UNITS HEAT RATE AND ELECTRICITY COMPETITIVE MARKETS.

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Abstract.- Under the title, *units heat rate and electricity competitive markets*, or *electricity generation, heat rates, efficiency & markets*, it is presented an ongoing research activity that tries to advance on the development of a *process* to review and establish a *improved knowledge base* about the, past evolution and present status of the power generating *units thermal consumption function or units heat rate, HR.*. Recently many *countries power generation system* have gone into a electricity competitive market and, after several years operating under such a new rules, was considered that could be of interest to review the existing units HR, its state & evolution in front of the today electricity markets requirements. The starting point was, the actual market available information, some past *ad hoc* data about the units, previous heat rate studies and algorithms to represent the heat rates in market simulations. The results of such a knowledge base could be useful for, some of the study models, so frequents under today electricity competitive markets, as well as to identify some energy efficiency new indicators, or universities today related scientific *studies*. The CO2 emissions and/or trading effect over electricity price, is not included at present time.

HEAT RATE, THERMAL CONSUMPTION, ELECTRICITY MARKETS.

1 INTEREST AND OBJECTIVES.

The objective of the study, or work interest, is to establish a process for identification of *units thermal consumption function*, their state and evolution, operating and associated power. After several years operating in the generation competitive market the old units continue to participate together with the new ccgt's, with changing strategies, increasing power offer, maintenance policies, fuel prices, their efficiency, the result is that they are suffering changes to identify. For that reason it is going to be systematized the indicated knowledge from market information or estimated from recent revisions, capture the nominal design data, already old, due to exploitation still forced under the new markets rules requirements.

The different *generation agents* compete on the production market for selling their electricity and optimising their generating units operation in the markets. To do this is necessary to plan both, the production and the units fuel consumption –and cost- requirements, so it is necessary to know the *thermal consumption function* HR, for all units, owns, and third party, required for an adequate, *global view of all the competitors*, control of possible or estimated revenues. Keeping this in mind, and also for longer term model analysis, these functions are broadly used, even to prepare offer to market, –and *lot of models, goals, schedule ST, LT, generation technologies, etc*.- were it is needed to consider all the power generating units with their HR algorithms and/or internal homemade statistical figures for each unit technology.

The work is also base on the know, spanish electricity sector transparency which always have actively participated in the better knowledge –and diffusion- of the technical characteristics for the different units of the spanish national electricity production system, specially relevant when –in the past- the units loads commitment *was* centrally decided, under MLE (*marco legal estable*). An example, the managed work at ancient *Government Delegation in the electrical system operation*.

At present time, as indicated, after the change to a competitive market, already with more than seven years of market clearing data, it was opportune to ask, what have happened with the generating unit HRs, and so it was started the present research with the objective to organize an improved global *knowledge base* about the units state, for all generation agents units, starting with the group of thermal power plants, in competence, helping to studies that utilize these data. Trying to avoid to convert in protagonist the mathematics of the *process*, as often happen, because of administrative scientific curricula needs, but far from offer, or intent to offer to the industry & country findings that could be of interest. Do not have also to be forgotten the efficiency value, that the findings could have, in today energy saving policies.

The figure will help to remember what should be understood for *thermal consumption* of a generating *unit*.

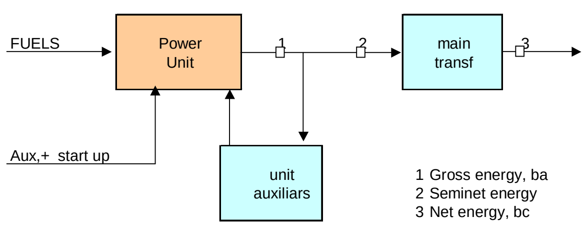


Figure 1. Units Heat Rate, thermal consumption.

Under previous *conservation efficiency policies*, and oil crisis around, some approaches were done by the spanish Energy Studies Centre, were the interest was the energy saving for all energy sector, and the HR of the electrical system. The IEA also study and debate, the right definitions about what should be understood by Heat Rate, *gross, net, etc*. as reviewed by Henderson [1].

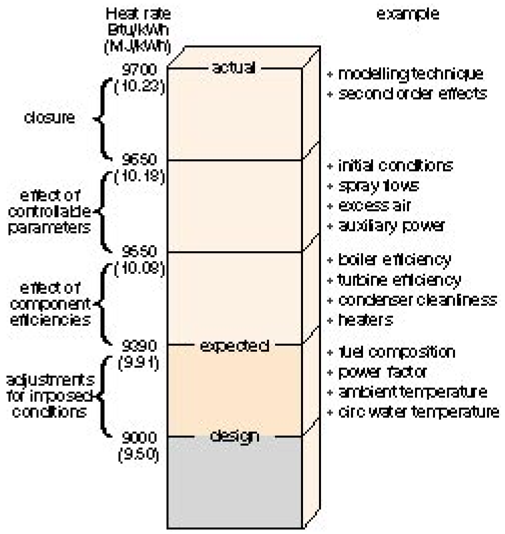


Figure 2. Power generating units Heat Rate concepts [1] Btu/kWh, (MJ/MWh).

Also, the *thermal and specific consumption,* here as HR in a generic mean, of an electricity generating unit -that should be differentiated from a company or industrial enterprise- evolves with their age, from their design specification, passing to the own of the technology of their components, installation place, the unit use that has been done, exploitation operating hours, fuel, emissions, etc. variables that will be seen in detail. The objective trays also to reflect the specialists experience as demands or needs for their study-models as well as on the use options of statistical data or mathematical algorithms that represents appropriately the HR.

As another important point of view, in the past, *generating agents* took advantage of low fuel costs, being,
- the HR something secondary in the generation, since
- the costs were transferred to system and the clients, but that scenario has changed little by little and lately on a quicker way, because of
- oil frequent crisis and oil indexed fuels prices practices,
- uncertainty and volatility of prices, but above all the
- competition in the kWh daily market, where the HR is again protagonist.

The scenario is now competitive in the generation and the HR value is highly relevant, an example could be the entities that are trying to introduce measures as presented at several meetings by EPRI heat rate conferences [2].

2 THERMAL CONSUMPTION RATE.

The algorithm or algorithms, or data tables, as will be seen, identifiers of units fuel consumption are characterized basically for some 'curves or function' varying according to the different load levels, from the technical minimum until the maximum nominal load. These are denominated as *specific consumption function*, SC, or thermal consumption for kWh produced, te/kWh, *hourly thermal consumption function* te/h, hourly HR also known as consumption-production or *input-output curve*, that is converted in cost, euros/h if a cost of the fuel termia (te) euros/te is assigned, and marginal cost MC, E/MWh or cE/kWh produced. A *termia* equals 4186 kJ.

There are many possibilities for group modeling, depending of the model goal, time of calculation, etc. A classical algorithm is represented by the expressions,

$$SC = SCi = ai + bi.\ P + ci.\ P^2 \qquad (1)$$
$$HR = HRi = a'i + b'i\ \ P + c'i.\ P^2 \qquad (2)$$
$$MC = MCi = \ b'i + 2.\ c'i.\ P \qquad (3)$$

Where, P MW loads, i subindice group and , a, a', b, b', c, c'. parameters, remember, independent, lineal and quadratic, leaving apart, for the moment, separated the terms for MC. In these, the starting point of the consumption functions, in their technical minimum, it is the fixed term of the expression and represent the group coupling or start consumption, so relevant factor of the solution in some models. See on figure units comparison.

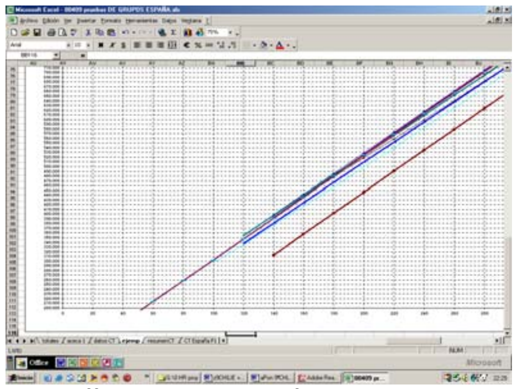


Figure 3. Effects on MT and PN for some Fueloil units. [9]

Additionally the identification of the multi-fuel groups HR could be more complex, even with alternating or simultaneous fuel use, and also in the new ccgt combined cycle units. The HR is presented in others forms depending on the models input flexibilities, some times perhaps a little confusing for the non-experts, but useful as arise from the work of Klein [3].

As a next step, the HR photo is not a fix one, and it must follow their evolution, because the groups change along their life, maintenance, type of exploitation, daily, weekly, of restrictions, etc. In the above mentioned functions, neither the value of MT and MN -max. or nominal- capacity remains fixed, and also should try to approach to their actual operative situation. One way by means of, the obligation to check the group -under authorized surveillance- values of capacity for the power guarantee pays, but also by the *actual* value of each group in the hourly market statistic data.

The influence in the HR is even wider standing out in works on characteristics of plant modeling, operative data as well as the so important economical one;
- in the operative, appear the related with the HR, for example, blocks of thermal capacity MW, from minimal load to 25, 50, 80 100%. Blocks of *medium HR*, te/MWh and *incremental HR* if considered more convenient for the unit owner.

- in the economical, appear as variable O&M cost, and fungibles, fixed operative cost and of course, the used fuel on each period and the emissions rate for all.

Also between the factors that affect the HR, it is necessary the distinction of *HR annual medium* and *HR marginal optimal* for a group of individual generation, a curve function falling with the load and depending from; their combustion technology, fuel type and quality, operating conditions, maintenance and operative practices, level of recurrent or cycling loads in the year, control technology, manageable therefore with the operating schedule, every day more difficult in markets in competition that rely on the *marginal cost price* MCP of the market in each place.

The HR functions have been modeled in many ways, in some cases as G. R. Drayton [4], with some complexity level, but always starting from the consumption rates of fuel, insisting in the option of continuous functions or values table, mean and marginal, with several pair of HR values capacity from the MT to the MN. In Drayton case are simultaneously contemplated with other variables, for example, the available capacity or remnant still not used by the group for each load and HR. Naturally, many of the utilized values are confidential as the HR and they are so treated under national standards, for example in USA.

Although the HR is a precise figure, there are electric markets analysis models, that represent them of varied form and they could confuse to the non specialist, some times because of models demands, more than for the necessary desirable flexibility in the moment of actual data capture of the groups statistics as studied by J. B. Klein [5]. As examples to remember are.

- I-O Curve, input-output. The starting curve is the of thermal consumption or the HR, for each load level and generating unit, as was said in (1).

- Curve of incremental consumption. The curve of incremental consumption by block of consumption,

$$dHR / dp = b + 2. c. P \qquad (4)$$

In order to compare, the incremental and the mean consumption, could also be calculated from the I-O curve taking two points of the same, x, and following with the previous example of parameters, a, b, c.

$$(y_2 - y_1) / (x_2 - x_1) = a. (x_2 + x_1) + b, \qquad (5)$$

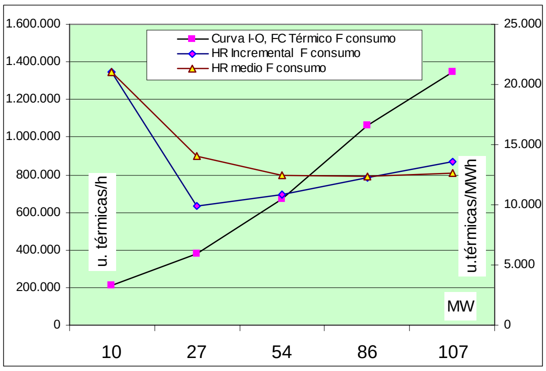
where x1= min. from the block and x2 max. from the same, in MW.

- Curve mean consumption. The consumption curve divided by the load in that point.

$$y / x = (a + b. x + 2.c. x) / x \qquad (6)$$

With the five blocks example, the represented group, with a stepping load from zero or technical minimum, to nominal. The first point of the HR incremental block should not be taken into account or given as valid.

Figure 4. Ej. curves I-O and CE (HR) incremental .



Additionally, it is frequent the construction of curves of actual groups as done by Klein [5] following this process by <u>blocks</u>, as examples of them the curves are similar,

- Consumption I-O group; frequently select a third order equation,

$$y = a x^3 + b x^2 + c x + d \qquad (7)$$

where x = MW production, y = combustible consumption te/hour and, a, b, c, d = group coefficients.

- Incremental consumption instantaneous; would be, the first derivative suitable and as before, the mean incremental consumption, it could be calculated of the I-O curve, dividing the incremental by the corresponding production in MW,

$$(y_2 - y_1) / (x_2 - x_1) = a (x_2^2 + x_2 x_1 + x_1^2) + b (x_2 + x_1) + c \ (8)$$

where: x1 = min. block production and, x2 =max. production on same block.

- Mean consumption; is defined dividing the I-O curve by the MW production. AHR

$$y/x = (a x^3 + b x^2 + c x + d) /x = a x^2 + b x + c + d/x \ \ (9)$$

It is of importance to check error control, between using *means instantaneous values <u>blocks</u>* in front of the *instantaneous HR* used in units dispatch.

Lately, even annalist or brokering entities, not generation units owners, establish their own internal regulation of adequate HR identification, establishing, clear standards; HR incremental, HR in turbines of steam and gas, cost of zero load, etc.

Finally, although could not seem so important to develop HR improvements, it is not so, as indicated in these days by many works, as for example by Hopson W. H. [6], insisting in, much better and clear measurements in order to improve it. Develop improvements also between the units operators, create internal revision committees, assign a HR engineer in charge of it, establish a specialist centralized group for control, install cost-benefit improvement measures and monitor them, create HR experts network, some benchmarks and correlates with the group readiness and good operative practice.

3 RESEARCH ACTIVITY.

The research work started last year at the *Electrical Engineering Area*, at the *Electrical System and Markets Management* line, at the UPMadrid-ETSIMinas, DSE, Energy Systems Dep't. in order to activate the *system generation units knowledge-base-process* improvement. The activities first contribution being systematized relates with a previous units *base-information* process for the –operating- spanish units and some others countries, as technologies references to compare and complete data.

Besides the seen HR models, it is also necessary to ad others units identification functions, as units start and stop, maintenance requirements, *fuel storage* needs or supply, etc. nevertheless in this first approach are out of the scope and postponed those related with environment, externalities, the *variable cost structure* or the effect of the ToP natural gas supply clause.

Also, the *ccgt's* combined cycle *units*, will also be considered, besides their complex HR, because of the increasing importance in the spanish power system.

The task, tries to obtain the *thermal consumption functions* data-base in te/h, as well as the related functions *specific consumption* as simplest base for a classic *economic dispatch*. The approach to obtain the corresponding parameters in their algorithmic form, via minimum square system, or throughout iterative weighted methods applied to data; *experimental* measured according to international recognized standards, in a given date of the unit life, or *statistical historical*, tested by DGESE [7], with corresponding performance output.

3.1 THE HR and ANALYSIS MODELS.

As already commented, the analysis, simulation or optimisation models for the electricity markets are numerous, valuables, even highly necessary today, but in some of them, the emphasis, and some times the development prestige is being made less in the true subject –the thermo-electrical units identity- and more on the used mathematical method and its adequateness for solving the problem, in front of the used for collages. That is because of the higher influence of Calculus Dep't. *-time needs, linearity, informatics' language, number of independent variables, optimisation algorithm, etc-*, in front of *Electro-energetic D*ep't, justifying mainly that, is better to use one or another; dynamic, integer or mixed programming, decomposition, knowledge methods, etc.

All is valuable and necessary, but it should not be forgotten the subject nature, *–part important of it is the electrical generating units identity and behaviour-* and, if for example, the objective is to simulate, a given mix of generation, an annual maintenance plan, emissions, market restrictions, externalities, the fuel availability, rest of the market decisions and possible, at the end, the optimisation *global social cost*, in all the cases would be justified to give a back look to, equipment identity state.

In our case, the generating units *and its representative function* and *scenarios* change, so it is recommended for certain models contributions about the data *input for these models, really the system data –and its evolution- to simulate,* finding a better solution. As an example, in many model algorithms, there are *expressions* using HR,

We cited as an algorithm example, that used by A. Ramos [8] in their model, showing that behind each sumatorio, period of analysis, the fuel HR in the group appear,

$$\sum_{nsp} D_{nsp} \sum_{t=1}^{T} \left[v_t a_t \alpha_{tsp} + v_t b_t p_{tnsp} + v_t c_t p_{tnsp}^2 + u_t p_{tnsp} \right] + \ldots \quad (10)$$

where, vt, cost of the fuel, ansp coupling decision, a_t, b_t, c_t, terms of the thermal consumption function, algorithm similar in case of follow up of fuel stock and mare complex as the natural gas clause TOP, tolls fixed and molecule variable part.

As examples of the different perspective of the HR use in models, it is presented a short view of the three of them, cost, market and simple case.

a) production costs models.
In typical models, HR are offers to the modelists as 'means values -as already indicated- by loads blocks, with levels of 25, 50, 80, 100%, between other incorporate; thermal consumption or I-O curve; blocks of mean HR and or equations of mean HR; block of mean incremental HR. Adding aspects as, group assignment, offer dispatch, marginal & production cost, etc.

Whatever the entrance form is, the calculated HRincre (incremental HR) is necessary in order to determine the unit block dispatch –what block of what unit- is next utilized. The HRmedio is not been usually employed to calculate the production costs, the HRincre are used by models in order to construct groups assignment scenarios for long term.

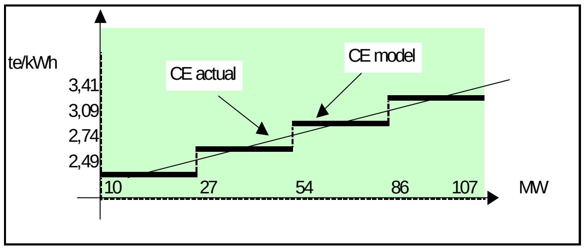


Figure 5. Approach I-O curve thermal consumption.

b) market analysis models .
In this case, to see the effect of the HR it is more complex since in these cases the priority is the offer which is what determines the dispatch, and a little less their operating costs. Would be two forms that require that the offer,
-- is determined by the model outside of and later introduced into their cost,
-- it is determined by the model.

Another relevant parameter is the relationship (R) between HRmedio and HRincre, will be therefore:
The minimal R (x1) and maximum R (x2) ratios, would be for minimal (x1) and maxim (x2) production.

$R (x_1) =$
$= [(a x_1^3+ b x_1^2+ c x_1+ d) / x_1]/ (3a x_1^2+2b x_1+ c)$ (11)
$R (x_2) =$
$= [(a x_2^3+ b x_2^2+ c x_2+ d)/ x_2]/ (3a x_2^2+2b x_2+ c)$ (12)

The mean value is, Rmedio, is gotten integrating R from minimal production (x1) to maxim (x2), and dividing this result for the production difference, [min]. and [max]. $(x_2- x_1)$:

$R\ medio = [ò R dx \{ d x_1 a x_2\}] / (x_2- x_1)$ (13)

Taking an example, with their function, a, b, c, d, and MW of 50 to 739 ; the ratio to prod. minimal: R (50) = 2,91 and to a maxim: R (739) = 1,02 the Rmedio mean = [R (739)- R (50)] / (739- 50) = 1,2596. a growing function R for the group of units.

c) Simple models.
In these models and attempting to approach to emulate competitive market, initially concentrate in the difference in the HR between HRmedio, represented by the market clearing cost MCP, and the CEincre, represented by the marginal cost of the dispatch. So for conventional groups, CT or typical CCGT, after ordering data blocks, would be as represented in the figure.

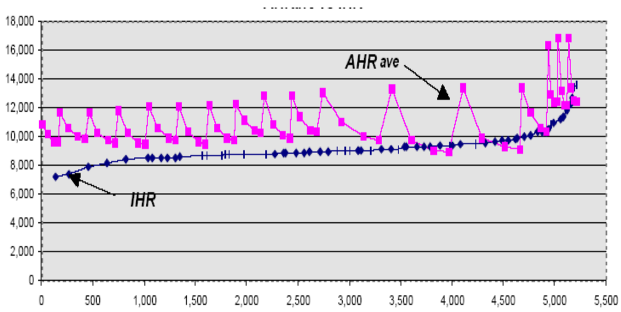


Figure 6. Representation of CEincre and (CEmean)mean.

3.2 The COMBINED CYCLES HR.

The combined cycles are also object of HR modelización, even with increasing interest given their novelty, complexity and less experience in their exploitation, see example on the figures.

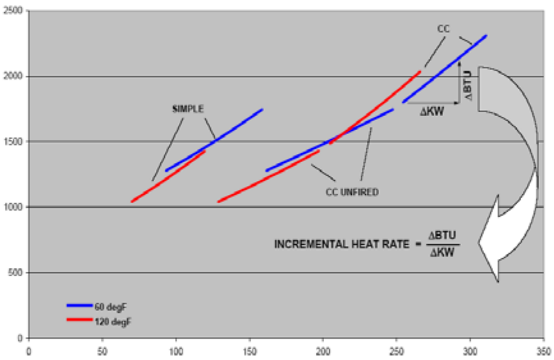


Figure 7. HR thermal consumption c. cycles functions.

Nevertheless today, many ccgt's uses several plant-specific *square-lineal functions* directly got from the units real operation, ad hoc for the of number gas turbine running with the steam turbine. We have deduced preliminary functions from similar consumption, contrasted with some exploitation data but still are so dependent of the involved specific technology. Also the ccgt loss path rate of efficiency each year is a fact known as increase the running hours before maintenance.

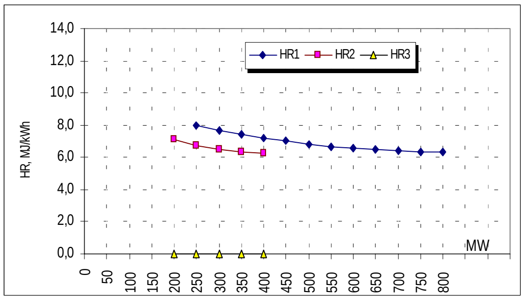


Figure 8. Ccgt's HR thermal consumption approach

Additionally, there have been identified, advances in distribution of HR in this type of units as well as preliminary intents of gas turbines HR algorithms and the global of the ccgt (K means unit capacity, R hrsg efficiency), in front of the more theoretic ones.

HRtv=[(HRx- HRtg) or (Ktg1+ Ktgi.+. .KtgN)+ (HRx or Ktv)]/ Ktv. (14)

$$HR_{cc} = HR_{TG} / \left(1 + \frac{Rcrc}{HRtv}\left(HR_{TG} - 0{,}86\right)\right)$$

4 DATA CAPTURE AND OUTPUTS.

The work is progressing with the tasks for identification, besides the study models, of the thermal consumption functions and the base parameters are of the after type.

Another aspect to revise, it has been the that the maximal and technical minimum capacity, both affect to the HR consumption function, it is understood that they are affected for the age -for the carried out maintenance, their new date of closing, level of utilization, etc-. The value maximal Pmax will be near to the maximum value that repeats a number of considerable hours in comparison with the hours of group operation along the year, (sustainable maximum), and as technical minimum value below the what should not operate and in fact have not operated the unit.

It is early, for concluding results, the tests that have been carried out, with caution could consider that the work is on road of classifying, at least, of coherent form the cited *thermal consumption functions* of the most representative groups of the current technologies, and in the next figures are some of the results.

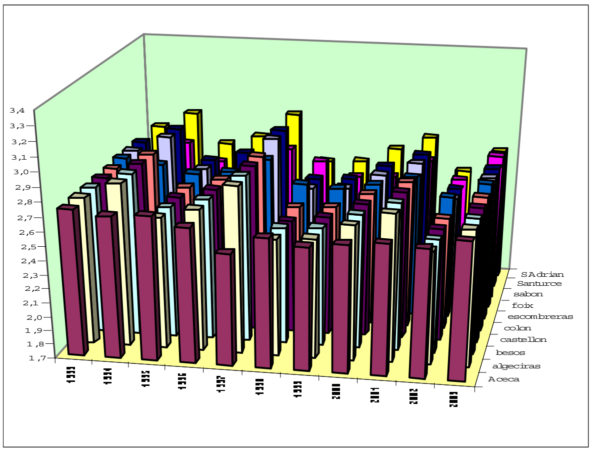


Figure 9. HR thermal consumption evolution of some units.

For example, the HR evolution of *specific consumptions* has not been clear in the last years, in spite of the importance of this in the competition between generators.

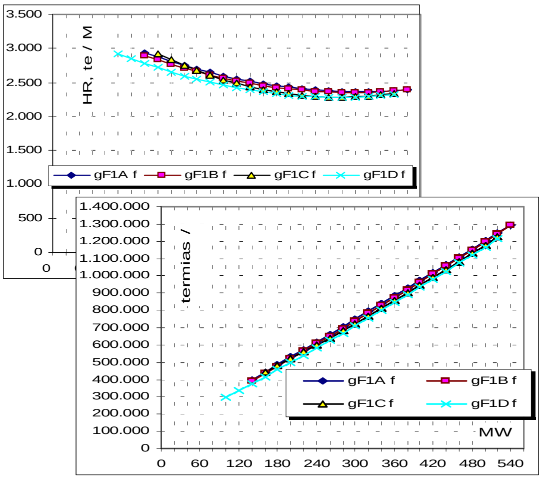


Figure 10. Specific &Thermal consumption functions units.[9]

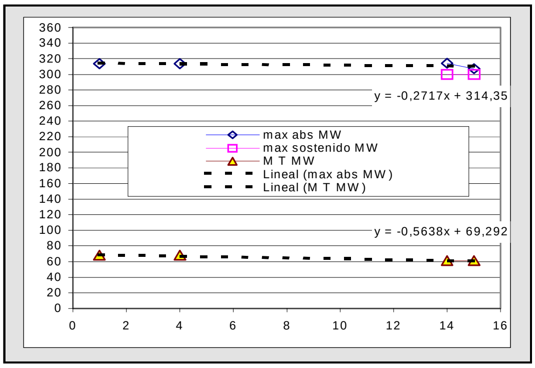


Figure 11. Capacities variation, MT limit and PN in I-O curve.

Other data test done relates to the expected decrease in Hr for units with more annual operating hours, that clarify the point.

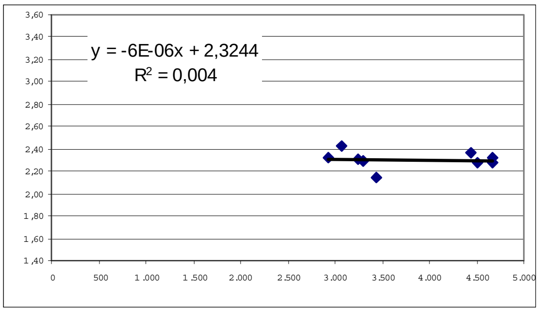


Figure 12. Example for thermal units HR with increasing age.

As a close result, the units *HR, specific consumptions & thermal consumption*, status and evolution in an adequate *data base* is of paramount interest for the industry and market, but also the different approaches about the progress of algorithm models to represent the technologies and benchmark models and practices.

Electricity generators optimise their generation portfolio by running their plants according to their marginal costs, so the HR is there, but today, emissions, and its trading, could increase /reduce some units generation marginal cost and gives the market signal to run other units. In practice, this will change the *unit merit order*, as it does the HR, and additional work have to be done to be dispatched. This first approach of the work do not include ‘CO2 effect’ at present time.

Finally the markets demand some new signals, indicators, etc. referring to the efficiency as the HR evolution for each technology and how to learn from the use of figures for hourly, daily, monthly, annual, but also to the market analysts tries to have figures to compare with, or to investigate future actions or scenarios, as for example the MHR *market heat rate* which it is under preliminary use by some countries for natural gas units, as it is already accepted today the spark spread index.

TABLE I. Thermal consumption examples, 4 units.

Unidad	Pmax	Pmin	a, c2	b, b2	c, a2
	MW br	MW br	te/h	te/MWh	te/MW2h
1A f	542	140	99.450	2.114	0,18
1B f	542	140	100.894	2.042	0,30
1C f	533	160	150.070	1.701	0,71
1D f	533	100	103.819	1.872	0,51

TABLE II. Some *generation agent* units study list.

BES3	0	0	CCGT BESOS 3
BES4	0	0	CCGT BESOS 4
CTN3	0	0	CCGT CASTELLÓN A
SROQ1	0	0	CCGT SAN ROQUE GRUPO 1
SROQ2	0	0	CCGT SAN ROQUE GRUPO 2
STC4	0	0	CCGT SANTURCE
TARRAG	0	0	CCGT TARRAGONA
PALOS1	0	0	PALOS DE LA FRONTERA GRU
PALOS2	0	0	PALOS DE LA FRONTERA GRU
TAPOWER	0	0	TARRAGONA POWER
STC1	0	0	C.T SANTURCE 1
STC2	0	0	C.T SANTURCE 2
ACE1	0	0	C.T. ACECA 1
ACE1	0	0	C.T. ACECA 1
ACE2	0	0	C.T. ACECA 2
ACE2	0	0	C.T. ACECA 2
ESC5	0	0	C.T. ESCOMBRERAS 5
FOI1	0	0	C.T. FOIX
ADR2	0	0	C.T. SAN ADRIAN 2
ADR3	0	0	C.T. SAN ADRIAN 3
ABO1	0	0	C.T. ABOÑO 1
ABO2	0	0	C.T. ABOÑO 2
ALL1	0	0	C.T. ANLLARES
ALL1	0	0	C.T. ANLLARES
COM4	0	0	C.T. COMPOSTILLA II 4

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