Chapter 2
Energy Requirements Estimation Models for Iron and Steel Industry Applied to Electric Steelworks

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Abstract The price of electric energy depends on additional factors since the introduction of renewable energy sources, which has changed the basics of electricity production and the determination of its price. Iron and steel industries strongly require forecasting procedures for the energy amount of their production cycles: today production planning is performed without taking into account that the difference in electricity price between night and day can overcome 500%. The aim of this work is to create a model allowing to estimate energy requirements for steel industry; the model correctness is assessed, for both energy and power analysis, by comparison with real data. A planning tool is employed to provide data to a computer platform able to assess, on the basis of required energy, the best market on which power can be purchased ensuring money saving for the steelworks.

Keywords Computer simulation · Consumption forecasting · Decision support system · Electric power · Energy market · Industrial process optimization Steelworks · Production planning · Production process · Software tool

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S.-I. Ao et al. (eds.), *Transactions on Engineering Technologies*,
https://doi.org/10.1007/978-981-13-2191-7_2

2.1 Introduction

Nowadays, electric grid users are very heterogeneous: from domestic user to second homes, from city lighting to industrial plants of remarkable consumption. Such a differentiated panorama implies the necessity to produce electric energy in the moment in which the same is required; therefore the installed power must be sufficient to satisfy a demand which is not constant with time. In steelworks industry [1, 2], not long time ago, the Companies focus was mainly turned to production process itself, to its control and automation. The success of this focusing is evident, and the quality standards offered by the market, which nowadays are taken for granted, are extremely high, so as applications, which are more and more advanced. In order not to risk the falling of the Occidental industries competitiveness compared to the big Asiatic Companies, it is necessary to become competitive not only on a technological and quality horizon, but also, and above all, to be able to excel in the customer satisfaction field, being able to suit in a repeatable manner, customers requirements in terms of delivery time, building a stable process of Planning, Insertion and Management of the orders. Such system requires firstly a production order and a definition of the status quo; after that, an optimized production planning needs to be implemented to satisfy the orders. It must be taken into account that during production problems may occur that can require an immediate production re-programming. The introduction of a virtual planning, in all the possible problems that can require a production re-programming, allows to assess in a virtual time the plant status; the system is able to process and show the new organization of the production line. At the same time, the system is able to interact in a continuative manner with the energy market basing on plant necessities. In this paper, the Authors propose a planning method for a complex steelworks plant. The proposed method performance is assessed by comparison with real data obtained by measurements on the plant. The analysis involved fully productive days, days with up and down power ramps, non productive days and anomalous days. To provide thorough terms of comparison, the MAPE (mean absolute percentage error), the Least Squares and the ANOVA (analysis of variance) methods were employed.

2.2 The Complexity of the Electric System

The complexity of the inter-relation between demand and offer, imposes an equally complex management of the electric system [3, 4], which can be divided into: (1) Power generation plants: these are characterized by a mix of technologies suitable for satisfying the time-varying behavior of the demand, which appears not only within 24 hours, but also within weeks and in general during the whole year. In order to assure power supply to users, the installed power needs to be 10–15% higher than peak demand power. In fact, other than maximum yearly demand, installed power needs to satisfy the power for programmed or extraordinary events, e.g. maintenance or renovation, failures or natural causes such as the incomplete filling of hydro-electric basins due to rain scarcity. For this reason, a certain number of power plants are kept in operation H24 (e.g. nuclear plants, flowing water plants and modern coal plants, which supply for the base-load), while the plants characterized by a short startup time (e.g. gas turbines, combined cycle plants, reciprocating engines and water basin hydroelectric plants) are employed to satisfy the peak demand.

(2) Transmission grid: this connects power generation plants to the distribution grid and represents the place in which electric energy demand and offer meet. Along the whole chain going from generation to final use, energy losses inevitably occur by Joule effect. Generally electric power is transmitted at high voltage to reduce losses, which increase with increasing distance between generation and use locations.

A transmission grid is composed by:

- three lines, usually overhead, which transport power connecting two electric stations, or an energy immission/withdrawal point;
- electric stations, used both to distribute the power between the lines of a network and for transferring electricity between different voltage networks;
- load rephasing systems;
- switches;
- regulation and control systems.

Electric power transmission grids are structured in a knit way, in order to make available alternative routes in case of breakdown or to share the load on the network.

(3) distribution grid: this brings electricity to the final consumer. The national transmission grid is connected to the distribution grid, which supplies the electricity to the final user with a voltage dependent on the type of use. It is divided into:

- High voltage (HV) grid, ensuring the primary distribution of electric power. This grid includes lines with voltage values between 30 and 150 kV;
- primary cabins, transforming electric power from high voltage to medium voltage;
- Medium voltage (MV) lines, from 1 kV up to 30 kV;
- secondary cabins, transforming electric power from medium to low voltage;
- Low voltage (LV) lines, characterized by voltage values lower than 1 kV;
- Low voltage grid, feeding all domestic users.

The energy produced by the electric system is subdivided into six classes, to account for internal uses and losses:

- Gross production: it represents the sum of the energy produced by all the plants;
- Net production: this represents the gross production minus the generation plants requirements;
- Energy for pumping: this represents the energy required in water basin pumping systems to pump the water from the lower to the higher basin;
- Production intended for consumption: this is net production minus the pumping energy;

- Electric energy required by the grid: this represents the energy production intended for consumption minus the exported energy plus the imported energy;
- Electrical consumption: this represents the energy required by the grid minus the transmission losses.

2.3 The Large Energy Consumers: Steelworks

The production size of electric steelworks is between 1 and 2 million tons per year; the furnaces casting capacity is limited, which imposes a high frequency of casting in modern systems to maintain a high cycle production. Electric-powered steelworks, smaller than the integral cycle ones, allow the construction of plants with an acceptable relationships between investment and production capacity.

Electric ovens are small ovens with a maximum production capacity of 12 tons approximately. Their development and use has in many cases been held back by the cost of energy, which significantly affects the cost of steelmaking.

The melting furnaces with electric heating can be divided into two large categories:

- electric arc furnaces (EAF);
- Induction furnaces.

Induction furnaces with magnetic cores are made of a metallic bath contained in an annular crucible of small cross-section forming the secondary of a transformer whose primary is wound on a frame-shaped iron core, located in a vertical plane. Alternated current is delivered in the primary, so that a low voltage but high intensity current is induced in the metallic bath, warming it by Joule effect. Their application in the iron and steel industry is very limited, while it is more extensive in the field of special metallurgy such as copper and nickel.

Induction furnaces without magnetic core have had a remarkable development for the production of high quality steel, or foundry for the production of cast iron.

In ovens without core, the primary consists of a copper spiral with a tubular section traveled internally by a stream of cooling water and wrapped around a refractory crucible containing the metal bath.

The arc furnace operates through an electrical discharge that melts the metal; to reduce the consumption of the electrode, steelworks have begun to introduce preheated scrap. This type of furnace is formed by a cylindrical crucible with a rounded bottom and whose walls form the vat. The vault covers the vat and, rotating on a peripheral vertical axis, opens the oven allowing to quickly load it from the top through the charging baskets.

The power involved may range from 500 to over 100 000 kVA; the potentiality of the oven is measured by the diameter of the basin. Consumption is in the order of 500–700 kWh per ton of product. Once produced in semi-finished steel, the final desired shape must be impressed. This part of the steelmaking process is common to the two oven types; there are two ways to proceed: casting into ingots and following rolling, or continuous casting.

The competitiveness of such plants is based on the ability to achieve very important economies of scale in terms of production volumes; the optimal production threshold for large steelworks ranges between 5 and 10 million tons per year.

2.4 Steel Manufacturing Plant

The first phase of the Electric Arc Furnace is the loading of the scrap, which usually comes from the demolition of steel structures or process residuals. The scrap is transported above the electric oven through a basket which, by overturning, allows the scrap to be poured inside the vat; here the scrap begins the melting process through the electric arcs that appear between the electrodes and the scrap itself. Once liquid state is reached, pressurized oxygen is blown in the reaction volume, enabling to withdraw undesired chemical elements, such as nitrogen and phosphorus. In this phase, slags are formed, collecting on the top of the metallic bath. When the steel has reached the prescribed value of alloying elements and the ideal temperature for the subsequent treatments, it is poured into the ladle; this is then taken to the Ladle Furnace, in which molten steel is kept in temperature by means of electrodes and is further added with alloying elements. In Fig. 2.1 is represented the Electric Arc Furnace, completed by the various flows of materials and energy and the main auxiliary equipment.

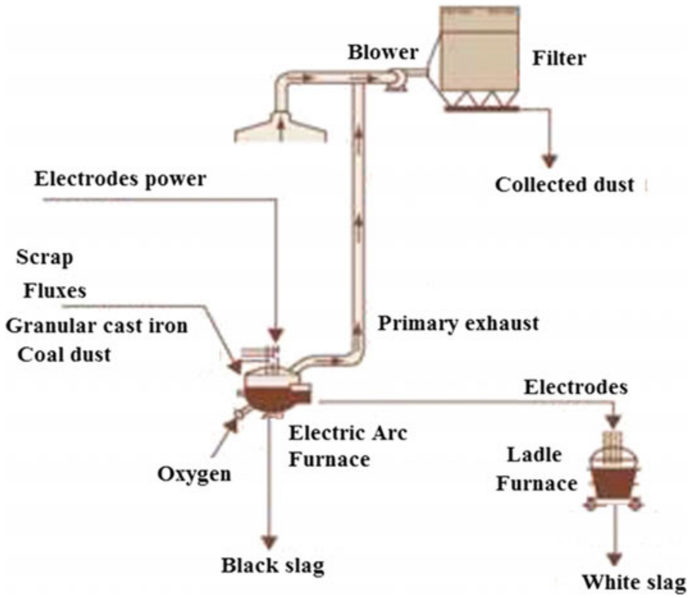

Fig. 2.1 Process of the electric arc furnace

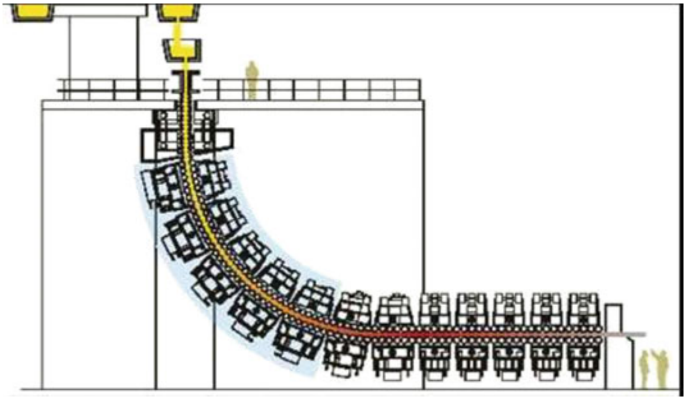

Fig. 2.2 Process of the electric arc furnace

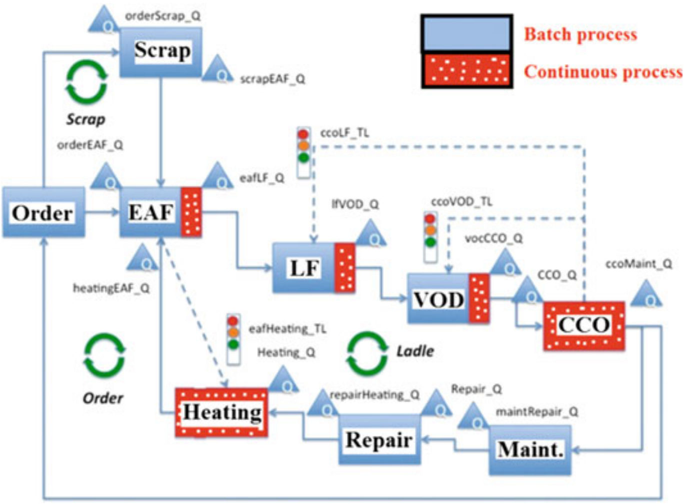

Fig. 2.3 Process scheme of the analyzed steelworks

According to the plant type, steel can then pass directly to a Continuous Casting Machine, assuming different shapes, or be placed in molds, solidified in ingots and then milled. Continuous Casting Machine is an oscillating mold, in which liquid steel is poured assuming the shape impressed by the casting channel. Usually, the mold is constituted by water-cooled copper walls.

The longer is the path made by steel, the longer will be the cooling phase, therefore modern machines are developed along a curved line, as visible in Fig. 2.2.

Figure 2.3 represents the scheme of the operations of the steelworks analyzed in this paper. The processes represented in figure are the following:

- *Order*: arriving orders;
- *Scrap*: scrap warehouse;
- *EAF*: Electric Arc Furnace;
- *LF*: Ladle Furnace;
- *VOD*: degassing treatment;
- *CCO*: Continuous casting;
- *Maint and Repair*: processes of repair and maintenance of the ladles;
- *Heating*: ladles heating process.

Rectangular blocks correspond to the processes, ie the treatments that the initial product undergoes to get the finished product. Triangles represent the queues in input and output of the processes.

Operations in full color (CCO and Heating) are continuous processes, those in dotted color are batch, those with both the colors (EAF, LF, VOD) present both a discrete and a continuous component. Continuous arrows indicate the processes temporal dependencies and order. Traffic lights and dotted arrows, with direction opposite to continue arrows, indicate the functional dependency between processes: the process from which arrow starts commands the process under the traffic light (for example, the EAF regulates the arrival of a ladle from the Heating process). The three green circular arrows identify three types of cycle:

- scrap cycle (Scrap) following the Scrap, EAF, LF, VOD, CCO and Order path;
- order cycle (Order) that follows the route Order, EAF, LF, VOD, CCO;
- ladles cycle (Ladle) that follows the path Heating, EAF, LF, VOD, CCO, Maint. and Repair.

The following Fig. 2.4 provides an overview of the plant studied in this work, highlighting for the mentioned components the hourly capacity of each individual machine.

In Fig. 2.4 is visible the flow scheme of the whole process, including the material flow rates processed by each component. The examined plant provides two production lines; in particular:

- EAF: Electrical Arc Furnace that can work 7 days a week; after that it requires maintenance (these operations take between 8 and 12 hours)
  - EAF A: processing every 75 min with 110t/h capacity;
  - EAF B: processing every 60 min with 150t/h capacity;
- LF: Ladle Furnaces with the same capacity of the EAF of its line; they consume 20 MW;
- CASTER: it is the station where casting starts. The plant has three casters:
  - NNS (Near Net Caster): capacity 100t/h, it mainly supplies billets to Large Section Mill (LSM);
  - B CASTER: capacity between 100 and 160t/h, it supplies billets to Medium Section Mill (MSM);

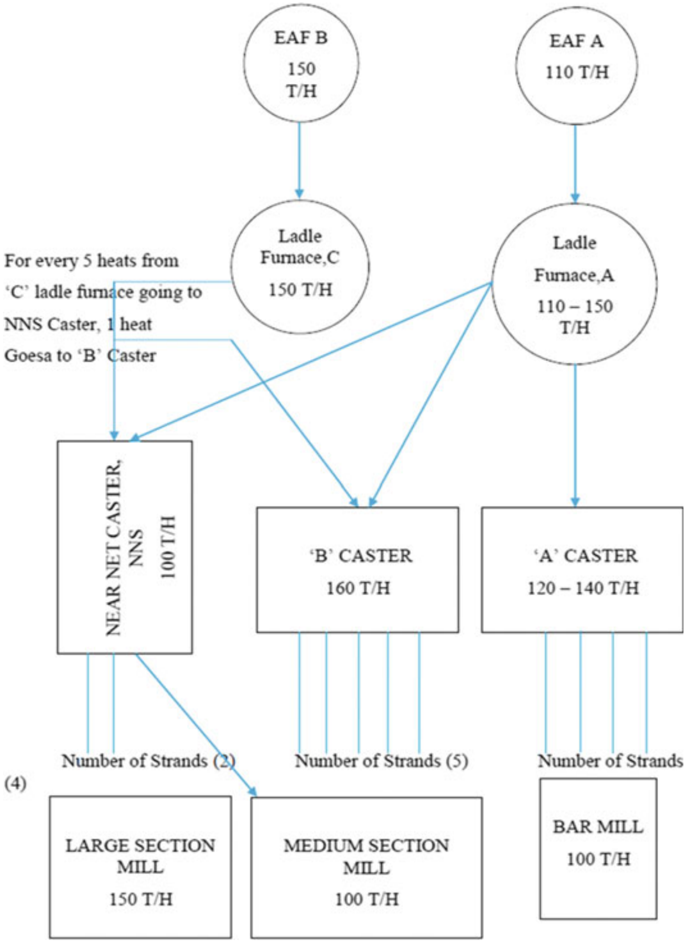

Fig. 2.4 Process flow diagram

- A CASTER: capacity 100t/h, it supplies billets to Bar Section Mill (BSM).

- MILLER: three rolling mills.

2.5 Consumption Data

The steelworks consumptions have been monitored and collected in a data-base for the period between 1/1/2010 and 30/9/2015, excluding the year 2012 for which it was not possible to obtain an exhaustive documentation.

Each day has been divided into 3 shifts (from 9 p.m. of the day before to 4.00 a.m. of the current day, from 5.00 a.m. to 12.00 a.m. of the current day, from 1.00 p.m. to 8.00 p.m. of the current day). The average of hourly required power has been calculated, such as the average of all day. Based on this, can be identified:

- Days of production: if the average of the absorbed power is 21 MW at least;
- Days of ramp down production if: (i) The second half of the first shift, the second shift and the first half of the third are productive; (ii) The day hasnt been classified as productive; (iii) The first half of the third shift, the second half of itself and the first half of the first shift (the one related to the day after) have to be characterized by a ramp down;
- We have a ramp down if:

  1. The second half of the previous shift is productive;
  2. The first half of the next shift is no-productive;
  3. The average of the half under exam is higher than the average of the next half;
  4. The first value of the half under exam is higher than the value associated to the last hour of the same half;
  5. The next half is no-productive.

- Days of ramp up production if

  1. The second half of the first shift, the first half of the second or the second half of the same must be characterized by a rising ramp;
  2. The second half of the second shift have to be productive just like all the third shift and the first half of the first shift (the one connected to the next day);
  3. The day must not have already been classified as fully productive.

- We have a ramp up if:

  1. the second half of the previous shift is non-productive;
  2. the first half of the next shift is productive;
  3. the average of the half in question is less than average of the later half;
  4. the first value of the half under examination, corresponds to the first hour of the same, is less than the value associated with the last hour of the same half;
  5. the half later is productive.

- Days are classified as no-production if:

  1. the first half and the second half of the first shift are not productive;
  2. the second and the third shift are not productive;
  3. the day hasn't been categorized as productive with one of the two ramps.

- Abnormal days: any day does not fit into any of the classes above described.

Each of the 1732 days analyzed has been assigned to the category with the following result:

- 336 whole days production;
- 523 no-productive days;
- 81 productive days characterized by ramp down;
- 88 productive days characterized by ramp;
- 704 abnormal days.

2.6 Construction of Production Profiles Based on Planning

In this section will be described the steps to create a simplified ideal production profile basing on which it is possible to organize and manage the purchase of electric energy, avoiding to buy useless energy in those days in which the plant is stopped or only partially operative.

An optimized production plan, based on times that each machine uses for fulfilling its task, was implemented. In particular, in the following are described the processing times for a complete production process.

EAF: 60 min; Transport between EAF and LF: 5 min; LF: 40 min; Transport between LF and CCO/VD: 5 min; Degassing (VOD): 20 min; Continuous casting (CCO): 40 min. The last two processes were considered as one for simplicity, creating a unique process CCO/VOD lasting 60 min.

The last two processes were considered as one for simplicity, creating a unique process CCO/VOD lasting 60 min.

For each of the three equipments, a chart was built (Fig. 2.5), showing the absorbed MW (y axis) in function of time (x axis); the equipment consumptions are estimated in 50 MW for EAF, 20 MW for LF and 1 MW per both degassing and CCO.

Planning begins from zero-day and the first process of each equipment doesnt consider the time interval needed to reach the processing temperature.

To optimize working time, in both the lines of the plant the second casting starts when the first semi-finished piece is exiting from the ladle furnace (LF) (gap time of 5 min) in order to avoid delays which would turn into costs for missed production.

The treatment in ladle furnaces LF-A and LF-B lasts for 40 min, after which billets are transported, in a 5 min time, to degassing machine. Degassing treatment lasts 20 min, downstream of which there is the continuous casting plant which terminates its work after 40 min.

Reporting on a single diagram the power required by all the three components (EAF, LF and CCO/VOD) in order to complete a production phase, in the ideal case of considering the temperature ramps instantaneous (zero startup time), to transform a whole steel batch into finished product, and overlapping of three of these optimized power diagrams, opportunely shifted in time one each other, the diagram in Fig. 2.5 is obtained.

Summing in function of time the power values and considering a base-load power for auxiliaries equal to 5 MW, the diagram of the total absorbed power is obtained, as visible in Fig. 2.6.

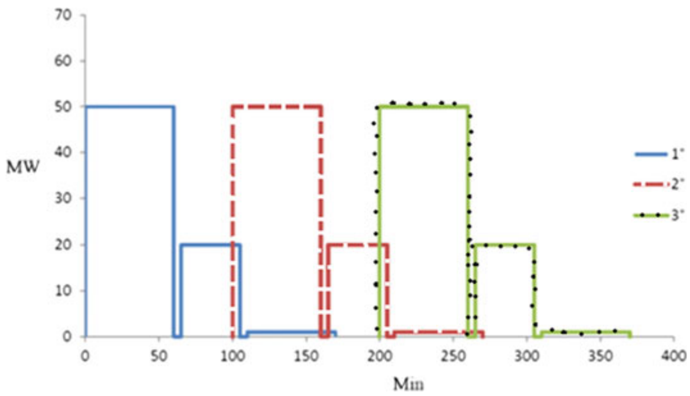

Fig. 2.5 Three cycles in series

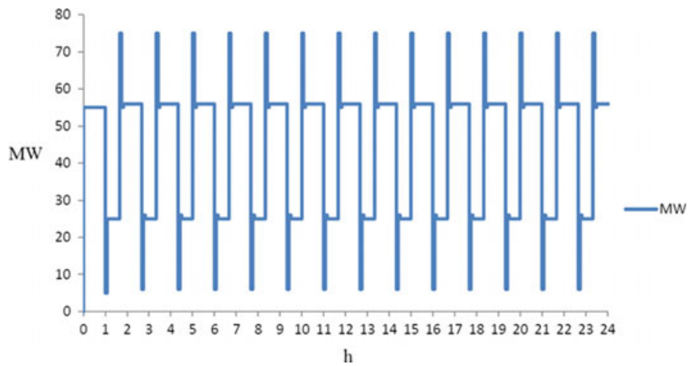

Fig. 2.6 Total absorbed power

From this diagram it is possible to estimate the energy amount required for each hour of plant operation, as visible in Fig. 2.7.

2.6.1 MAPE

The MAPE (Mean Absolute Percentage Error) is defined as: (Expected Value-Real Value)/Real Value. Such value was calculated for all the days typologies above described, both for energy and for power values, obtaining the following results:

- production days: 27,2% (energy) and 32% (power);
- no-production days: 76,7% (energy) and 84% (power);
- production days with ramp up: 12,7% (energy) and 13% (power);
- production days with ramp down: 80,4% (energy) and 81% (power);
- anomalous days: 38% (energy) and 76% (power).

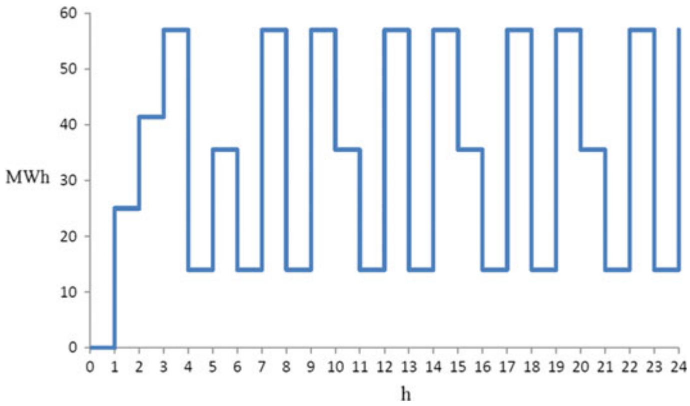

Fig. 2.7 Energy consumed in each hour of plant operation

It is an optimization technique that allows to determine the linear function that minimizes the sum of squares of distances between data. The general formula of the straight line is: $y = mx + q$, where y in this case is the actual plant data, x is the planning data. The parameters m and q are found by fitting the data by using least squares. Also in this case the analysis is carried out for all the five day typologies.

It was first calculated the hourly average of relative power errors for the days from which were determined:

- Average Error: the average of the power errors;
- Error^2: square of all the related errors;
- Average Error^2: the average of the values just above;
- Average Hours: the average of the twenty four hours per day;
- AverageHours^2: the average of the squares of hours;
- Error*Hour: the product of the errors and their hours;
- Average (Err*Hour): the average of the 24 values calculated above.

The coefficient m is given by:

$$m = \frac{(x \cdot y)^* - x^* \cdot y^*}{(x^2)^* - (x^*)^2} \quad (2.1)$$

where

$(x \cdot y)^*$: it is the average of the product of the actual data for the ideal ones;
x^* : it is the average oh the ideal data;
y^* : the average of real data;
$(x^2)^*$: it is the average of the square of the ideal data;
$(x^*)^2$: it is the square of the average of the real data.

The known term q is given by $q = ymx$. The calculation of the correlation coefficient (CP), also called Pearson coefficient, gives us an indication on the goodness of our approximation: its range is [−1, +1], more its value tends to 1, better was the approximation.

$$CP = \frac{(x \cdot y)^* - x^* \cdot y^*}{\sqrt{[(x^2)^* - (x^*)^2] - [(y^2)^* - (y^*)^2]}} \tag{2.2}$$

As for the power analysis:

- For productive days CP is 0,1167
- For no-productive days CP = 0,066
- For abnormal days CP = 0,7670
- For productive days with ramp CP is 0,739
- For productive days with ramp down CP = 0,33.

As regards the energy analysis is obtained:

- For productive days CP = −4,5E−02
- For no-productive days CP = 6,9E−02
- For abnormal days CP = 7E−02
- For productive days with ramp CP = 1E−02
- For productive days with ramp down CP = 3E−02.

2.6.2 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a collection of statistical models used to analyze the differences among group means and their associated procedures. It is based on the test null hypothesis: H0 = the average of different populations are the same; indicating with 1, 2, 3 the average dimensions of populations, the null hypothesis can be written as H0: 1 = 2 = 3 = = k. Once we have gathered data, the solidity of the null hypothesis can be gauged. The variability measured between k average (on groups) are compared to variability on each population (in groups). The comparison between variance on groups and variance in groups gives F-value: low F-value means that H0 is true, high F-value means that H0 is false. In this context, the P-value is defined as the probability that the observed data come from the null hypothesis or from the alternative hypothesis. In particular, high P-values favor the null hypothesis, while low P-values are against the null hypothesis. The P-values calculated for the different day typologies are presented in the following:

For productive days: 6,85E−73

- For no-productive days: 1,05E−50
- For abnormal days: 1,24E−271
- For productive days with ramp: 1,55E−06
- For productive days with ramp down: 1,91E−34

Such small values are an evidence against the null hypothesis, but relative errors are not classifiable, thus it is not possible to establish their nature by means of this analysis [5].

2.7 Electric Market

2.7.1 Market Structure

Since 2005, the spot energy market has been divided into Day-ahead market (MGP), intraday market (MI), adjustment market (MA) and the market for ancillary services (MSD).

1. The day-ahead market presents an auction system where both bidders and buyers take part; bids are characterized by quantity and unit price for energy, the purpose of this market is to point out the possibility to sell and/or to buy energy not at a lower price than the one that has been proposed. GME (Electric Market Manager) arranges bids and purchase offers and it draws two graphs: (i) The sale curve: bids are ordered by descending price. (ii) The purchase curve: purchases offers are ordered by descending price.
   The intersection of the two curves (point P*) defines how much energy can be ex-changed, the reached price, the approved offers and injection and withdrawal pro-grams. The selling price of the accepted offers is not higher than P* and the purchase price is not lower than P*.
2. The intraday markets (MI). Also these markets are managed by GME. The price calculation and the method of acceptance are the same as MGP. MI is divided into 4 submarkets (MI 1 to MI 4) according to the opening hour.
3. Adjustment market (MA). It opens at 10.30 after communication of the results of MGP, it have to allow operators to modify programs that have been determined after results of MGP; they can make new bids and it closes at 14.00.
4. The market for ancillary services (MSD). It opens at 14.30 after results of MA and it closes at 16.00.

2.7.2 Software Tool for Energy Purchase on the Market

To complete the optimization tool for steelworks, a software able to forecast energy price in the market based on energy price historical data was implemented. It provides a support system to decisions (Decision Support System) for managers and all people who must make strategic decisions and has the purpose of allowing to extract in a short time and in a flexible way, by large size data, the information needed to support and effectively improve the process decision.

The developed software platform uses two types of values: on the one hand the forecasts of market prices, on the other the simulation data of the plant. Both of these data must be estimated on purpose: in particular the expected consumption of the plants are generated with the aid of the simulator, energy prices are processed using statistical methods starting from previous market outcomes. The platform incorporates the simulator and after receiving the production orders, generates the simulation.

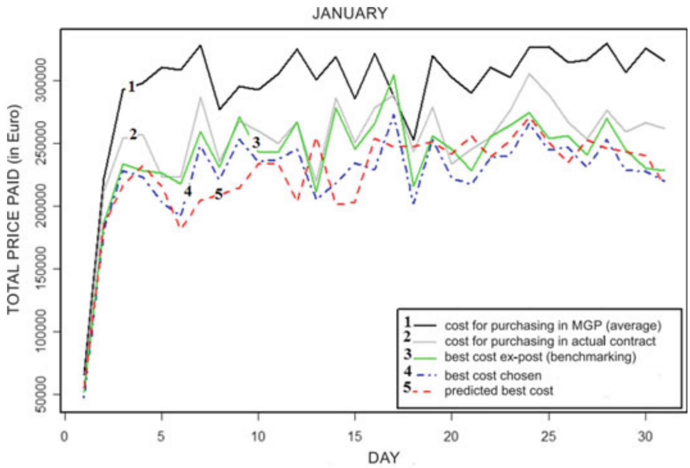

Fig. 2.8 Comparison diagram for energy purchase decision making

Once the hypothetical hourly consumption is acquired, these are crossed with the price forecast generated by a SARIMA model: it is a combinatorial calculation, so there will be a huge number of possible scenarios; therefore, they are filtered, and only the most significant ones will be kept. The first will be to buy at the price of contract, although in reality each contract provides a variable unitary price in function of the power delivered in the hour and based on the number of power peaks that overcome the limit. Five other scenarios are those of purchasing the whole energy required in the corresponding five markets of the Electricity Exchange. The most important scenario is the one with the best expected prices; for each hour the tool selects the most advantageous market, indicating the offer price and on which market the purchase should be made.

Starting from the production Gantt diagram, the total consumption in MWh is determined for each hour, and such data are crossed with the forecasted market price. The result of the forecast of the purchase scenarios is given in the form of bar chart (see Fig. 2.8), in which the total purchase price is shown so as the total energy price and the different mix of purchase markets. In Fig. 2.8 is visible the graphical interface that helps the user to make decisions about the possible power buying options, this model was implemented using Systems Dynamics formalism based approach tested by Authors in many applications [6]. Each bar of the diagram shows the total price of energy if we act on markets in different way; referring to the graph in Fig. 2.8:

- Plot 1: all the energy is purchased at MGP.
- Plot 2: all the energy is purchased at the current contract.
- Plot 3: all the energy is at the best market price (MGP, MI 1, MI 2, MI 3, MI 4),

i.e. benchmarking.
- Plot 4: purchase price suggested by the tool.
- Plot 5: predicted best cost.

2.8 Conclusions

This paper presented a planning methodology for a steelworks production. The methodology efficacy was tested by comparison with real power and energy data collected from an operative plant in a long observation time. The comparison between real data and planning was carried out by three mathematical methods, whose main results are summarized in the following.

1. For the MAPE method is:
   - Acceptable for productive day and productive days with ramp up (for both energetic and power analysis)
   - Not acceptable for no-productive days and productive days with ramp down both for energetic and power analysis.
2. For least squares:
   - Acceptable for productive days with ramp and abnormal days for power analysis
   - Non acceptable for no-productive days for power analysis and for all 5 types for energetic analysis.
3. Analysis of Variance:
   - Errors are determined by events, so it is not possible to classify with this analysis.

Finally, using the proposed methodology with a market analysis tool is was possible to obtain significant savings on energy purchase.

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