electricity and Gas, the independent authority that guarantees the promotion of competition and efficiency in the sector with regulation and control functions.
- Terna S.p.A, a company that manages with security the national transmission grid and high and very high voltage and the electric power flows through the

dispatching, balancing, that is, supply and demand of energy 365 days a year, 24 hours a day.

- The Manager of Energetic Services (GSE), a corporation for public capital actions that has a central role in the promotion, incentive and development of renewable sources in Italy. The GSE controls two companies: the Single Buyer (AU) and the Market Operator (GME).
- Single Buyer (AU), a corporation for actions which is assigned the role of ensuring the supply of electricity in the service of greater protection and safeguard in the Decree Law 18 june 2007, n. 73, converted with the law 3 august 2007, n.125.
- The Market Operator (GME), a corporation for actions that organizes and manages the electricity market from an economic point of view, according to criteria of neutrality, transparency, objectivity and competition between producers while ensuring the availability of an adequate level of power reserve. GME, in particular, manages the energy markets, divided between Spot Electricity Market (Day-ahead Market, Intraday Market and the Market of Ancillary Services) and Forward Energy Market.

1.2.2 Relevant aspects of electric system

Some definition and identification set by the regulator are relevant for the market model. In particular:

a) the grid limits that are fundamental in defining energy production and withdrawal plans
b) the minimum amount of energy to be considered for production and consumption plans
c) the identification of the operators to be considered responsible for programs execution and lack of observance.

Geographical and virtual zones

GME uses a simplified grid representation in order to verify transmission plans and remove possible congestions caused by the programs or by bilateral contracts. The simplified grid scheme points out only the principal transmission limits, i.e. the ones among geographical zones, international connections and limited production poles. In particular, the grid is composed by:

- 6 national geographical zones (North, Centre-north, Centre, South, Sicily, Sardinia);
- 6 foreign virtual zones (France, Switzerland, Austria, Slovenia, Corse and Greece);
- several Limited Production Poles, i.e. zones constituted by production units only, which interconnection capacity toward the grid is below the power installed in the same units.

The shaping of these zones is determined by GRTN (Gestore della Rete di Trasmissione Nazionale) on the basis of the criteria adopted in the management of transmission along the peninsula and the characteristics a communicated to GME along with the transmission limit among neighbouring zones.

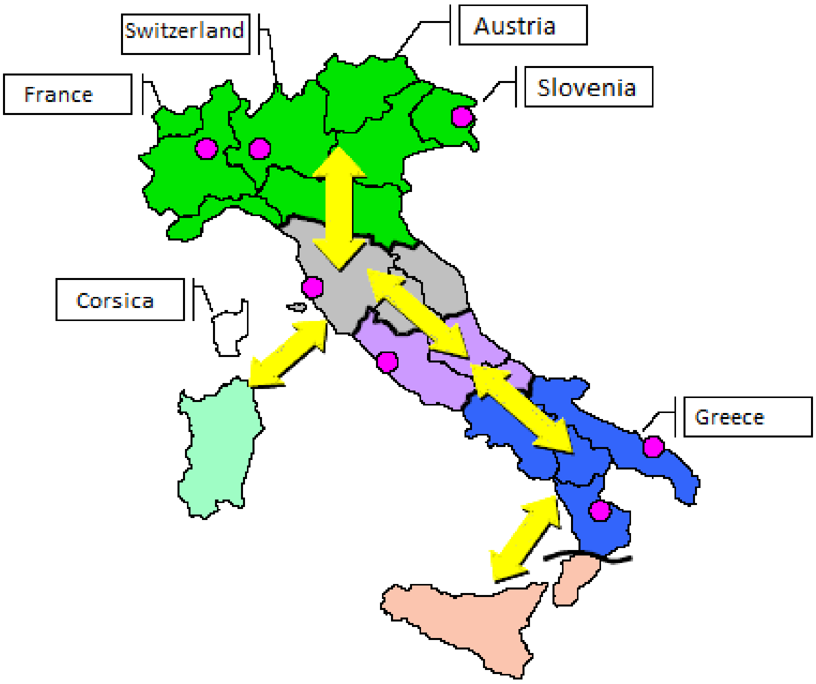

Fig 1.2 Virtual zones and geographical areas of the national transmission grid

1.2.3 Electricity market organization and operation

The Electricity Market is organized in the Spot Electricity Market (MPE) and the Forward Electricity Market (MTE) with the obligation of delivery and collection. The Spot Electricity Market is the set of the Day-ahead Market (MGP), the Intraday Market (MI) and the Ancillary Services Market (MSD).

- The Day-ahead Market (MGP) is devoted to the wholesale energy exchange among producer and traders (or eligible customers), to the setting of injection and withdrawal plans for each hour of the following day and to the allocation of the transport capacity available, for each pair of zones, to market operators and to bilateral contracts. This market is held in the morning of the day ahead, all the operators and Points of Offer are admitted to participate.

  Sale offers can be referred only to *input offer points*, while buy offers can be referred only to *output offer points*: this means that multiple offers can be represented either by sale only offers or by buy only offers. Moreover there are offer points to which both sale and buy offer can be referred. These are the *mixed offer points* which are groups of both virtual and physical points, such as for example production and pumping plants that use energy when they pump water into the reservoirs and produce energy when water is released. Multiple offers that are referred to mixed offer points can be jointly made of sale and buy offers

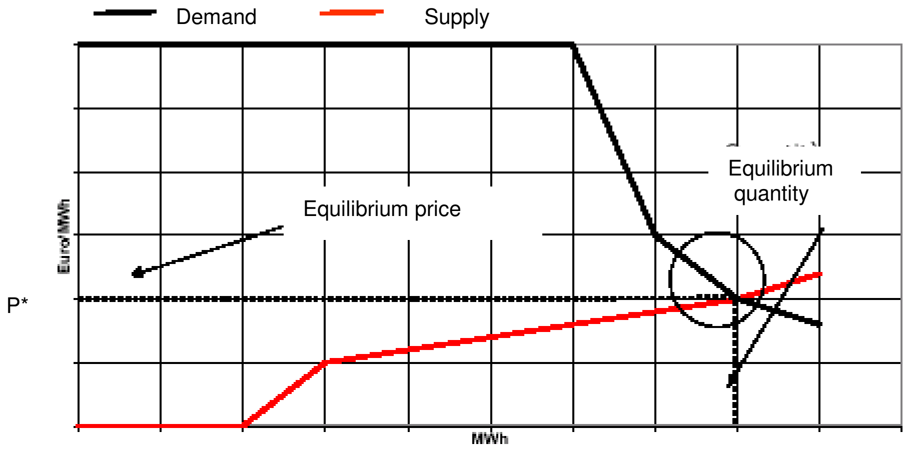

Fig 1.3 Point of market equilibrium

- The Intraday Market (MI) is the trading venue of purchase offers and sale of electricity for each hour of the next day with the purpose of modifying the injection and withdrawal programs defined in the MGP. Bids are accepted in order of merit compatibly with the limits of residues transit downstream of the MGP. If accepted, the offers are paid at the zonal clearing price. Accepted offers change preliminary programs and determine the updated programs of injection and withdrawal of each supply point for the next day. Participation is optional.

- Ancillary Services Market (MSD) is the trading venue of selling and purchase offers of ancillary services used by Terna S.p.A for intra-zonal congestion resolutions, the supply of reserves and the balance in real time between injections and withdrawals. MSD is only open to enabled units to the provision of ancillary services and offers can be made only by dispatching users. Participation in MSD is compulsory. The MSD returns two different outcomes: the first outcome relative to the accepted offers by Terna S.p.A a program for the purpose of the congestion resolution and the establishment of an adequate reserve margin; the second outcome relative to the accepted offers by Terna S.p.A in real time (by sending balance orders) for the balance between entries and withdrawals. Bids accepted on MSD determine the final programs of injection and withdrawal of each offer point. On MSD offers are accepted on the basis of economic merit, compatibly with the need to ensure the proper functioning of the system. Accepted bids are valued at bid price (pay as bid).

The Forward Electricity Market (MTE) is the venue for the negotiation of term contracts of electricity with the obligation of its delivery and collection. On this market are allowed all operators admitted to the electricity market.

On this market GME acts as central counterparty and, being a qualified market operator, has an energy account on the PCE on which records the net position in delivery, corresponding to sale and purchase transactions completed by the operator on the MTE.

Negotiations on MTE are held in continuous mode and the sessions are held from 9.00 to 14.00 in the market days. Two types of contracts can be traded:

1- Baseload, whose underlying is the electricity to be delivered in all relevant periods of days belonging to the delivery period.
2- Peakload, whose underlying is the electricity to be delivered during the relevant period from ninth to twentieth of the days belonging to the delivery period, excluding Saturdays and Sundays.

1.3 THE ELECTRICITY MARKET IN SPAIN

The electricity market in Spain was restructured on January, 1998, according to the Electricity Act 54/1997, of November, known as Law of the Electrical Sector. This Law established the legal base to implant an electricity system whose central item was the creation of an electricity wholesaler market.

The liberalization process followed by Spain was not by any means an isolated movement. During the 1990s, a wave of reforms started in the electricity sectors worldwide. From monopolies and implicit regulations, all electricity-related sectors moved to different levels of unbundling, competition and explicit regulation. The paradigm changed: from scale economies and electricity as a “strategic good” to electricity as a commodity and competition. In the case of Spain, the restructuring process followed the liberalization in the UK electricity market and was enacted almost at the same time with liberalization of the electricity market in California (United States).

The centre-piece of the restructuring was a spot market known as “Pool”, in which a day-ahead market is implemented based on an hourly auction process managed by a market operator, through which buyers and sellers submit their bids for each hour of the following day. Power supply has gradually been liberalized, leaving qualified consumers free to participate in day-ahead market.

The Spanish wholesale market is currently organized in a sequence of different types of markets: day-ahead, intra-daily and ancillary services (secondary reserves, tertiary, etc). These markets are managed by two different operators: the market operator and the system operator. OMEL (Operadora del Mercado Español de Electricidad) is the market's wholesale operator and is responsible for its economic management and for the system of electricity sale and purchase, guaranteeing the efficient development of the electricity generation market. Red Eléctrica de España (REE) is the system operator and manages most of the transmission network. It is responsible for the technical management of the Spanish system in order to guarantee electricity supply and proper coordination between the supply and transmission system, as well as the management of international electricity flows. The system's operator and the market operator carry out their duties in coordination.

The purpose of the day-ahead market is the execution of the electricity transactions for a scheduling horizon of the following day, divided into 24 hourly periods. This market operates on a two part model: firstly, once the bidding period has closed the market operation produces the clearance obtaining the hourly prices that will apply for the following day. Secondly, the system operator receives the information and checks for the existence of technical restrictions. Such restrictions, as well as changes in the forecasted demand are solved latter with the intra-day market and ancillary ser-vices.

In the case of the Spanish market, even from the beginning of the liberalization process, the vast majority of the wholesale transactions of energy are realized in the day-ahead market. However, during 2006, it has entered into force a new regulation (Royal Decree Law 3/2006, of 24 of February) which promotes the use of Physical Bilateral Contracts as an alternative to trading in the pool, modifying the mechanism for matching bids for energy submitted simultaneously to the day-ahead and intraday production market by electricity agents belonging to the same business group. Since then, a gradual growth of the use of bilateral contracts has been observed, with a continuous development, in terms of number of participants and liquidity (Capitan & Monroy, 2008).

1.3.1 Electricity market

The electricity market is the set of transactions arising from the participation of the market agents in the sessions of the daily and intraday markets, forward market, and from the application of the System Technical Operation Procedures. Physical bilateral contracts concluded by buyers and sellers are incorporated in the production market once the daily market has closed.

Market participants are companies authorized to participate in the electricity production market as electricity buyers and sellers. Entities that are authorized to engage in the market are electricity producers, last resort resellers and resellers, direct consumers and companies or consumers resident in other countries that are authorized to participate as resellers.

Producers and direct consumers may participate in the market as market participants or sign physical bilateral contracts.

Direct consumers wishing to participate in the production market may have access to all the possibilities that the market offers other electricity applicants, regardless of their size. However, if their participation is restricted solely to purchasing electricity to cover their daily consumption requirements, their participation in the market is very simple; they may purchase any electricity for future consumption that they deem necessary and receive invoices for electricity actually consumed from the market every day.

The economic management of the electricity market is entrusted to Operador del Mercado Ibérico de Energía – Polo Español, S.A.

The processes in the production market are as follows**:**

- Most transactions are carried out in the daily market. All available production units must participate in this market as sellers and are not linked to a bilateral contract, as well as nonresident retailers registered as sellers. Buyers on the daily market are last resort resellers, resellers, direct consumers and nonresident retailers registered as buyers. The result ensures that maximum interconnection capacity with external electricity systems is not exceeded, considering physical bilateral contracts that affect international interconnections.

- Resolution of technical constraints. Once the daily market session has been held and national physical bilateral bids have been received, the system operator evaluates the technical viability of the operating schedule of the production units in order to guarantee the safety and reliability of supply on the transmission network. If the result of daily market matching and physical bilateral contracts does not respect the maximum exchange capacity between electricity systems or the mandatory security requirements, the technical constraints solution procedure is applied, which consists, firstly, of the modification of purchases or sales from external electricity systems responsible for this excess in interconnection exchanges and, secondly, of the assignation of the power of the production units.

- The intraday market is an adjustment market that is open to production units, last resort resellers, resellers, direct consumers and nonresident retailers engaging as buyers and sellers who are market agents. In order for buyers on the daily market to be able to participate in the intraday market, they must have participated in the corresponding daily market session or must have executed a physical bilateral contract.

- The purpose of ancillary services and deviation management is to ensure that energy is supplied under established conditions of quality, reliability and security and that production and demand are balanced at all times. The system operator incorporates regulating band ancillary services in the viable daily schedule after the daily market sessions have been held. After every intraday market session, the system operator manages any deviations in real time using ancillary services and the deviation management procedure.

1.3.2 Prices evolution in Europe

Prices in the European electricity markets have evolved similarly and tend to converge to each other in the short-term, except in the case of the Italian market. These markets reflect volatile prices during the year 2009, showing a trend of falling prices in the fourth quarter, which is maintained throughout the first quarter of 2010.

Regarding the monthly change it should be noted that during 2009 there has been a significant decline in prices in all European markets. At the top stands Italy with 76,5€/MWh.

In the third chapter it has been made a more accurate analysis of the Italian electricity prices. Below is the evolution of prices of a set of organized markets from 2008 until March 31, 2010.

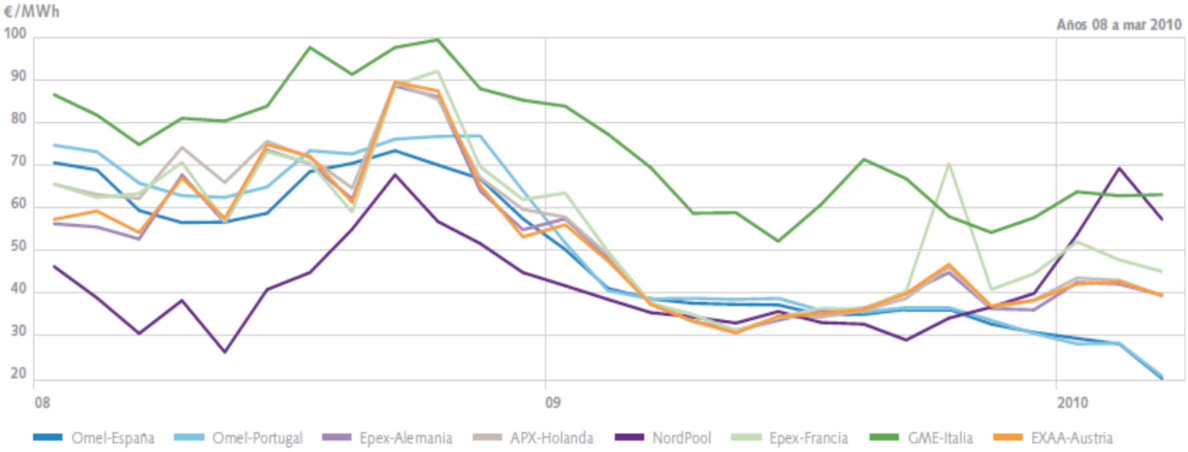

Fig 1.4 Europex average monthly price

Analysis of monthly average prices in the period from 2008 to march 2010 reflects the increasing convergence followed by European prices, except Italy. In 2008, widespread increases were seen in all markets. Since the beginning of 2009 there has been a decline that lasted until mid-2009. This is undoubtedly related to the trend followed by the prices of energetic raw materials markets.

1.4.1 Gas prices in Italy

The year 2010 ends with a growing demand of gas respect to the previous year, driven by increases in all sectors with an exceptional evidence for the industrial sector that returns to "pre-crisis" levels of 2008. Compared to 2009 prices recorded on PSV (Virtual Trading Point) show upward trends while remaining below the levels reached two years ago. In December of the last year began its operation the spot market of the natural gas, developed and managed by the GME.

The year 2010 end with a level of gas consumption equal to 83.021 MCM, increased respect to last year (+7%) but still slightly lower compared to "pre-crisis" level of 2008 (-2%). The increase respect to 2009 is mainly driven by appreciable recovery of the industrial sector, whose consumption levels return to those in 2008 reaching 14.422MCM (+18%). Moreover, it is also decisive the contribution of the domestic sector rising to 36.586 MCM (+8%), even higher than in 2008 (+10%). Finally, the contribution of the thermoelectric sector to the growth is negligible with a stable consumption of 29.155 MCM, confirming values lower than in 2008 (-13%) due to the persistent low level of electricity consumption and the growing contribution of renewable sources.

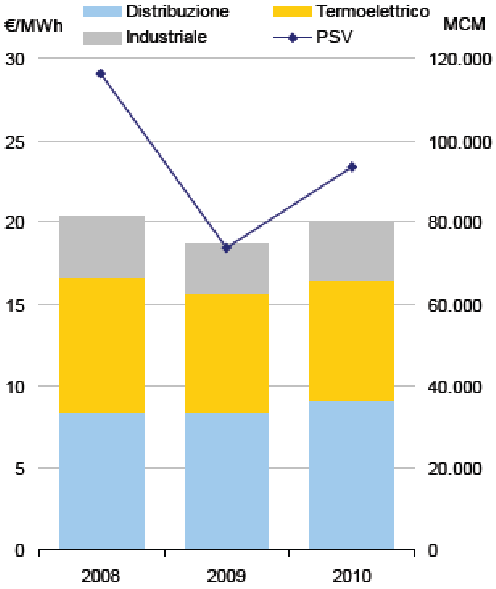

Fig 1.5 PSV price and demand volume

The recovery in consumptions with the rise in the Brent prices have induced an appreciable recovery in the price in the Virtual Trading Point, ascended to 23,34€/MWH (+27%) while staying at a sensibly lower level than observed in 2008 (-20%).

The rise in consumptions has led to the interruption of the downtrend in prices on PSV, which has grown after 3 months of continuous reductions, amounting to 25,05 €/MWh (+3%). This value is still higher than the level recorded last year (+19%), though below to the 2008 values (-22%).

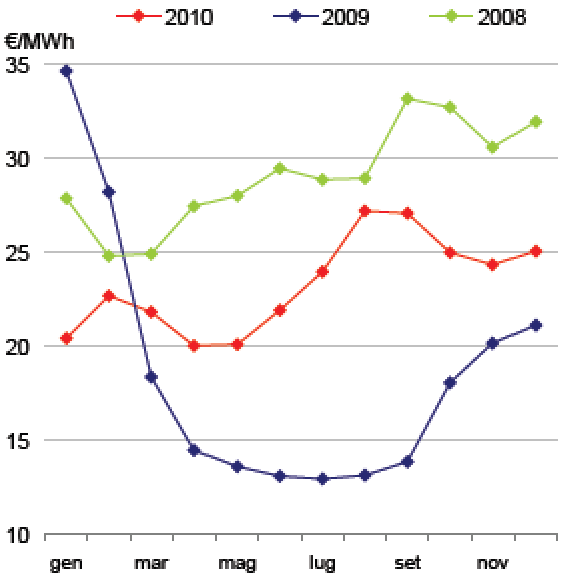

Fig. 1.6 PSV price

The start of the new year is characterized by a weak downward trend in gas consumption driven by a decline in domestic consumption, against the timid increases on industrial and thermoelectric sectors. The prices recorded on the PSV are substantially stable compared to the previous three months, rising respect to a year ago and in sensibly decline compared with the values in january 2009, historical maximum.

1.4.2 Gas prices in Spain

The accumulated demand of the year in november 2010 has decreased a 0,3%, reaching a value of 361,03 TWh. The total computation of the gas demand from the national market in november 2010 shows an increase of 11,8% compared to the same month of the last year, reaching a value of 37,74 TWh since the conventional demand has increased by 18,3% and gas supplies for electrical generation have remained invariant respect to this month.

In november, the combined cycles involved the 77% of the thermal gap.

The factors that cause these variations are:

- Increase of hydraulic and nuclear generation.
- Decrease in the generation with coal.

The total demand for electrical power generation was 11,91 TWh that represents the 31,6% of the total gas demand.

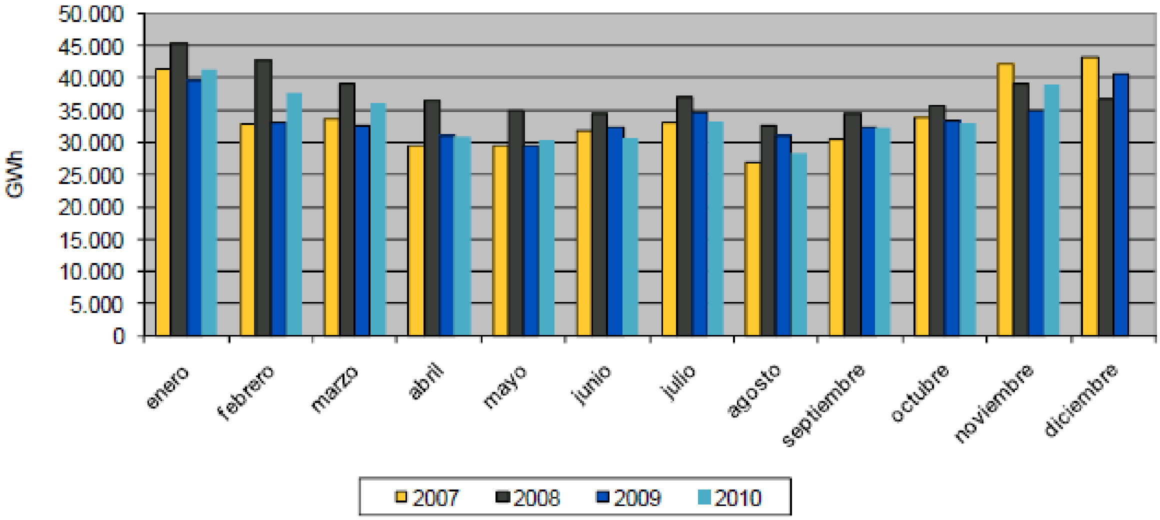

Fig. 1.7 Monthly demand

The CNE has developed an index of cost of natural gas supply from customs data published by the tax agency, in line with other European regulators such as: the CRE (Energy Regulatory Commission, France) that publishes in his report "Monitoring of gas and electricity markets" the reference index of long term contracts; or the german national customs agency (BAFA) that publishes the border prices of natural gas monthly.

In the website of the tax agency are published statistics on foreign trade for all products registered at customs. Between these products are natural gas and liquefied natural gas. The available data at the tax agency are the volume, price of the transactions made in the border, country of origin and province of the gas inlet.
The historical data starts in january 2002.

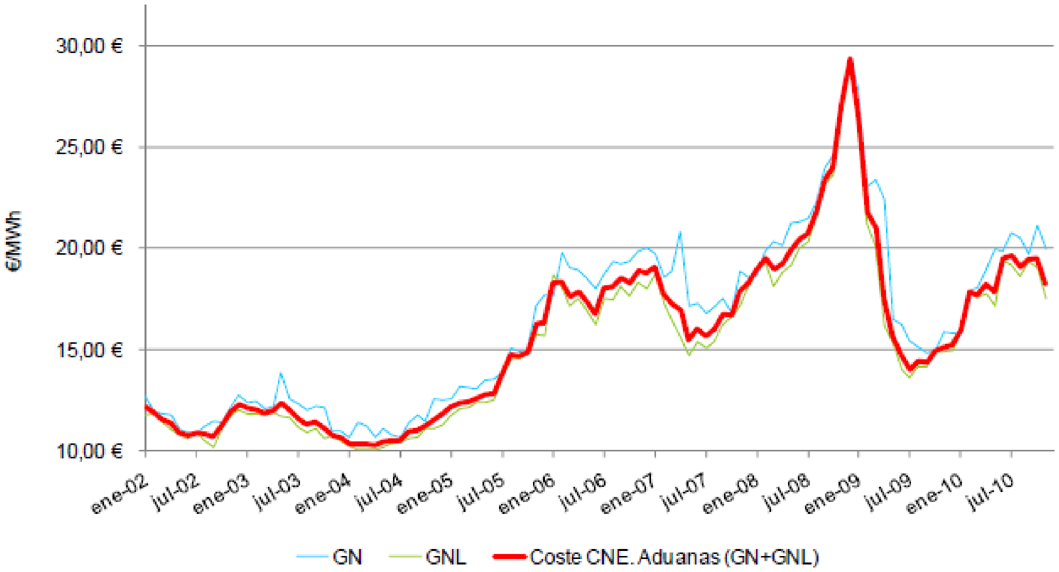

Fig. 1.8 Cost of natural gas supply (€/MWh)

The cost of natural gas supply in the Spanish border, which since july 2009 showed a continued rise and had remained stable over the past four months, decreases in the month of november 2010 by 6,3% respect to the month before. Regarding the value off july 2009 (14,03 €/MWh) the cost of supply remains above 26% in november 2010 (18,25 €/MWh) according to customs data processed by the CNE.

CHAPTER 2 DAMAGE DESCRIPTION

2.1 FAILURE MECHANISMS OF HIGH TEMPERATURE COMPONENTS

The principal failure mechanisms of high temperature components include creep, thermal fatigue and their interaction. Older baseload fossil units were designed, almost by definition, to operate predominantly under creep conditions. None of the older design codes for power plants (for example, ASME, British Standards [BS], and Deutches Institut für Normung e.V. [DIN]) placed any specific requirement on the designer to consider fatigue as a failure mechanism. The design codes assumed that the effects of fatigue were contained within the conservatism of the design stresses. This was an adequate assumption for baseload plants, but it is now recognized that fatigue, especially in conjunction with creep-degraded material, is a significant concern.

2.1.1 Creep

In principle, because creep is both time and temperature dependent, two-shifting and low load operation would be expected to reduce damage caused by long-term creep. During a unit start or at periods of low-load running, there may be some circumstances when localized overheating can occur. While these problems are well known to plant operators, it should be recognized that the cumulative effects of repeated overheating during thermal and load cycling can give rise to extended periods of operation above the design temperature, which may result in accumulation or acceleration of creep damage.

Creep damage can take several forms. Simple creep deformation can lead to dimensional changes that result in distortions, loss of clearance, wall thinning etc. Examples are steam turbine casings, blades and piping systems. Localized deformation can cause swelling and eventual leaks in headers, steam pipes and superheater reheater (SH/RH) tubes. Long term creep failures generally tend to be brittle failures involving cavitation and crack growth at interfaces and at highly stressed regions. The cavitation form of damage has been found in SH/RH tubes, rotor serrations, occasionally rotor bores, highly stressed areas in piping pertained to dissimilar welds in superheater/reheater tubing, welds in headers and in hot reheat and main steam piping.

2.1.2 Thermal fatigue

The most common problem experienced as a result of two-shifting is thermal fatigue damage. This is manifest either in the form of cracking of an individual component or in the mechanical failure of structures.

Cracking of a component is attributed to severe thermal gradients arising from excessive steam- to-metal and through-wall temperature differences associated with rapid rates of steam temperature change as generally observed during startup, shutdown, and load changes. The principal components at risk typically comprise any thick-walled sections, such as boiler superheater headers, steam pipework, valves, high-pressure (HP) and intermediate-pressure (IP) steam chests, and turbine inlet belts. HP heaters and economizer inlet headers are also frequently exposed to similar effects as a result of rapid cooling by cold feedwater. Thin-walled sections, such as boiler tubes and reheater headers, are less prone to the problem.

2.1.3 Creep-fatigue interaction

Creep-fatigue damage induced by thermal stresses is of major concern with respect to the integrity of many high temperature components. The concern has been exacerbated in recent years due to cyclic operation of units originally designed for base load service. Materials behave in a complex way when both creep and fatigue mechanisms are present.

Creep-fatigue damage is generally the result of thermal stresses induced by constraint to thermal expansion during transient conditions. The constraint may be internal such as in the case of heavy section components (e.g. rotors, headers, drums, casings) where thermal gradients arise between the surface and the interior or vice versa. Internal constraint may also arise from internal cooling of components subject to rapid surface heating such as in combustion turbine blades. The constrain may be external such as in the case of different coefficients of thermal expansion (dissimilar metal welds).

The creep-fatigue interactions are not currently well defined, and the limit line (shown as a solid line in the figure 2.1, [6]) represents the design life limit, expressed in fraction of material creep life and fatigue life for a 2.25Cr1Mo steel. This limit line is used to establish the effect of combining the two mechanisms and demonstrates how they act together to reduce the effect of the individual processes. Original design criteria assumed that the two processes were entirely independent.

Although the line is a highly conservative representation of the phenomenon, it does demonstrate the effects of the interaction.

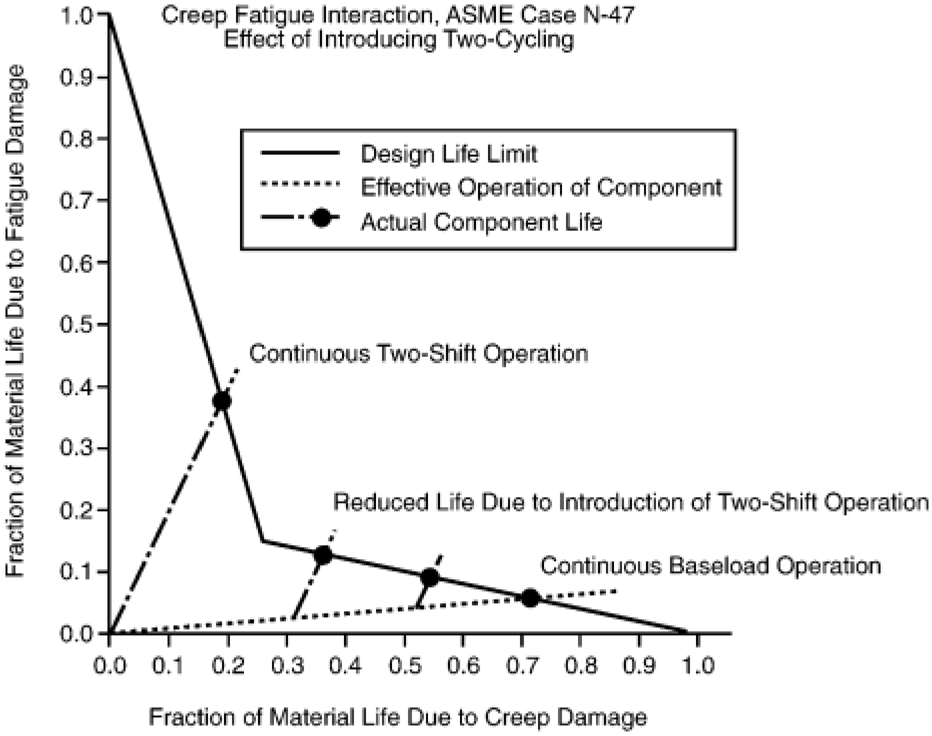

Fig. 2.1 Interaction and Consequences of Creep and Fatigue
(Based on ASME N-47) for a Typical Power Plant Steel (2.25Cr1Mo)

For example, consider a component originally designed for 10,000 cycles, which might have been designed to operate in a unit that two-shifts on a daily basis over 30 years. Assume also that the component operates in the creep range and was designed for 150,000 hours of operation. If the unit were to operate on a baseload regime, it will accrue some thermal cycles—probably about 1,000—over the projected life. The dotted line in Figure 2.1 indicates the effective operation of the component. The actual component life is given by the point at which it intersects the broken line (see Figure 2.1). This intersection indicates a reduction of the component life to about 75% of its predicted creep life. Similarly, if the component operates on a two-shifting unit with 300 cycles per year while operating in the creep range, the actual life may be as low as 40% of the anticipated fatigue life. Where operational cycling is introduced on a former baseload unit, the residual life can be greatly reduced to between 40% and 60% of the original design life because of the combined effects of creep and fatigue.

The key implication is that older units designed for baseload operation and used in this capacity over many years are susceptible to component failure when they are eventually forced to cycle regularly.

Thus, while increases in failure rates due to cycling may not be noted immediately, critical components will eventually start to fail. Shorter component life expectancies will result in higher plant equivalent forced outage rate (EFOR), longer scheduled outages, and higher capital and maintenance costs to replace components at or near the end of their service lives. In addition, shorter component life expectancies may result in reduced total plant life or require more capital to extend the life of the plant.

The example component previously provided demonstrates the way in which two-shifting plants originally designed for baseload conditions can significantly reduce the integrity of components to a far greater degree than might otherwise have been anticipated. Note that this methodology is highly conservative and does not take into account the timing or amplitude of the thermal cycles, which may further influence the remnant life of components. More refined analysis methods are currently being developed.

2.2 OPERATION CONDITIONS CONSIDERED

The request of following the daily and weekly demand variations is reflected in an exigency of:

- reducing characteristic times of startup and transient load;
- extending the field of possible operating conditions by increasing the nominal and peak power or reducing the technical minimum load.

From a practical point of view, the most important magnitudes for the combined cycle flexibility are the temperature and pressure. The last one is interesting as it influences the specific volume of the fluid especially in conditions close to saturation. The two magnitudes are often related, so if two different operating conditions involve the same temperature profiles in all components, then the transition from one to another can be very quickly.

Generally, faster transients and more extensive operating fields can lead to higher gradients and thermo-mechanical solicitations. New operating conditions to take into account are analyzed below.

2.2.1 Startup

It is considered that if the ratio between the number of equivalent hours of operation and the number of startups/shutdowns is higher than 80 ÷ 100, the plant satisfy the base load. If that ratio is lower than 10÷ 20, the plant can be considered of peak. Intermediate values define a unit for the modulation of production. This means that, at least from the point of view of startups, the transition from a base load exercise to one in modulation does not necessarily imply a change of possible operating conditions, but also a higher recurrence of transient conditions already provided.

This phase is critical in the exercise due to various reasons. Firstly, during this phase operate many components that are inactive in the normal exercise. Often, the redundancy for these components are lower than for those used in normal exercise, so failures and anomalies during startup may cause severe effects. Also, eventual problems connected to the control and regulation systems emerge more clearly due to fewer opportunities of manual intervention and the value of time factor. Startup can lead the system to operate in unstable conditions that may cause the operation failure.

Furthermore, if the number of starts increases, two factors assume more importance: the consumption of plant's useful life for each start and its duration and cost. A startup is generally equivalent to ten hours of operation at nominal load. In addition, increasing the number of starts per year, manufacturers advice to make more frequent inspections.

Regarding the duration and cost, it is important to note that during the start the plant consumes fuel, water and electricity but produces a little energy. On average, the specific consumption of a combined cycle during the 3.5 ÷ 4.5 total hour of startup can be 30% to 35% higher than the nominal value. Therefore, one of the flexibility objects is the reduction of unproductive times and consumptions.

2.2.2 Shutdown

In a startup initial and final conditions are imposed, the first by the conditions of the plant at the beginning of the procedure, and the second by the constraints of exercise. In a shutdown initial conditions are also determined by the conditions of the plant at the beginning of the procedure, but those finals are not placed a priori. Therefore, shutdown can be considered concluded when the alimentation of fuel to the gas turbine is interrupted and the extraction and alimentation pumps are stopped.

The indetermination of plant conditions at the end of the shutdown allows a significant reduction of time compared with startup. Regarding the boiler, the plant could be stopped instantly at any moment, close all the valves of the cycle and the dampers on gas flues to avoid the flushing of components and allow the plant to cool down and depressurize in a passive way, with long time and low thermal gradients. However, this is not entirely possible because the gas and steam turbines must decrease the load gradually and the steam generator must necessarily follow their gradual cooling at least until the machines are separated from parallel with the electrical grid.

During the phase of load reduction prior the shutdown of the plant, the limits for the maximum thermal gradients, and so the times, are essentially the same as in the startup.

2.2.3 Partial load operation

The request of following the energy demand not only entails a higher number of startups and shutdowns, but also an operation with a load that varies in a field as wide as possible. In general, a plant capable of operating stably even at low loads may be required a minor number of startups and shutdowns.

2.3 IDENTIFICATION OF THE MAIN DAMAGE MECHANISMS AFFECTED BY FLEXIBLE WORKING MODES

2.3.1 Steam generator

Malfunction of steam generators

The necessary prerequisite to an optimized management of steam generators with fossil fuels is the careful observation of the conduction parameters, whose divergence from the typical values may be indicative of incipient failures. Among these symptoms, in the steam generator, can be reported as an example:

- abnormal distribution of temperature and pressure on the gas side in the different sections of the generator;
- increased concentrations of unburnt in fly and heavy ash;
- difficulties in achieving the temperature in the RH;
- high frequency of damaging the pipes.

The search for causes of malfunction in a steam generator, in order to study the response actions designed to prevent outside services and/or serious damage to the generator, requires a difficult analysis that led to choose the objective reasons of the above symptoms and that may emanate, for example, from anomalies:

- caused by fouling and slagging in different parts of the boiler: combustion chamber, superheater and reheat;
- in the distribution of heat release;
- due to fouling of the regenerative heater of the air;
- of fan operation;
- of mills operation
- of excess of air in the combustion.

The identification of the type of failure is not unique and requires analysis of operating parameters and specific diagnostic tests. In case that the generator has simultaneously malfunctions the diagnosis becomes even more complex and may require an incompatible timing to restore the operating parameters within the normal ranges.

Lack of uniformity of temperature on gas circuits and imbalances of the combustion chamber can be determined by analyzing the distribution of oxygen or carbon oxide at the exit of the boiler, performing measurements upstream of the regenerator. Major losses of steam from generator tubes are more easily determined by the operators, but even in this case, a specific instrumentation can help find the losses quickly.

Analysis of unburnt in heavy and fly ash are made constantly by the plant laboratory or with on-line tools, so that the increase of unburnt in the ash is determined by comparing the value with historical data. Problems of exchange at the RH level are also easily determined once the operating data is available and managed by the supervision system.

The temperature of the gas leaving the boiler is usually measured and recorded but it is not always immediately to select, from the increase of this parameter, specific malfunctions especially where the operation is realized with coal of different quality or where the boiler has been modified from the original project.

An increase of the gas temperature at the exit of the steam generator, compared with that determined by the project, produces an increase of the generator losses and therefore a loss of plant efficiency. It means searching quickly which of the many sections that make up the generator (including air pre-heaters) is absorbing less heat than expected. In this case, for a full understanding of the phenomena, are necessary sophisticated mathematical models and/or special instrumentation, as a measure of heat flow, for determining the exchanged power at the level of: combustion chamber, superheaters, economizer and air preheater.

Cycling duty and low load upgrades

As older, smaller units are retired from service, large 400+ MWe boiler systems will need to cycle and operate effectively and efficiently at low loads to economically meet total load demands. This is a particular challenge for large units designed for baseload service since many boiler and auxiliary components are affected. Selected issues for the boiler pressure parts include: fatigue failures in the economizer and lower furnace tubes, structural damage to such areas as windbox supports, large transient temperature differences of 200 to 400F (110 to 220ºC), and low individual circuit flows when load is reduced to 15% of maximum continuous rating. In addition, turbine issues such as temperature cycling limits and slow response may require modification to the boiler systems because of the mismatch between steam and gas flow requirements.

Some of the upgrades and modifications to address these issues include:

- An off-line recirculation system for drum boilers to provide a small amount of circulation through the furnace and economizer to prevent temperature stratification and potential thermal shock upon start-up.
- Revised circulation systems for once-through boilers where series and parallel panels can be changed by control valves to maintain sufficient flow rates in all tubes at all loads.
- Superheater bypass and dual pressure capacity to permit better matching of steam pressure and temperatures from the boiler to the steam turbine. These systems can greatly enhance the start-up speed of the boiler from low load or an “off” condition.
- Spiral circuitry furnace replacement may provide an economical option where significant cycling service from 100% down to 15% MCR is desired for once-through boilers. This design is more flexible in meeting the cycling/low load conditions than the older Universal Pressure designs used in virtually all U.S. baseload once-through boilers in operation. Extensive experience with this type of design has been obtained in Europe and Japan.

2.3.2 Life consumption assessment of Heat Recovery Steam Generators

All HRSGs are designed to produce a certain amount of steam at given pressures and temperatures. The mechanical design is set by the rules as given in the applicable codes and the designer’s standards. Most of the codes take into consideration fatigue in setting up the allowable stress values. However, while the broad rules of the codes apply to the major components, they may not be satisfactory for the local points or sub assemblies. The problem is not with the code but with the stress calculation methodologies for the intricate geometries. For example, ASME code addresses the tube and header design rules very adequately, but evaluating the tube to header joint becomes tricky when the exact geometry is not very specific.

The detailed analysis then becomes necessary when fatigue becomes a factor due to cycling. While most of the boiler, designed with base load considerations only, will still be good for cycling, some ‘critical’ components may be affected by fatigue. A detailed and comprehensive analysis is therefore necessary for these critical components.

HRSG damage mechanisms and effect of cycling

Various damaging mechanisms affecting the HRSG are listed in the following table (Table 1) along with the effect of cycling operations [13].

As is evident from the table, cycling operation and resulting fatigue increases the damage factor or decreases the life expectancy. While all the boiler components are affected by the damaging mechanisms, some are more vulnerable to a certain damaging factor than others.

The following table (Table 2) shows the main HRSG components and the principal damaging factors affecting the life expectancy. It should be noted that the list is based on most common experience. The impact of a certain factor on a particular component may be different if the loading or geometry is different [13].

	How it works	Effect of cycling
Low Cycle Fatigue	Damage occurs at low cycles when the strain is high. This is prevailing mechanism in Boilers	Increases due to higher number of cycles
Creep	Damage due to material being at high temperature for considerable amount of time	In addition to creep damage, creep- fatigue damage reduces the available life
Thermal Shock	Impingement of cold water / steam on hot surfaces can damage the material	Increases
Oxidation	Oxidation and exfoliation due to high temperature	Not affected
Differential Expansion	If adjacent tubes or pipes are at different temperature, uneven expansion can stress both the tubes. Piping supports can also affect Stresses	Transient spikes may get metal into plastic region
Corrosion Fatigue	The crack initiation happens due to corrosion and damage is caused by fatigue and corrosion. Typically occurs 300°F to 500°F	Accelerates the corrosion effect
Corrosion in Tubes	Due to Chemical imbalance	Common chemistry imbalances at start-ups can exacerbate the effect
Flow Assisted Corrosion (FAC)	Corrosion Accelerated due to chemistry and flow	Reduced water chemistry controls increase the possibility
Corrosion Product Migration	Migration of corrosion product may cause further corrosion or other damage	Intermittent heating and cooling can dislodge the deposits
Scale and Deposits	Temperature fluctuations may result in deposits	Due to effect in chemistry
Erosion	Transient high velocities may initiate or perpetuate erosion	Low steam pressures at starts cause high velocities
Corrosion Outside the Tubes	Due to various gas constituents	Frequent shutdowns results in more frequent condensation
Erosion Outside the Tubes	Due to particles in gas and high velocities	No effect
Corrosion - Non-Pressure Parts	Condensation of acid and/or water on cooler parts causes corrosion	Increases
Differential Expansion in Non-pressure Parts	The liner plates, structural supports, etc., get damaged due to uneven heating and expansion	Increases

Table 1. Damaging mechanisms affecting the HRSG

HRSG Component	Low Cycle Fatigue	Creep	Thermal Shock	Differential Expansion	Corrosion Fatigue	Oxidation/ Exfoliation	Chemical Corrosion	Flow Acc. Corrosion	Corr. Product Migration	Depositions	Erosion Inside Tubes	Erosion Outside Tubes	Corrosion Outside Tubes	Non Pressure Part Corrosion	Erosion of Non Pressure Parts	Expansion – Non Press. Parts
Superheaters	●	●	●	●		●	●				●					
Attemperators	●	●	●	●			●	●	●		●					
Reheaters	●		●	●	●	●	●		●		●					
Evaporators	●			●	●	●		●	●	●						
Economizers	●			●	●	●		●	●	●	●					
Drums	●	●			●	●			●	●						
Piping	●	●	●	●	●	●			●	●	●					
Valves		●	●		●	●			●	●						
Fins & Tubes	●	●	●	●	●	●	●				●	●	●	●	●	●
Liners, Casing Etc.	●	●	●	●		●								●	●	●
Ducts	●	●		●		●								●	●	●
Dampers	●	●		●		●								●	●	●
Structurals						●								●	●	●
Stacks					●	●								●	●	●

Table 2. Main HRSG components and the principal damaging factors affecting the life expectancy

How cycling impacts the life affecting mechanisms

Most of the time cycling either creates or enhances the effect of mechanisms which affect the life of the component. Creep damage by definition is caused by a prolonged exposure to high temperature and stress. Creep may be the only mechanism which is not caused or enhanced by cycling.

Fatigue and Fatigue damage are the most prevalent mechanisms affecting the boiler life and are a direct consequence of cycling. Water chemistry upsets which result in corrosion may be due to cycling or because of failure of water chemistry controls.

For example for a rapidly starting HRSG, the superheater is exposed to high temperature on the outside of the tube and headers whereas inside may still be cool. This creates high thermal stress. Some typical examples of how cycling creates or enhances the damaging mechanisms are given below.

Superheaters and Reheaters

- *Fatigue*: The impingement of hot gasses on cold surfaces at start-up or of cold gasses on hot surfaces at shut down creates thermal gradients. Similarly the condensed steam in the tubes after shutdown impinges on hot surfaces if the condensate remains in the tubes. The high pressure components are more vulnerable to fatigue effects due to higher thicknesses.
- *Thermal Shock*: Condensate in Superheater or cold reheat in hot and dry Reheater would result in thermal shock to the inner surfaces of the tubes and headers.
- *Creep*: Only the high temperature components are prone to creep damage. High temperature transients and continuous high temperature operation may increase the creep rate. However if the creep is coupled with fatigue due to cycling, the damage will be much higher than that which can occur if the same fatigue or creep is working alone.
- *Oxidation*: Exposure of the metal to higher temperature than what it was designed for particularly during initial start-ups can result in oxidation. Oxidation and exfoliation can happen inside and outside due to gasses and steam. Dry Reheater designs are particularly vulnerable.
- *Differential Expansion*: Uneven heating of tubes due to flow mal-distribution and due to temperature mal-distribution can cause adjacent tubes to expand differently. Both compressive and tensile loads are imposed.

Evaporators

- *Low Cycle Fatigue*: LCF occurs in natural circulation evaporators during startup because circulation has not been fully established.
- *Differential Expansion*: Uneven heating of tubes due to flow distribution and / or temperature distribution may cause adjacent tubes to expand differently. Both compressive and tensile loads can be imposed.

- *Depositions*: Uneven heating or heat flux anomalies may result in local dry-outs and deposition of salts in evaporator tubes. These depositions result in further distorting the flow and heat flux distribution.
- *Flow Accelerated Corrosion*: Two phase flows result in FAC, particularly in low pressure systems.
- *Corrosion Product Migration*: The corrosion products formed at one location may migrate to another place and under right condition may form deposits there. These deposits then result in uneven heat fluxes causing problems.
- *Erosion*: Solids in the water and water in the two phase flow systems can cause erosion at higher velocities.

Economizers and Feed water heaters

- *Low Cycle fatigue*: The impingement of cold water on hot surfaces particularly at a very quick shutdown and restart sets up LCF.
- *Differential Expansion*: Uneven heating of tubes due to flow distribution and / or temperature distribution can cause adjacent tubes to expand differently. Both compressive and tensile loads are imposed.
- *Depositions*: Uneven or excessively fast ramp rates can result in solids precipitation and deposition causing uneven heating
- *Flow Accelerated Corrosion*: Single Phase FAC in economizers is being recognized as one cause of failures. Often it occurs because, during start-ups and at transition time, the water chemistry may be out of control.
- *Corrosion Fatigue*: Chemical imbalances can create corrosion and the cycling loading can enhance the effect due to fatigue.
- *Erosion*: Solids in the water can cause erosion at higher velocities

2.3.3 Steam turbine

Two-shifting problems associated with steam turbines

Most large turbines currently in use conform to a set of standard modules, usually comprising HP, IP, and LP turbines based on a manufacturer's standard configurations. HP cylinders are typically single flow with double-shell construction, and IP and LP turbines are usually doubleflow, single-shell construction. The majority of rotors are monoblock with two journal bearings located outboard at each end of the cylinder. The thrust bearing is usually located between the HP and IP turbines. Blading is usually a disk and diaphragm construction.

Operation in a two-shift regime has two main effects:
- Thermal fatigue and associated creep-fatigue
- Mechanical fatigue as a result of load and speed variations

Creep-fatigue associated with thick walled components, including governor and stop valves and HP and IP turbine inlet belts, is described below.

Another area of concern has been the effect of embrittlement and fatigue on the critical crack size of HT rotors. The potential for embrittlement is largely a function of residual or tramp elements, which are strongly influenced by the steelmaking process. In generally, only older rotors have a significant potential for embrittlement. Significant embrittlement can result in the material behaving in a brittle manner at high temperatures, which could be experienced under weekend warm start conditions. Although severe embrittlement is rare, it should be assessed in older rotors under cyclic operation.

Mechanical fatigue issues arise from two sources. First, during turbine run-up, the rotor passes through a series of critical speeds where vibration levels increase significantly. This is a well- understood phenomenon, and the critical speeds are well defined for most machines. It is important to pass through these speeds as quickly as possible. Over a number of starts, the number of cycles at critical speeds can accumulate to significant values and subject components such as turbine blades to unacceptable high cycle fatigue levels.

The area most vulnerable to mechanical fatigue is LP blading. Blade length subjects the root area to very high centrifugal stresses, and any defects within this area significantly reduce blade integrity. The inspection of disk slots on some older units with large numbers of starts has identified the formation of fatigue cracks in the root serrations where stress levels are concentrated. These cracks are believed to propagate slowly and have not resulted in any major problems, although blade replacements have been required. More modern units have employed design and analysis methods to improve the blade-root detail, which should eliminate this potential problem. Where mechanical fatigue problems are encountered with LP (or any) blading, it is usually possible to re-blade the rotor with a modern blade design to reduce or eliminate the problem. In some instances, re-blading may be combined with other improvements in efficiency. Where the LP blades are cracked, the cracking may be exacerbated by the onset of corrosion fatigue. During this study, the possibility of resonance-related LP blade failures was revealed for large load cycling units, but this has not yet been confirmed.

Four minor potential problems have been identified:
- Increased wear and tear on turbine valve gear
- Overheating of turbines as a result of windage
- Turbine differential expansion
- Erosion as a result of oxide (scale) impact on HP and IP blades

Cyclic operation requires increased operation of turbine governor valves and stop valves. Additional wear and tear will occur on the valve seats and valve stems, especially under throttling conditions when flow-induced vibration can lead to mechanical fatigue and wear. This wear and tear can usually be contained by redesign of the valve head, modification to the steam flow path, and the use of stellite or similar hardfacing materials on wear surfaces.

As the flow through a turbine cylinder is reduced, conditions could arise where the turbine is actually driving the steam, which can lead to a degree of overheating. This occurs on HP cylinders where a bypass system is engaged; as the discharge pressure of the HP cylinder increases, the flow through the cylinder decreases until a no-flow situation can arise. This has resulted in high HP cylinder temperatures and subsequent damage. A similar problem can occur with LP cylinders at low loads where the flow is reduced to below the threshold value, and the last stage blade may impart energy into the flow.

Below it is presented information on turbine expansion problems relating to rotor and casing differentials, gland sealing, and blade tip clearances. When moving from a baseload situation where efficiency is of particular concern (and hence the need to minimize blade tip and gland clearances), review the clearances and make adjustments appropriate to a two-shift operating regime where reliability may be increased at the expense of efficiency.

Where new turbines are to be installed for two-shift operation, the following design features should be included:

- A fully integrated solid forging construction to reduce rotor manufacturing time and decrease the likelihood of intergranular stress corrosion cracking
- Ample axial and radial clearances to accommodate thermal expansion and differential thermal expansion
- Use of high-strength materials to minimize wall thickness on steam chests, valves, and turbine casings to maximize thermal response and minimize thermal transients
- Application of FE modeling of the new turbine to optimize thermal transient effects
- A bypass system

Cracking of thick wall components

All thick sectioned components, such as boiler and turbine stop valves, governor valves, loop pipes, and HP turbine inlet belts, are prone to thermal fatigue cracking as a result of through-wall temperature differences during startup and shutdown. These heavy section components are often produced as castings and tend to be thicker than the forged equivalents. Despite this, these components are generally regarded as being more tolerant of thermal transients.

Thermal fatigue cracking tends to be focused at stress concentrations, such as at changes in section (which result from the casting or forging process) and where subsequent machining has led to a poor geometry (for example, the grooves for valve seat placement). Fortunately, this type of cracking is fairly innocuous. It generally propagates to less than 10 mm into the wall and then stabilizes with little further growth. In new components, the tendency for cracking can be greatly reduced by avoiding sharp corners and using high-quality castings.

In older castings, which have seen service, small thermal fatigue cracks can be ground out and the section re-profiled to reduce stress concentrations. In practice, such defects often regenerate.

In these cases, it is probably better to leave the defects and to monitor their growth in situ because continued machining and repair welding may be more damaging in the longer term. The problem needs to be managed through a program of routine inspections and planned replacement and repairs at scheduled outages.

Many boiler stop valves fitted to older boilers were not designed with regular thermal cycling in mind and suffer the effects of thermal cycling, resulting in cracking of valve bodies, seats, and disks. They also exhibit operational problems as increased usage causes wear and tear on the valve stem and driving gear.

Recent developments include the use of P91 (9CrMoNbV) steel, which significantly reduces the overall wall thickness and has thus been expected to reduce tendency to cracking.

Differential expansion of turbine rotors and casings

Expansion and differential expansion of the turbine rotor and casing are not usually problematic under two-shift operation, although it is essential to have a good turbovisory indication of turbine movement and clearances.

Some older machines that have previously been on baseload may exhibit “sticking” if the keyways have not been adequately maintained and lubricated. This problem can usually be overcome by renewal of the keyways during a planned outage. Note that this work may require removal of the turbine cylinders.

Relative movement between the rotor and casing during turbine run up is always a potentially critical period when rubs can occur both on turbine blade tips and on shaft seals. Where two- shifting is introduced, it is important to understand what is happening within the turbine from the turbovisory equipment. Each case must be evaluated on its own merits. Where problems arise, the solution may require changing the operating procedure or increasing clearances, albeit at the expense of efficiency.

There have been instances (especially on older machines) of thermal distortion as a result of turbine support pillars “flexing” under the influence of temperature changes. The pillars tend to bow toward the hotter side. Although such movement is small—probably less than 1 mm—the movement combined with the tilting effect may be sufficient to disrupt turbine alignment and clearances. The problem can usually be overcome by thermal insulation of the pillars.

Low-pressure (LP) rotors have posed problems because of their construction with shrink fit diaphragms. Cyclic loading may endanger their integrity. To combat this, some LP rotors have been replaced with monoblock forgings.

2.4 IDENTIFICATION OF THE FACTORS LIMITING THE FLEXIBILITY OPERATION

2.4.1 Steam turbine

In this case it is important to distinguish if the turbine has been designed for a combined cycle or if it was initially inserted in a traditional steam cycle. In the second case, the turbine is usually designed for pressures higher than those characteristics of combined cycles, so it results oversized and imposes some operative restrictions.

Generally, the exercise of a steam turbine must avoid the risk of excessive thermal inhomogeneities, which may produce unacceptable differential expansions, and the condensation in zones different from those near to the discharge in the condenser.

The classification of starting mode for the steam turbine can be summarized referring to the field of the first stage metal temperature of the turbine, being this run down by the steam at higher temperature.

As an example, Figure 2.2 shows “isoconsumption of life” curves for a steam turbine. The metal wear and tear is essentially determined by the metal temperature at the beginning of the manoeuvre and its speed, characterised by the temporal gradient of temperature [2].

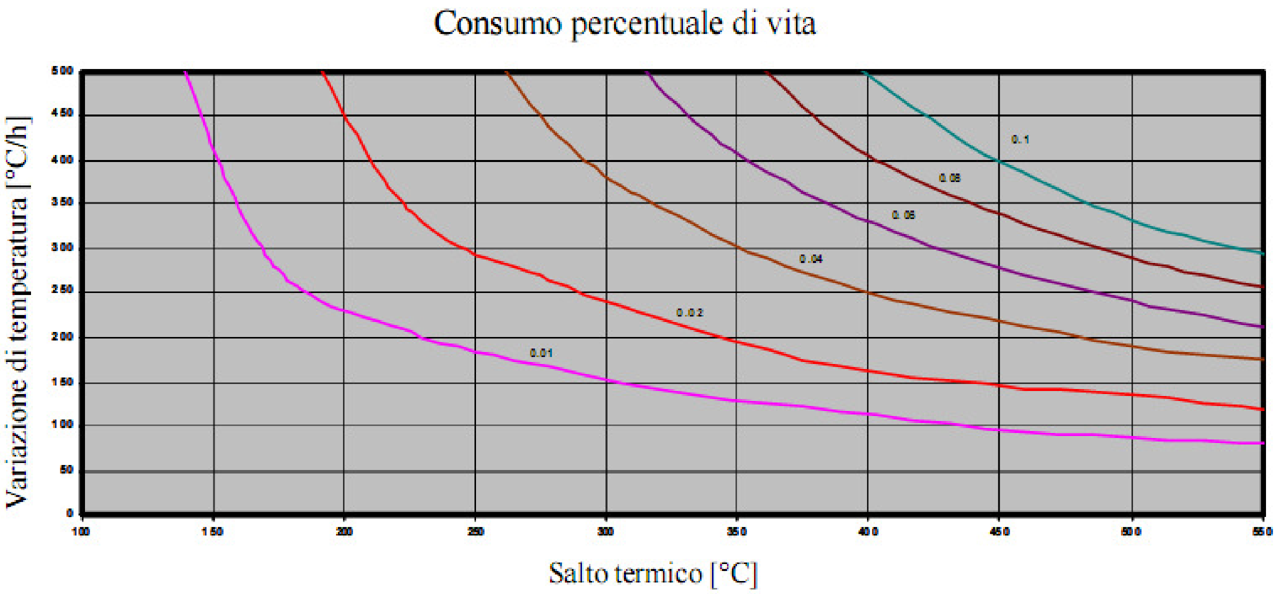

Fig. 2.2 Consumption rate of the steam turbine life according to the speed of variation of the temperature profile and the temperature difference between the entering steam and the metal at the beginning of the maneuver (source: Techint)

Start-up for steam turbine involves the following steps:

- Generation of a small steam flow for the low pressure estates. In order to start this operation without having to wait the steam generator operation, combined cycles are equipped with an auxiliary boiler whose steam is also used to heat the gas fuel, preheat the turbine and prepare the vacuum in the condenser.
- Taxiing turbine up to rated speed (3000 rpm), possibly with a break at a medium speed to allow a first temperature regimen. This phase can last from three quarters to one hour depending on the turbine characteristics and its initial conditions.
- A period of about 5 minutes for the temperature regimen. Often this time is longer because in this stage the parallel with the electrical grid must be completed.
- Loading ramp can take about 1,5 hours to get to full power. Turbines designed for combined cycles can have more restricted times, but this flexibility cannot be fully exploited due to limitations imposed by the steam generator.

2.4.2 Gas turbine

The gas turbine maximum temperatures are the highest of the cycle, reaching values that can vary between 1160°C and 1325°C depending on the machine. However, gas turbines do not represent the component that limits more the plant capacity to adapt quickly to variable load conditions.

From an operational point of view, the limitations imposed by the gas turbine are listed below:

- turbine taxing time (from 0 to 3000 rpm) of about 15 ÷ 30 minutes (typically 25 minutes);
- required time for temperatures regimen at the taxiway ending of about 5 minutes;
- power load from 0 to 100% no less than 10 ÷ 15 minutes;
- maximum temperature difference in areas of gas exhaust from the turbine of about 40°C. This restriction is explained not only by the possible thermomechanical stresses that may arise, but also in the fact that the temperature difference observed may be a symptom of a burning fault or severe internal damages.

As regards the consumption of life, a start-up is equivalent to 10 hours of nominal conditions operation, while one hour under peak load is equivalent to 3 hours.

The above considerations could lead to the conclusion that the gas turbine can be considered sufficiently flexible so as to allow a secondary regulation. However, from the point of view of a low load exercise, with major load variations and more starts and stops, other aspects must be taken into account.

Firstly, frequent and wide exercise variations entail strong thermo-mechanical stresses that can lead to cracking with serious integrity injury of the whole machine. Therefore it is necessary and important to make more frequent inspections and/or appropriate use diagnostic tools for early detection of these potential problems. This aspect contributes to higher production costs.

The second aspect is related to environmental issues. The reduction of fuel flow to a premixed flame burner DLN ("Dry Low Nox") has two consequences: the combustion gases temperature reduces, thus decreasing the thermodynamic efficiency of the turbine, and the premixed flame may become unstable, until being torn from its anchorage. This problem can be solved intensifying the anchorage diffusion flame, but this leads to an increase of the nitrogen oxides emissions. If, instead, in parallel to the fuel, the air flow is reduced acting on the compressor aspiration valves, the CO emissions would be increased. Therefore, gas turbines are set to maximize efficiency and minimize emissions in an operating range of at least 60% ÷ 85% of the load, depending on the turbine. Below these values the production of nitrogen oxides is higher than the nominal values. Environmental legislation allows these emissions for short periods. But in some cases there have been protests from the surrounding population, which may block authorisations.

2.4.3 Steam generator

The steam generator is the largest component of the combined cycle and part of it is concerned by steam at the conditions of maximum pressure and temperature of the cycle. Consequently:

- the thickness of some of its components, specially the cylinder of the high pressure section, may reach also ten centimetres.

- the propagation of disturbances through the steam generator (eg. an increase in the aliment flow) can also require several minutes before its effects are perceived in all its parts (such as the temperature of the reheat steam).

However, the limitations that places to the flexibility of a combined cycle are not as serious as its dimensions may suggest. Indeed:

- has no moving parts;
- most of the mass that reaches high temperatures is made up of tube bundles where takes place the main heat exchange between the fluids of both cycles. Therefore, due to their small thickness, they have the ability to adapt quickly to temperature variations.

Another factor that affects the exercise flexibility of the steam generator is the fact that inside it takes place the phase change of the fluid, and this must be controlled and only inside the evaporator. The possible loss of control of the phase change in terms of quantity or location may lead to inadmissible thermomechanical stresses or the loss of control of the level in the cylinder.

During normal operation, metal surfaces are covered with an oxide film which provides protection against corrosion to the underlying material. With the deformations induced by transient the oxide, with lower ductility than the metallic material, cracks discovering the bare material. This one, without protection and under values of mechanical effort, may be subject to corrosion of different types: general, pitting, stress corrosion and fatigue corrosion.

From the different parts of the steam generator, those which may limit the flexibility are mainly the cylinders of high and medium pressure and high pressure superheater. The cylinder is critical due to their thickness, their size and the difficulties, in some circumstances, to check its level. Instead, the superheater of higher temperature is the first component that is affected without damping by the temperature variations of the gas from the gas turbine.

The cylinder

In most combined cycles, particularly in those older, all the evaporators are equipped with a cylinder. This component has the function of separating the steam from the liquid, ensuring that the evaporation process takes place only in the evaporator. In the low pressure circuit the cylinder has also the function of water reserve and degasification.
From a point of view of flexibility, the presence of a component which ensures that the liquid cannot reach the superheater simplifies the control and regulation of the plant and allows a wide variation of operating conditions. However, the cylinder is the largest and thickest component with numerous punctures for the connection of pipes, so it is the most requested in case of temperature variations. Typical values of maximum allowable thermal gradients are of the order of 6°C/minute. Consequently a circuit with a cylinder can be run without any special problems even at very low load, provided that load variations occur slowly. The absence of this component allows more rapid load changes but in a more restricted field of operation.

The flexibility of circuits with cylinder is also limited by dynamic fluid factors, especially if the circulation in the evaporator occur by natural convection. The disadvantage is the flooding of the cylinder or the discharge of water from the cycle by expansion or formation of large amounts of steam in the evaporator. This can happen after a startup or depressurization, i.e. in cases where in the evaporator tubes is generated more steam than which is moved to the cylinder.

In the startup the circulation of water in the evaporators is gradually established as the fluid density in the tube bundles is reduced compared to the density in the tubes of descent. If the heating is too quickly, the degree of vacuum in the evaporative tubes increases rapidly, the liquid in the cylinder raises the level and if the discharges of security are not opened, the cylinder is flooded.

Similarly, a rapid depressurization of the steam circuit gives rise instantly not only to the expansion of steam bubbles existing in the mass of liquid, but also the adiabatic vaporization of a new fraction of liquid. There is also the risk of flooding of the cylinder. From this point of view, the forced circulation of the water in the evaporator favours the drag of the steam to the cylinder and is a factor in favour of the exercise flexibility and the speed of startup.

These exercise problems concern the circuits of high and medium pressure, the first because are affected immediately by the variations of the exhaust gas temperature, and the second because the cylinders are smaller and have more restricted margins of adjustment.

The collectors and the banks of tubes

If the superheater tube bundles of high pressure are the first to be invested by hot gases from gas turbine, their material is the most directly affected by the temperature variations. But if the tubes are not very thick and can adapt quickly to varying thermal conditions, not so are their collectors, whose diameters, lengths and thicknesses are difficult to reconcile with rapidly changing temperatures.

Compared with cylinders, the collectors are less heavy and thick, but from the point of view of the thermomechanical stresses also present a disadvantage, as their temperature cannot be controlled by adjusting the pressure.

From the listed aspects above mentioned of the gas and steam turbine and the steam generator, it can be concluded that the flexibility limits of combined cycle envelop the limits on the flexibility of the gas turbine and steam cycles: the first sets a limit to the modulation of load amplitude, and the second is a constraint to starup times and load variations.

Here is a summary of the flexibility limits to the gas, steam and combined cycles.

Operative flexibility	Technical minimum	Time of startup
Conventional steam cycle	15% (with cylinder) – 40%	8 – 12 hours
Gas turbine in simple cycle	60%	30 minutes
Combined cycle	60%	3 hours

CHAPTER 3 ECONOMIC ANALYSIS

3.1 MANAGEMENT STRATEGIES

Currently, the power plant of Fusina, due to the low price of coal and the pollution abatement plants (it was one of the first ENEL plants to adopt the denitrification and desulfurization system), has succeed to be one of the plants selected by the power exchange to provide electric power to the grid. Its load factor remains quite near to the unit both during the day and the different periods of the year, except for a month between July and August in which two groups (including the group 4 analyzed) are shutdown when the condenser cooling water exceeds the temperature limits allowed for the Venice lagoon.

To develop an economic comparison between different operation modes of the plant it has been necessary to analyze the plant operation on a long period in order to extract significant loading ramps for the study.

Two possible management strategies for the plant, different for both structural and economic consequences, have been presupposed from the data analyzed:

a) Management 1, very similar to the pre-power exchange management, with constant maximum load during diurnal hours and a reduction in nocturnal hours and on weekends of about one-third of the maximum load, obtained by modulating the steam flow rate without variations of its temperature and pressure.
b) Management 2, typically of the electricity market that follows the industrial requirements and provides a production at maximum load for both day and night and a shutdown on weekends.

It is confirmed that with the management 1 thermal and mechanical fatigue are absent except those due to possible unplanned shutdowns during the exercise, while creep phenomena are present and constant at the maximum temperature. With the management 2 there are about 50 annual cyclic phenomena of thermo-mechanical fatigue in addition to the creep at the maximum temperature.

Below the costs and revenues of both strategies will be analyzed, simulating a progression over a long period (20 years) enough to verify if the type of management most advantageous in the short period can be economically sustainable also in the long term, since the most stressed components, such as the superheater, shorten its life with a flexible/cyclic operation during the year.

3.2 ECONOMIC CONDITIONS

In the economic analysis carried out there have been some hypothesis, based on literature and developed by experts, in order to simulate as closely as possible the boundary conditions in which the plant operator will have to work. The expenditure items of a coal-fired power plant have been analyzed with the income obtained or obtainable under the actual conditions of the free energy market. In order to make possible further comparisons between different types of management both costs and incomes are expressed in €/MWh produced.

3.2.1 Coal price

The coal used in the Fusina plant has the characteristics shown in the following tables:

	South African coal reference
HHV	26210 kJ/kg
LHV	25460 kJ/kg

total range variation	
min	max
25960	30150
24930	28930

Table 3.1
Low and high heating values

	South African coal reference
Humidity	7,4%
Ash	13,6%
Volatile	24,6%
Fixed Carbon	54,4%

total range variation	
Min	Max
6,53	15,53
3,53	18
22	40
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Table 3.2
Instant analysis

		total range variation	
	South African coal reference	Min	Max
Carbon	65,9%	63,39	71,93
Hydrogen	3,6%	3,54	4,81
Humidity	7,4%	6,53	15,53
Ash	13,6%	3,53	18,0
Sulphur	0,6%	0,3	1,0
Nitrogen	1,6%	1,19	1,69
Oxygen	7,3%	5,92	11,47
Chlorine dry basis	0,014%	0,001	0,3
Fluorine dry basis	34,6%	9,1	250

Table 3.3
Elemental analysis

		total range variation	
	South African coal reference	Min	Max
SiO2	39,35%	39	60,78
TiO2	1,56%	1,02	1,75
Al2O3	30,88%	18,8	32,0
CaO	10,82%	2,11	11,0
MgO	3,14%	1,55	3,14
Na2O	0,76%	0,12	2,38
K2O	0,67%	0,5	2,51
P2O5	1,027%	0,15	1,76
Mn3O4	0,099%	0,06	0,1
SO3	0,85%	0,19	4,85
Fe2O3	4,51%	3,9	6,58
Other	6,30%		

Table 3.4
Ash analysis

		total range variation	
	South African coal reference	Min	Max
Hardgrove Index	51	41	61
Size to pulverizers	0 - 100 mm	0	100

Table 3.5
Physical properties

	South African coal reference	total range variation	
		Min	Max
Initial deformation	1340ºC	1150	1395
Softening point	1360ºC	1212	1444
Hemispherical point	1380ºC	1242	1482
Flow point	1410ºC	1294	1482

Table 3.6
Fusion temperatures

The coal market has followed the trends that have affected the prices of other fossil fuels, falling back quickly from the maximum 220 $/tonne that were registered in the European market in July 2008. The prices went down below 60 $/tonne in March 2009 and after a period of relative stability there has been a new uptrend, intensified at the end of year, with a closure around 80 $/tonne. Instead prices in China, between September and December 2009, went from 87 to 120 /tonne due to high demand, driven by higher rates of economic growth.

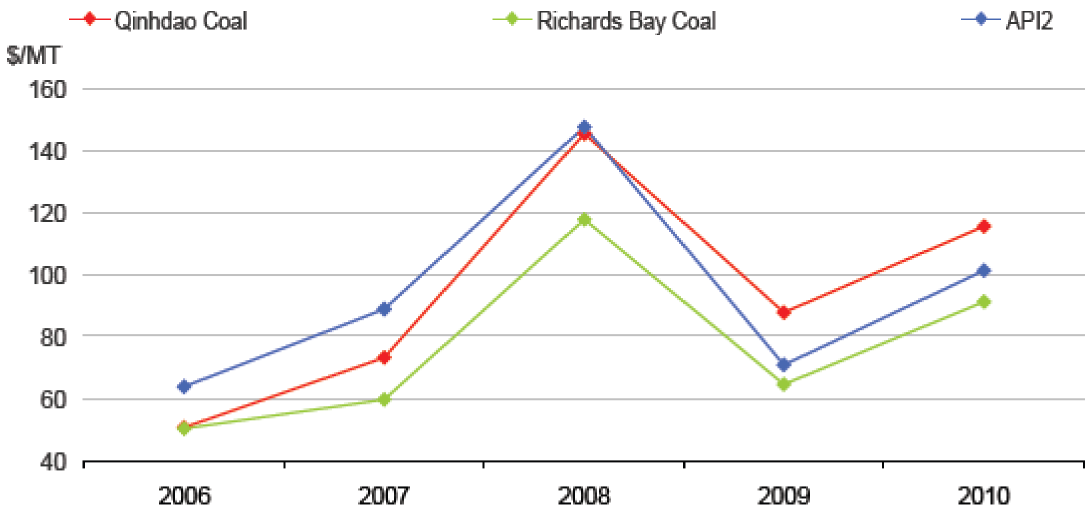


Fig. 3.1
Annual evolution of spot and future coal prices. Arithmetic mean.

After severe declines registered in 2009, last year marks a recovery in prices of all fuels, mainly concentrated in the last trimester. On the contrary, the exchange rate has divergent trends from those observed in the energy markets, since for the first time in the last five years reaches an annual average of 1,33 $/€ (-4,9% compared to 2009).

This level indicates an additional loss of power of the euro against the U.S. dollar since the exploit of 2008.

By reviewing the European markets of the main energy commodities, in 2010 are observed similar growth levels to the crude oil, its refinery products and coal.

In 2010 prices of coal were up over 101$/MT (+43% trend), the second historical maximum after the peak in 2008 and above the level proposed by the operators in the previous year. Even more evident than appreciated on crude, the increases were concentrated in the last quarter of the year, a period in which prices have reached high levels close to those of 2008, showing a pronounced growth on European reference.

In the beginning of 2011 the price of European coal reaches its highest value since september 2008 (124,2 $/MT), converging on the chinese stock levels. The first signs of slowdown of the trends observed in the last quarter of 2010 produce minimal increases in respect to december (+1,1%), leading to a slight decrease in annual increases, which are still high (+44%).

Although the decline in growth on future markets is modest, it generates slightly slowdown expectations for the short term and a substantial stability on the planned levels for february for all 2011.

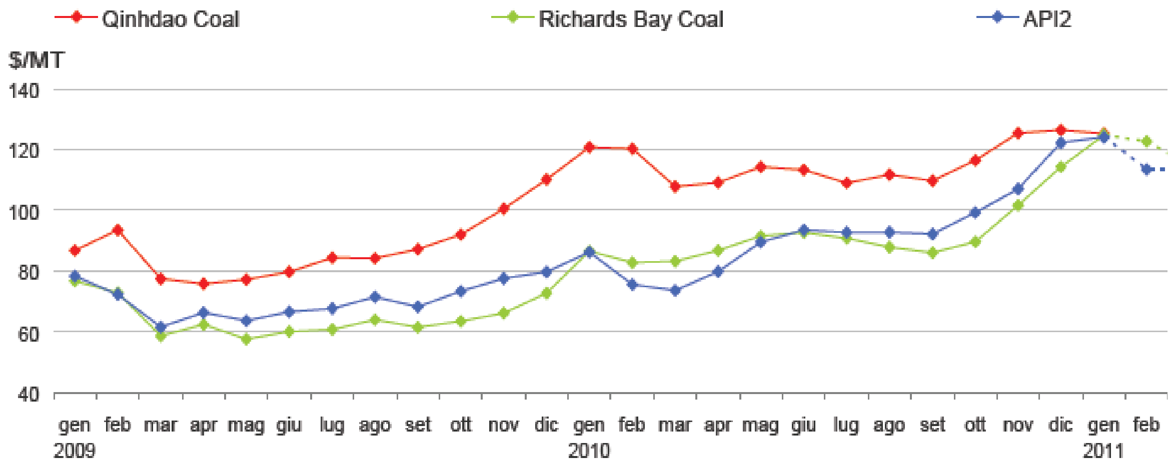


Fig. 3.2
Monthly evolution of spot and future coal prices. Arithmetic mean.

For this analysis the data obtained from GME summaries have been used, which show the FOB price of South African coal Richards Bay.

Based on predictions and on the previous data processed by the GME, which show a quite constantly trend in coal prices over the past decades, it is considered as a reference value the average price seen in 2010 with an increase over the years equal to that of inflation, that is 2%.

3.2.2 Production costs

The cost of generation of kWh can be considered the sum of three different items (excluding the cost of purchasing fuel):

1) The depreciation charge of the invested capital and all the financial charges concerned to this.
2) The operating costs related to the plant management, starting with staff costs, materials (spare parts, reagents, lubricants, etc.), external resources (outside companies subcontracted to work on the plant), insurances, taxes and fees.
3) The externalities arising from environmental impact due to the construction of the plant and its exercise.

The sum of the first two terms (in which must be added the fuel price) is the industrial cost (i.e. the cost of generating a kWh poured to consumers), also called internal cost.

The last term is the external cost that values in monetary terms the effects on the environment by the construction and the exercise of the plant. In a general discussion, the economic competitiveness among the different types of production or operation rarely takes account of external costs.

In order to evaluate properly the cost of generation it is necessary to distribute the initial investment on all the energy produced by the plant along its useful economic life. This operation must also recognize that the generation of energy is deferred in comparison to the period in which the investment is sustained and include the financial charges arising from this time lag.

The methodology used assesses the impact of the investment on the electricity production through an analysis of the annual cash flows over the useful life of the plant or a long enough period of years.

The economic analysis here reported has taken into account the particular and real situation of Fusina plant. Therefore, the amortized cost of investment of the plant during the years of operation has not been considered. In fact, in this case a comparison among different types of plants was not requested, but a comparison among different types of management of the same plant.

Therefore, the production costs considered have been those relative to the superheaters installed at the break of the first, the cost for the plant management and the cost of the plant externalities.

Cost of plant management

The expenditures of the plant (excluding the fuel cost) that are fundamentally related to the management and maintenance for optimal functioning of the plant are described and evaluated below. Each of them is considered in Eq. 3.1 that shows the specific cost per MWh produced for the cost of production. As regard the operating costs related to the plant management, should be noted that the fixed quota includes the costs that are independent from the effective production of the plant (personnel costs, insurances, etc.), while the variable quota refers to the dependent costs of the production (lubricants, chemicals, waste disposal, etc.).

The evaluations of the individual items of expenditure are:

- The fixed costs for staff has been estimated at 15 €/kW (es1), while the variable cost has been considered equal to 3 €/MWh.
- The cost of external resources (materials and supplies, third-party services, general costs) is about 3,6 €/kW for coal plants (es2).
- Taxes and fees have a cost of about 2 €/kW (es3).
- The cost due to start-ups is about 1 €/MWh (A).

Therefore, the cost of the individual kWh expressed in €/MWh is:

Eq. 3.1

$$c = \frac{es1 + es2 + es3}{Nf_c} + \frac{nA}{PNf_c}$$

where N is the number of operating hours per year, f_c is the load factor, n is the number of startups per year and P is the installed power (320 MW).

For these costs, excluding the fuel previously treated, it is assumed an annual increase of 2% equal to the average inflation in the past ten years.

Cost of externalities

The production cost of the kWh previously reported is defined as an "industrial" cost of generation, closely related to the process of converting primary energetic source (fossil fuel) into electricity. It is also true that the use of an energetic source involves a damage to different receptors, that is the human health and the ecosystem. Such damage implies additional costs, called "external costs of electricity generation" that can not always be included in the market price of energy. For many years these externalities have been ignored because it was not possible to compute them. Nowadays at least a part of these costs can be evaluated economically in terms of pollutants to be removed from the place of production.

The growing interest in environmental problems along with the need to propose energetic and economic growth policies compatible with the ecosystem, has led European states and international organizations to focus their attention in the quantification of the externalities associated with the different generation technologies. There are European studies (for example, the ExternE project [2]) that aim to develop a unified and shared methodology among all member states to quantify these externalities. In particular, the assessment approach should follow what are called the "impact paths" which identify and quantify the pollutants and the priority impact paths, that is the pollutants in the environment that are more likely to lead to significant damage on specific receptors (human health, flora and fauna, buildings and monuments, etc.).

The study reported in [8] estimates the external costs of generation through the "monetization" of different types of externalities (priority impacts) such as:

- Accidents on workers or population
- Effects of pollution on materials
- Effects of pollution on forests
- Effects of pollution on fauna
- Impact on global warming
- Effects of noise
- Effects arising strictly from the fuel cycle (process of extracting coal, lignite, oil and gas)

In the analysis shown in [8], for coal-fired power plants, it is reported an economic value for externalities of 15 c€/kWh without considering the impact of carbon dioxide.
In the analysis presented here this cost has been considered in part because the plant, to be within the limits of the law as regards the emission of major air pollutants, has been forced to acquire new equipment to capture pollutants and eliminate them. Also the management of the waters within the perimeter of the plant provides specific and purifier plants that were not required before. Therefore, those that have been considered are the operating costs of the "ambientalization" of plants to reduce the pollutants contained in the gases of combustion. The costs of plant installation are not considered because the comparison is done for the same plant.
The cost per weight of pollutant has been translated in terms of cost per unit of energy produced in order to be added to the value obtained with Eq. 3.1. The value calculated for the Fusina plant is about 18 €/MWh.

Cost of the superheater

According to information provided by the purchasing department of the Fusina plant, every high-temperature superheater has a cost of about 1.200.000 € and its replacement takes about 20 days of work. If the replacement does not take place at the shutdown of august, then it must be added the loss income to the purchase cost. The price has been updated to the year of replacement.

3.2.3 Carbon dioxide emissions

As part of the EU "burden sharing" agreement in the implementation of the Kyoto Protocol, for the 2008-2012 period, Italy has to reduce their emissions of greenhouse gases to 93.5% of the value in 1990. The overall cut is therefore 6.5%.

The Council and the European Parliament, the 13 October 2003 approved the Directive 2003/87/EC establishing, with effect from 1 January 2005, a community system for the exchange of greenhouse gas emissions called Emission Trading System (ETS), in order to reduce emissions "according to criteria of cost effectiveness and economic efficiency" (Article 1). The system allows the reduction of the emissions by the mechanism of acquisition or sale of emission rights.

The Emission Trading System is a kind of "Cap and Trade" system, which provides a maximum limit (cap) on emissions produced by industrial plants that produce greenhouse gases. This limit is set by allocating a certain number of emission units at each plant in the categories provided by the Directive.

Any surplus of units, that is the positive difference between units allocated and the actual emissions released, may be set aside or sold on the market by the end of the reporting period, while the deficit can be covered through the purchase of permits.

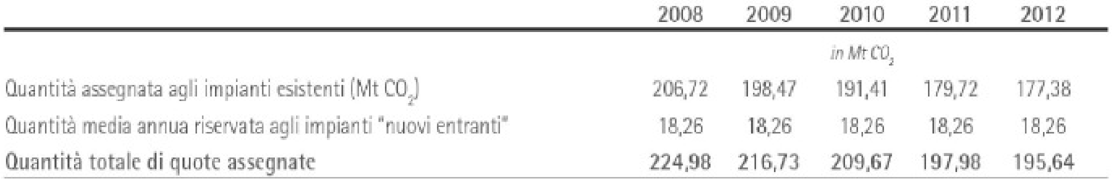
The idea is that plants with lower abatement costs to reduce their emissions more than plants that have high abatement costs and to sell them their credits. Through this exchange takes place the minimization of abatement costs and therefore, the efficiency.

Regarding the allocation of quotas, the traditional options are two: assign a number of quotas proportional to the historical production or to the historical emissions of the plant. With the criterion of historical production, in practice, all plants would receive the same number of quotas in equal production, while with the criterion of historical emissions the most efficient would receive fewer shares. Therefore, the criterion of historical production rewards businesses with greater environmental efficiency.

Italy has chosen to adopt the criterion of production for some industries (lime, steel, ceramic, cement, cogeneration energy) and the criterion of emissions for others (paper, clay, refining, glass). For the more traditional electric generation, that generates only electricity and not heat, and which constitutes the most important part of emissions covered by the directive, Italy adopts the atypical criterion of the expected emissions.

However, in recent years, emissions in Italy rather than closer to the provisions of the Kyoto Protocol are far from it, mainly because in Italy it was thought that it would not achieve the sufficient number of signatories for the ratification and then to enter into force. The amount of emissions to be cut is then grown. Actually, the total emissions of CO_2 in 1990 were 210.2 Mt, calculating a reduction of 6.5% in 2012 should be 196.5Mt. Instead, in 2000 emissions were 224 Mt. With the directive mentioned above it has been necessary to reverse course and begin a return plan and for this reason Italy has to change the shares that had considered in the PNA (National Assignation Plan) and deliver a new national plan.

The quantity of units assigned in the italian PNA sent to Brussels in february 2008 and approved in november 2008, expressed in $MtCO_2$, is shown in table X below.



	2008	2009	2010	2011	2012
			in Mt CO_2		
Quantità assegnata agli impianti esistenti (Mt CO_2)	206,72	198,47	191,41	179,72	177,38
Quantità media annua riservata agli impianti "nuovi entranti"	18,26	18,26	18,26	18,26	18,26
Quantità totale di quote assegnate	**224,98**	**216,73**	**209,67**	**197,98**	**195,64**

Table 3.7

Italian National Allocation Plan for the period 2008-2012 (GME)

The biggest difference compared to the PNA 2005-2007 regards the thermoelectric and refining sectors. Specifically, for the thermoelectric sector, the new assignment proposal has decreased from an average of 131,06 Mt CO_2/year to 100,66 Mt CO_2/year, while for the refining sector has decreased from an average of 23,76 Mt CO_2/year to 20,06 Mt CO_2/year.

For the "existing plants in the first period", no cogeneration, the annual assignment of metric tons of CO_2, under the new PNA, is determined as follows:

Eq. 3.2

$$Q_i = \frac{E_{2005} * \alpha}{1000 * T_i}$$

- E_{2005} denotes the gross production of electricity produced by the plant in 2005 (MWh) as reported by the operators communication in accordance with the article 15 of Lgs.D. n 216/2006 and verified in accordance with the article 16 of Lgs.D. n216/2006;
- α denotes the coefficient of emissions for the specific group of plants (in $kgCO_2/MWh$) and for steam condensing coal plants is equal to 0.757;
- T_i denotes the coefficient that describes, for the year i, the tendency of energy productions for each category of technology/fuel taken as reference and vary from 1,00 for the year 2008 to 0,80 for the year 2012.

Therefore, the share of emissions for group 4 of the Fusina plant is 1.211.682 tons for 2010, 1.144.365 tons for 2011 and 1.077.050 tons for 2012 and the following years. Although the decisions of the Italian legislature and European organizations are not yet known for the next years and due to the need of reducing emissions before 2012 an additional 11% nationally, the share of emissions will be reduced according to Eq. 3.2 until 2012. After this date the value calculated for 2012 will remain constant.

The allowed emissions limit will be compared each year with the value of the real emissions of the plant. In the absence of reference from the plant, the calculation of emissions will be referred to the following table provided by ENEA.

Plant and source	**CO_2/kWh**
Coal	0,946
Fuel oil	0,711
Natural gas	0,467
Natural gas combined cycle	0,402
Natural gas combined cycle with cogeneration	0,278-0,287
Renewable energy sources	0

Table 3.8. Specific CO_2 emissions by type of plant and source (ENEA)

The limit for the cost of exceeding emissions will refer to the European market prices of emission allowances. As shown in the Fig. X the price has remained between 13 and 15€/ton in 2009.

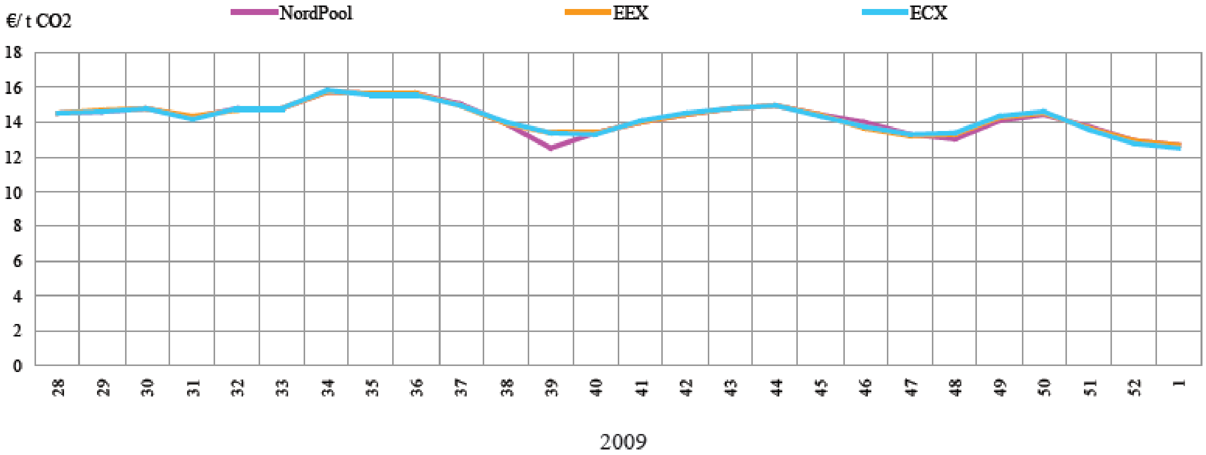


Fig 3.3 Markets to term for the units of CO_2 emissions in Europe, weekly rates (GME)

The tendency of prices in 2010 has shown a stable trend in the first half of the year, with the contract in December 2010 that has fluctuated around 13 €/ton. From the second quarter, and until the end of the year, prices have stabilized between 14 €/ton and 16€/ton, varying within the trading range in a quite regular mode.

The analysis has been carried out considering a purchase/sale price of 15 €/ton with an average increase of 2%, equal to inflation.

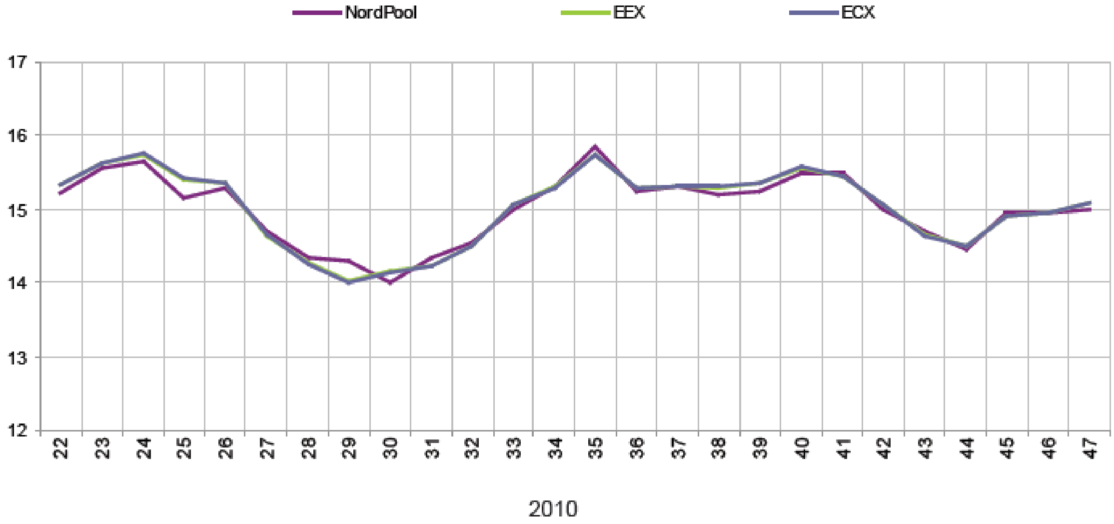


Fig 3.4 Markets to term for the units of CO_2 emissions in Europe, weekly rates (GME)

3.2.4 Energy selling price

Electricity is subjected to the law that regulates markets, that is the law of supply and demand. The energy price varies considerably not only during the year, but also during the day and between different days of the week.

The following figures show the evolution of the average purchase price (PUN), unique in Italy. In this study will be referenced at this sale price of electricity, which provides a double value; peak and off-peak. The peak hours are those between 8.00 and 20.00 from monday to friday, and the off-peak hours are those between 20.00 and 8.00 from monday to friday and all hours on saturdays, sundays and holidays.

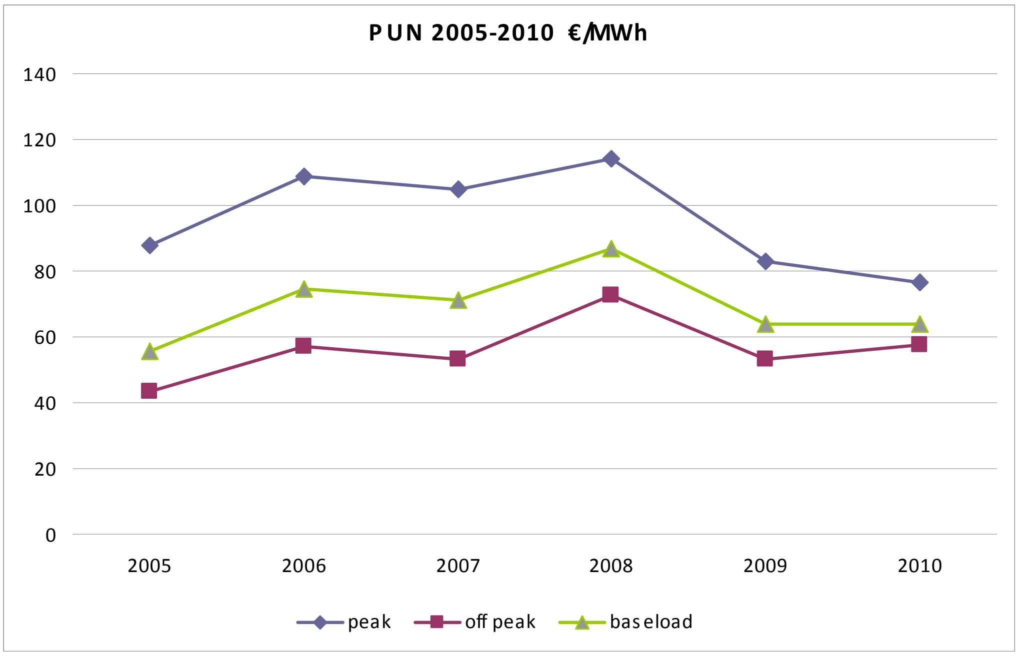


Fig 3.5 Evolution of the average purchase price (PUN)

	2005	2006		2007		2008		2009		2010	
	€/MWh	€/MWh	Var	€/MWh	Var	€/MWh	Var	€/MWh	Var	€/MWh	Var
baseload	55,59	74,75	34,5%	70, 9	-5%	86,99	22,5%	63,72	-26,8%	64,12	0,6%
peak	87,8	108,73	23,8%	104,9	-3,5%	114,38	9,0%	83,05	-27,4%	76,77	-7,6%
off-peak	43,18	57,06	32,1%	53	-7,1%	72,53	36,8%	53,41	-26,4%	57,34	7,4%

Fig 3.6 Annual average trend for all types of operating hours

The year 2008 is configured as a year of particular significance to the evolution of prices on the Italian electricity market. On one hand, driven by strong growth in the prices of fuel on international markets, the PUN recorded the highest level since 2004. On the other hand, the increase of PUN was less pronounced than the one of fuel prices and quotes of other stock markets, showing a decrease in the growth of prices and a narrowing of the differential with the rest of Europe.

To the international electric markets, 2009 was a year characterized by a strong wave of declines in wholesale prices due to the combined effect of the fall in fuel prices and the drastic slowdown in energy consumption induced by the economic crisis. This trend has also marked the PUN that has registered the most pronounced decline going back to prices close to those of 2005.
The average purchase price in 2009 was 63,72 €/MWh, the second lowest after the one in 2005, with a fall of intensity never recorded in the Italian market (-26,8%).

The average purchase price of energy in the power exchange (PUN) in 2010 amounted to 64,12 €/MWh with an increase of only 40 c€/MWh compared to 2009 (+0,6%). The analysis by groups of hours shows that in the peak hours the PUN, after the drastic decline of over 30 €/MWh in 2009, was further reduced by 6,29 €/MWh (-7,6%), its lowest level since 2005. In the off-peak hours, however, the PUN increased by 3,93€/MWh (+7,4%). Therefore, the ratio peak/baseload has fell to a historic minimum under 1,20.

The evolution of the monthly prices shows the typical seasonality of PUN, excluding the trend dynamics induced by the evolution of the fuel prices. In particular it can be confirmed higher prices in summer and winter months, characterized by high demand, and lower prices in spring and autumn months when demand is lower. As an example, it is shown in Figure X the monthly trend for the year 2010.

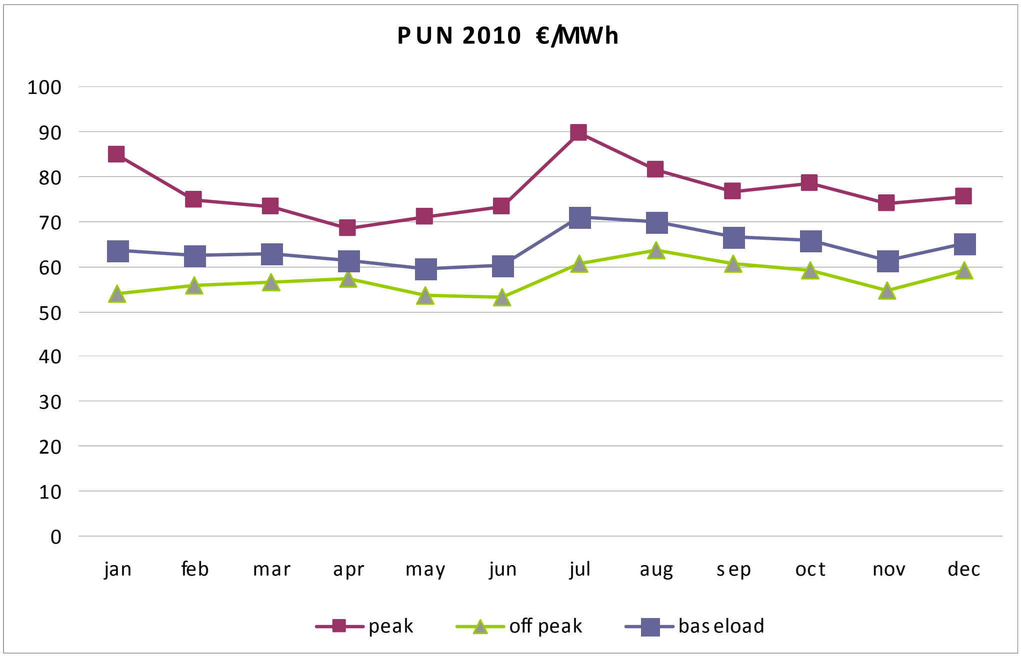


Fig 3.7

Evolution of the average purchase price (PUN) for different types of hours in 2010

The assessment of the posterior yearly increase has been based on technical considerations on the Italian electricity system, since not having a sufficiently large historic. Most of the plants use petroleum products or natural gas and the offer is heavily influenced by these two variables.

What has happened to the selling price in recent years (between 2007 and 2009) appears to be a temporary event, unexpected and atypical. Therefore, it has been chosen for the whole period of analysis (20 years) a growth rate of 6% for the peak hours thinking about a possible future slowdown of prices. For the off-peak hours, as there is a strong competition with the nuclear imported, is has been chosen a minor increase of 4% annual.

3.3 ECONOMIC RESULTS

To compare two different management strategies of the plant two economic instruments commonly used in the comparison of different types of investment can be used: Net Present Value (NPV) and Internal Rate of Return (IRR). Usually these tools are used to compare different types of investment, so the discount rates chosen are quite high as they must be representative of the gain rate that the investor obtains from its investments. This particular case is rather quite atypical as it compares two different management strategies of the same plant already in operation, then the discount rate chosen will be unique and equal to the nominal discount rate, i.e. for Europe the rate fixed by the ECB (3,5%), while individual costs and incomes will grow with the trend seen previously.

So each individual cash flow (Rj) in the year 'j' will be discounted (DCF discounted cash flow) according to the expression:

Eq. 3.3

$$DCF = \frac{R_j * (1+f')^j}{(1+r)^j * (1+f)^j}$$

where *f'* is the growth rate selected for that cash flow, r is the nominal discount rate (chosen for the analysis equal to 3,5%) and f is the rate of inflation (chosen equal to 2%). The Net Present Value is then defined as:

Eq. 3.4

$$NPV = \sum_{j=1}^{N} TDCF_J$$

where the Total Discounted Cash Flow for the year 'j' (TDCFj) is the sum of all the Discounted Cash Flows in that single year. In Eq. 3.4 does not appear the initial investment since it is considered an existent situation (with the superheater cost already considered) compared with another with the same superheater but with a different management. Investments that maximize this magnitude are those economically more suitable and in this case the management with a higher NPV is the one that is more profitable.

3.3.1 Main calculations

To proceed to the economic calculation of both strategies it is necessary to summarize all the initial data and the hypothesis made in their annual increase, as well as the calculation of some other parameters regarding the coal cost and the sale price of energy.

		2010	2011
FOB Price	$/t	90	124,2
Freight	$/t	9,96	
CIF Price	$/t	99,96	
Positioning	€/t	7,39	
Duty	€/t	2,6	
Change $/€		1,33	
CIF Price	€/t	74,04	
Total price	€/t	84,03	
Specific consumption	Mcal/MWh	2485	
Heating value	Mcal/Kg	6,3	
Total price	€/Mcal	0,013	
Strike price	**€/MWh**	**33,15**	**43,14**

Fig 3.8. Calculation of the coal price

Fig. X shows the sequence of calculations for the coal strike price based on FOB price of south african coal expressed in $/ton. The FOB price (Free On Board) means all the costs until the port, including the costs of obtaining licenses and documentation for exporting from the original country and customs operations. From this price, adding the cost of the freight of the ship, results the CIF price (Cost, Insurance and Freight). At this point the price is converted into euro and it is added the duty. With the Lgd. D. 26 of 2/2/2007 has been abolished the so-called carbontax and introduced a duty of 2,6 €/ton for coal used for electricity production. The total price in euro per unit of weight has been converted into a price per unit of energy produced.

Fig. X is updated to the average FOB price of south african coal in 2010. It has been considered also the price of January 2011 for an additional comparison, since prices are increasing significantly.

Regarding the selling price of energy, calculations have been made with the 2010 data as reported above. The growth rate for the management 1 results from a weighted average of the peak and off-peak hours growth rate, while the price of management 2 is calculated according to the effective hours of operation. In particular, the result is a weighted average price where as a weight has been used the application time (days*hours) and the load factor for those hours depending on the different ways of managing. The same has been done for annual increases.

For the rest, the values used for the analysis of both strategies are summarized below.

	Management 1	Management 2	annual rate
Peak Power [MW]	308	308	
Annual operating hours [h]	8016	5760	
Load factor	78	98	
Annual production [MWh]	1925763,84	1738598,4	
Real emissions [t/year]	1821772,59	1644714,09	
Fuel cost [€/MWh]	33,15	33,15	2
Emissions quota cost [€/t CO2]	15	15	2
General costs [€/MWh]	24,29	24,65	2
Energy price [€/MWh]	63,56	67,07	4,75 / 6-4

Table 3.9 Summary table for the economic comparison

Note that:

- The load factor is related to the operating hours indicated in Table 3.9 according to the chosen management and not to the 8760 hour of the year.
- The real emissions are calculated by multiplying the coefficient in Table 3.8 with the annual production.
- General costs are obtained using the formula Eq. 3.1 and the hypothesis contained.

3.3.2 Comparison between different strategies

From the calculations of the structural damage of creep and thermo-mechanical fatigue on the SH, as seen in literature [X], it results that with the management 2 with 50 cycles of on/off per year there are four replacements of SH over the 20 years. The fact of operating the plant in a flexible mode leads to a net reduction of the component life, but this is translated into higher incomes in the short and long term. According the hypothesis considered and the values described in Table 3.9 below are showed the results of calculations on cash flows and NPV of both types of management.

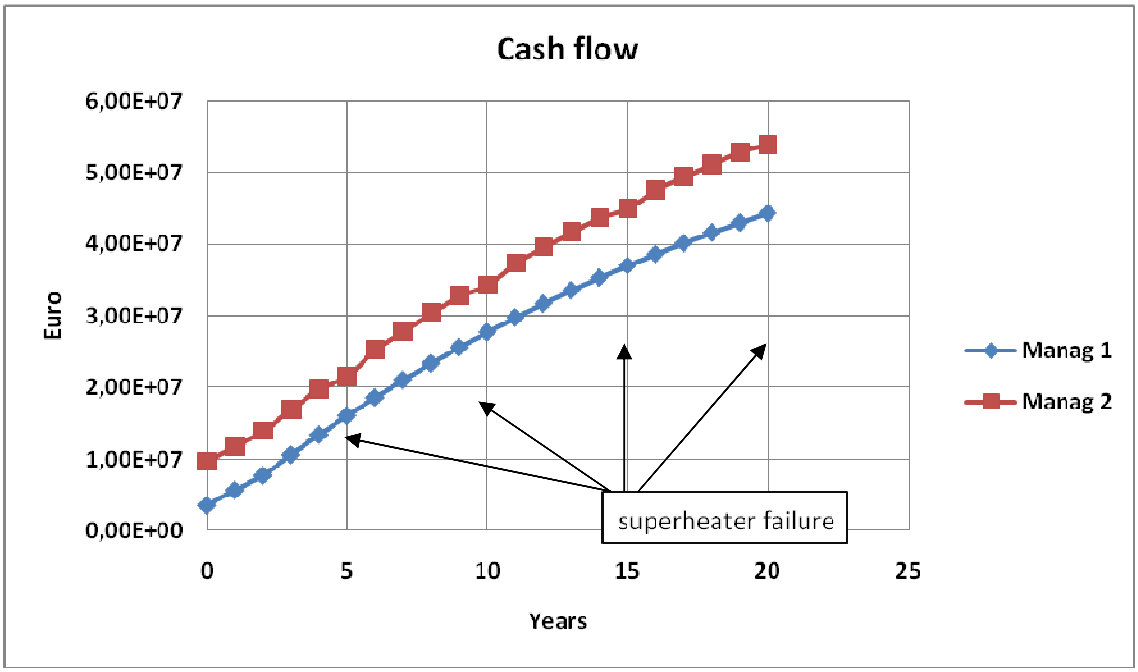


Fig 9. Cash flows of both managements

The results show that in a long perspective of twenty years the difference between the two managements of the plant is sufficiently clear from the beginning. As shown in Fig.10, the NPV of the management 1 is 547.988.964 € while for the management 2 is 706.930.761 €. It can be seen also that the management 1 is always economically less convenient and the difference increases over the years.

In the fourth year it can be seen an inflection point in the curves of Fig. 9 as the burden due to emissions is estimated not to grow under the current laws, but it is likely that in view of new and more stringent rules on emissions the convenience of the second management may increase. Also as it is possible to buy emission permits it is possible to sell their own shares. Therefore, the second management would have this additional benefit.

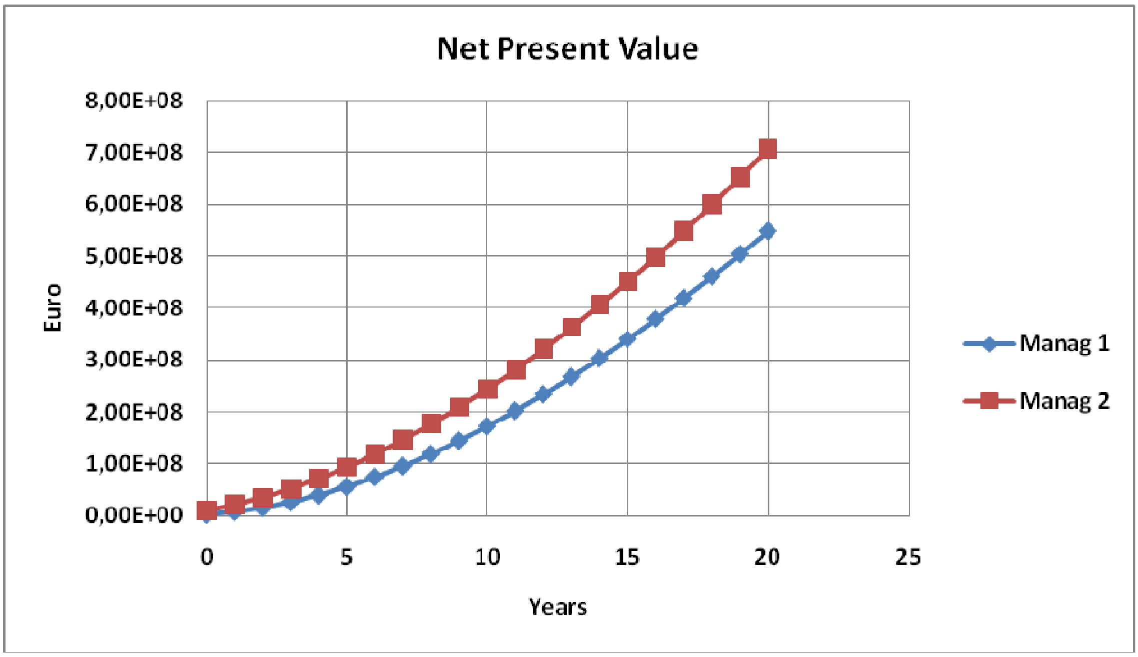


Fig 10. Net present value of both managements

From the analysis carried out it has been verified that one of the factors that strongly influence the results is the price of carbon. As mentioned above, the price of coal in 2011 is increasing significantly from the last two years, from 33,15 €/MWh in 2010 to 43,14 €/MWh in january 2011. Below are shown the effects that would cause this current price to the results of the analysis. The management 2 continues being more convenient in this case, but it is demonstrated the inconvenience in case of installing a coal plant respect to another typology of fuel.

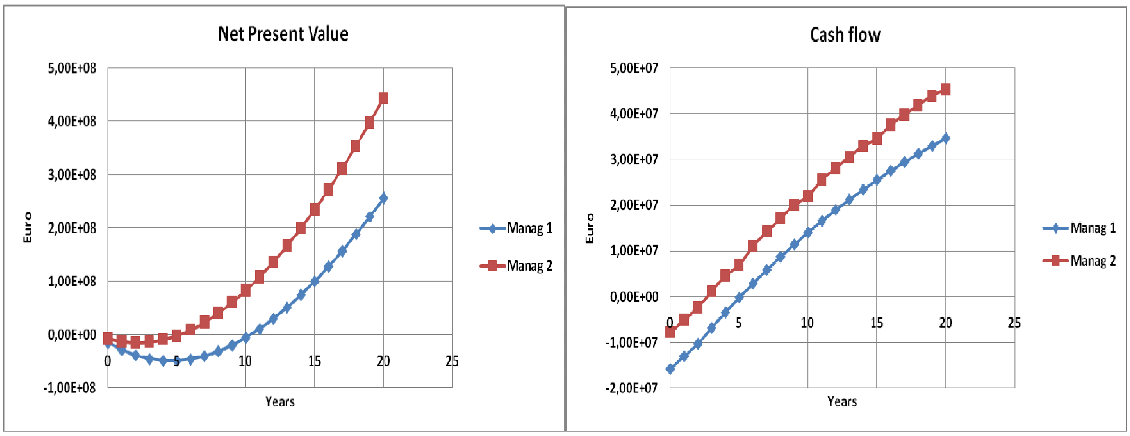


Fig. 11

Net present value and cash flow of both managements. Price of coal equal to 43,14€/MWh

It is also reported as an indication the trends of cash flow and NPV referred to comparisons between the management 1 and other more flexible types of management 2. In Fig. 12 it is considered, for example, that the management 2 is exercised only during the day (peak hours only). In this case it is expected 250 cycles on/off and a replacement of one SH per year.

As it can be seen in this case the management 2 remains more appropriate than the 1, although over the years the two managements have almost the same cash flow. In this case the NPV and the cash flow are lower than the initial ones. Therefore, this type of management 2 is less suitable than the first one.

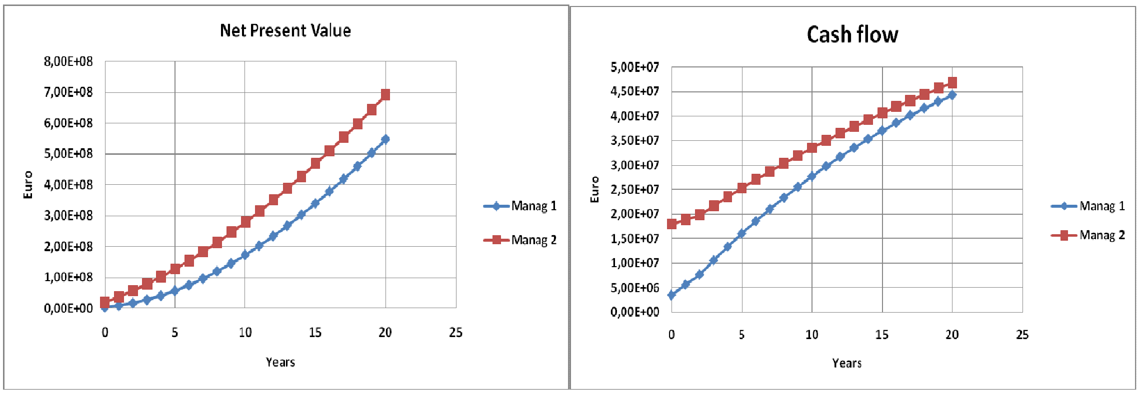


Fig 12 Net present value and cash flow with the management 2 modified (only during the day)

In Fig.13 there is the comparison with the management 2 exercised only during the day (peak hours) in the six months where the selling price of energy is statistically more convenient. The other six months is exercised also during the night. Therefore, there are 150 cycles on/off and the replacement of 13 SH in the 20 years of the analysis (about two every three years).

In this case management 2 continues being more convenient than the 1, approaching to the values of the initial management 2.

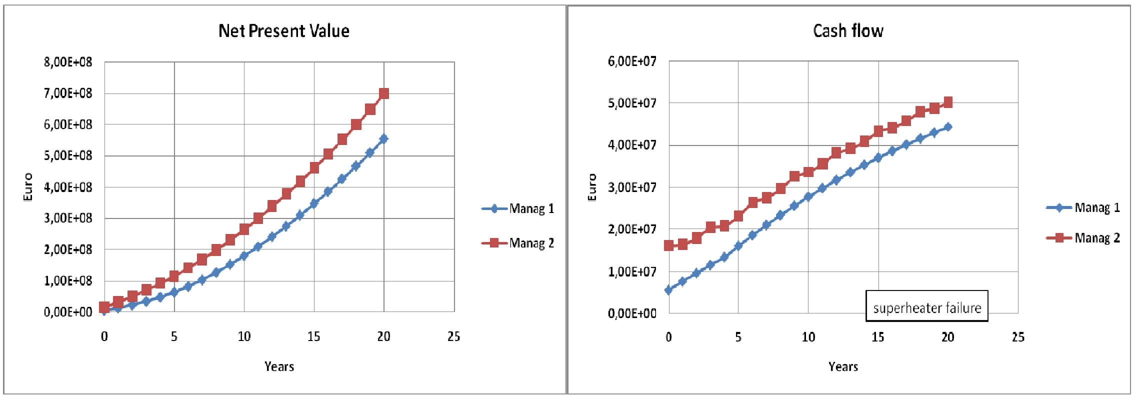


Fig. 13 Net present value and cash flow with the management 2 modified (six months only during the day)

It has been also performed in an analysis to determine the economic desirability of the flexible exercise focused on the SH of high temperature. In fact, in the Fig 14 are shown the number of SH replaced over the 20 years, as a function of the on/off cycles during the year, with the trend of the NPV for the different possible cyclic managements. All this is confronted also with the trend of the management 1.

The same thing has been done in Fig 15 under other conditions regarding the price of coal. As it has been seen before the coal price has increased significantly this year, therefore it is necessary to compare the analysis with both prices.

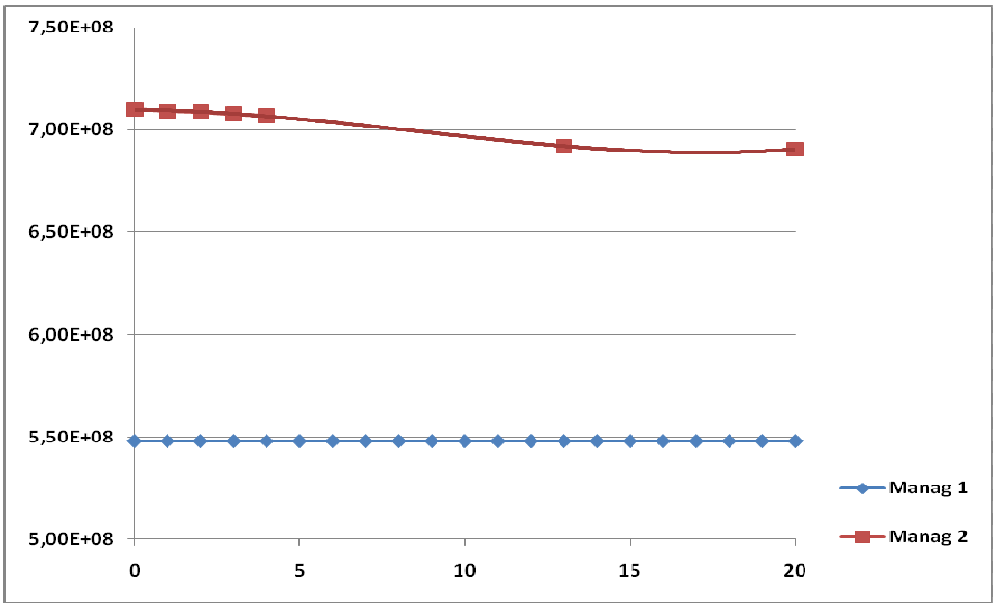


Fig 15 Trend of the net present value of both managements according to the superheaters changed in 20 years

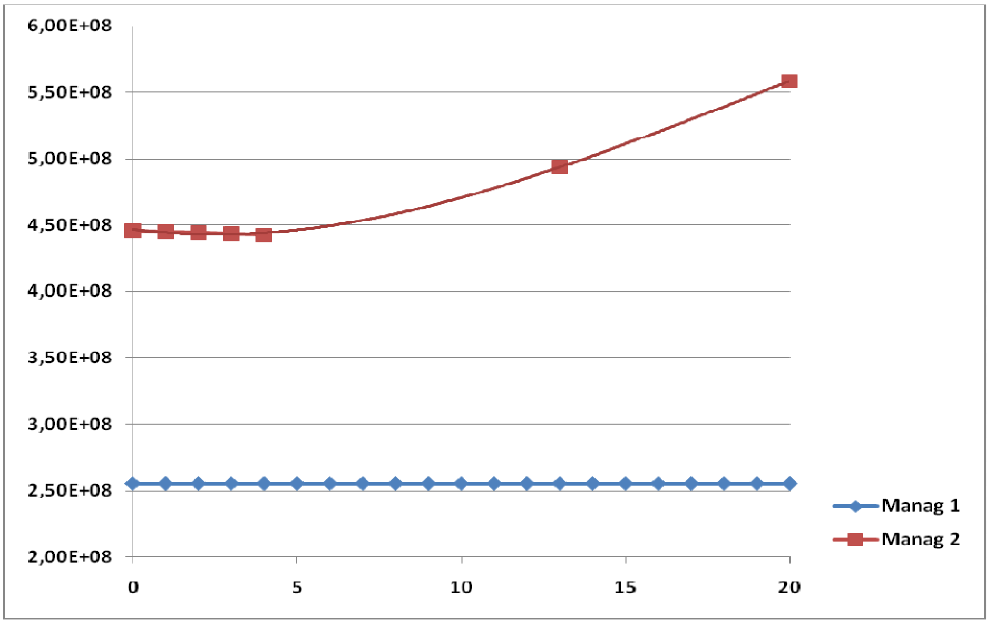


Fig 16 Trend of the net present value of both managements according to the superheaters changed in 20 years (price of coal 43,15€/MWh)

As mentioned above the management 2 results the most convenient in any of the cases studied. As it can be seen in the graphs above, with the rising price of coal, the more flexible management 2 is, more beneficial results even reaching a shutdown per day.

3.3.3 Conclusions

The two different managements have been compared from an economic point of view to ensure their convenience in the short and long term.

It has been reported an analysis to define the selling price of the Italian electricity market and hypothesis for production costs of the power plant of reference (coal, externalities, industrial cost, CO_2 emissions).

The economic comparison has take into account a large period in order to assume constant variations. In fact, it has been shown that the values, both prices and costs, in 2007-2009 have suffered a sharp rise followed by a rapid descent. It has been assumed that the annual increase of plant costs was 2%, equal to the average change of inflation. Instead, the selling price of electricity has been considered of 6% per year for the peak hours and 4% per year for the off-peak hours.

With these hypotheses the comparison has given reason to the flexible management both in terms of cash flow and cumulated result in the 20 years.

Other plant managements which included a high number of stops have been compared. Also in these cases the management in base load has given a worse result. The same conclusion has been reached considering a higher price of coal.

It has been also performed in an analysis to determine the economic desirability of the flexible exercise focused on the SH of high temperature and with the rising price of coal, the more flexible management 2 is, more beneficial results even reaching a shutdown per day.

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