

# Energy efficiency technologies in cement and steel industry

Silvia Maria Zanolì<sup>1,3</sup>, Francesco Cocchioni<sup>2</sup> and Crescenzo Pepe<sup>2</sup>

<sup>1</sup> DII, Università Politecnica delle Marche, Ancona (AN), Italy

<sup>2</sup> i.Process S.r.l., Falconara M.ma (AN), Italy

<sup>3</sup> s.zanolì@univpm.it

**Abstract.** In this paper, Advanced Process Control strategies aimed at energy efficiency achievement and improvement in cement and steel industry are proposed. A flexible and smart control structure constituted by several functional modules and blocks has been developed. The designed control strategy is based on Model Predictive Control techniques, formulated on linear models. Two industrial control solutions have been developed, oriented to energy efficiency and process control improvement in cement industry clinker rotary kilns (clinker production phase) and in steel industry billets reheating furnaces. Tailored customization procedures for the design of ad hoc control systems have been executed, based on the specific needs and specifications of the analysed processes. The installation of the developed controllers on cement and steel plants produced significant benefits in terms of process control which resulted in working closer to the imposed operating limits. With respect to the previous control systems, based on local controllers and/or operators manual conduction, more profitable configurations of the crucial process variables have been provided.

## 1. Introduction

Cement and steel industries require high energy amounts for the conduction of the involved process phases. Complex chemical, physical and thermodynamical reactions characterize these phases: multivariable subsystems, delayed responses and large nonlinearities represent some examples of typical features of cement and steel processes [1, 2]. Among the different processes phases, a great relevance is detained by the clinker production phase in cement industry and by the reheating phase in steel industry. These steps are crucial from an energy efficiency and product quality point of view: clinker represents the main cement component while the steel industry reheating phase is fundamental for a correct semi-finished products reheating [3-5].

Nowadays, in many cement and steel industries, single sub-processes are piloted through local standalone controllers and/or operators manual conduction based on their skills and experience. Due to the difficulties caused by the complex processes nature, these solutions often neglect the requirements more strictly related to energy saving and environmental impact decreasing. Significant energy efficiency margins can be evaluated through preliminary benefit studies. Advanced Process Control (APC) solutions can be adopted for the improvement of processes control aimed at a major processes optimization. In [6], advantages of APC solutions for refining and chemical/petrochemical industries are discussed, while in [7] a state-of-the-art of APC economics benefits is presented. Among the most effective APC techniques, Model Predictive Control (MPC) represents a widely used control strategy, due to its certifiable high performances in the management of constrained multivariable processes [8].

In this paper, two industrial control solutions are described, both including an MPC control strategy based on linear models: the first is tailored to cement industry clinker production phases (rotary kilns)



while the second represents an ad hoc solution for steel industry billets reheating furnaces. The two industrial products, denoted “i.Process | Cement” and “i.Process | Steel – RHF”, respectively, share a common basic APC technology based on two-layer linear MPC strategy and based on cooperation policies between the different functional modules and blocks. “i.Process | Steel – RHF” has been patented [9]; both controllers have been installed on different European steel and cement plants, providing major benefits with respect to previous control solutions, in terms of more profitable trade-offs between energy saving, emissions reduction, product quality improvement, and production maximization.

The paper is organized as follows: section 2 presents a description of the considered processes; two Italian case studies are proposed. Section 3 describes the basic APC framework together with examples of customization procedures within “i.Process | Cement” and “i.Process | Steel – RHF” industrial solutions for the proposed case studies. Section 4 depicts process control and energy saving results related to the field applications while conclusions are summarized in section 5.

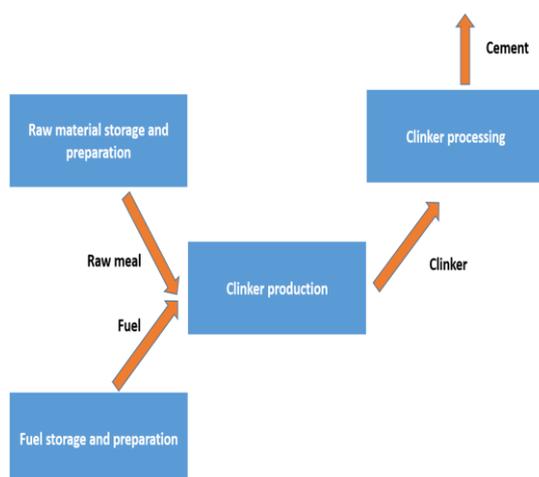
## 2. Cement and steel industry case studies description

This section gives a detailed description of the considered Italian industrial processes, i.e. the cement industries clinker production phase and the steel industry billets reheating phase. Moreover, the control requirements, the selected APC process variables and the modelling phase are summarized.

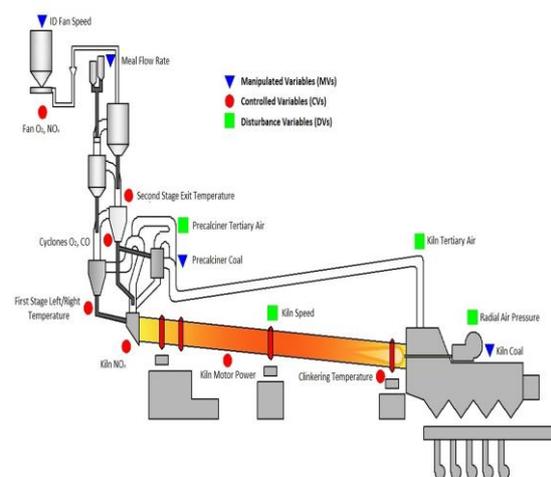
### 2.1. Cement industry clinker production phase

Figure 1 summarizes the main phases of a dry process cement production: raw materials are processed in order to obtain raw meal; raw meal is thus exploited for the production of the main component of the cement, called clinker. The clinker production phase is schematically represented in figure 2.

The clinker production phase is triggered by raw meal that is subjected to a baking procedure within a rotary kiln (figure 2, right side). Before the kiln inlet, raw meal is involved in different phases. Firstly, raw meal is fed into a four-stage cyclone suspension pre-heater (figure 2, the “tower” on the left side) where it is preheated and dried (temperature range: about 650 [°C] – 900 [°C]). In this phase also exhaust gas acts which is pulled by an induced draft (ID) fan. In the considered case study, combustion reactions inside the rotary kiln are triggered by two air/fuel burners, located near the furnace outlet (kiln burner) and near the furnace inlet (precalciner burner), respectively. At the exit of the rotary kiln, a cooler decreases the clinker temperature for the next process phases.



**Figure 1.** General cement industry workflow.



**Figure 2.** Clinker production phase.

In the previous process management, raw meal ([t/h]), kiln coal ([kg/h]), precalciner coal ([kg/h]) and ID fan speed ([rpm]) were the main control inputs manipulated by plant operators; they were usually manipulating these variables in order to correctly drive the crucial measured process variables

of the clinker production. Temperatures ( $[^{\circ}\text{C}]$ ), oxygen, carbon monoxide and clinker free lime concentrations ( $[\%]$ ), and nitrogen oxides levels ( $[\text{ppm}]$ ) are examples of these controlled variables (figure 2, Controlled Variables (CVs)). In addition, plant operators were keeping into account the control effect of additional input process variables: rotation kiln speed  $[\text{rpm}]$ , kiln tertiary air  $[\%]$ , precalciner tertiary air  $[\%]$ , and radial air pressure  $[\text{mbar}]$ .

*2.1.1. “i.Process | Cement” APC system setup.* In order to set up “i.Process | Cement” APC system, the same CVs previously listed for the manual conduction have been selected (figure 2). In the Manipulated Variables (MVs) group, raw meal, kiln coal, precalciner coal and ID fan speed have been included. Finally, rotation kiln speed, kiln tertiary air, precalciner tertiary air and radial air pressure have been included as DVs. Through identification procedures, linear time invariant asymptotically stable strictly proper minimum phase models with delays have been obtained for the controller design.

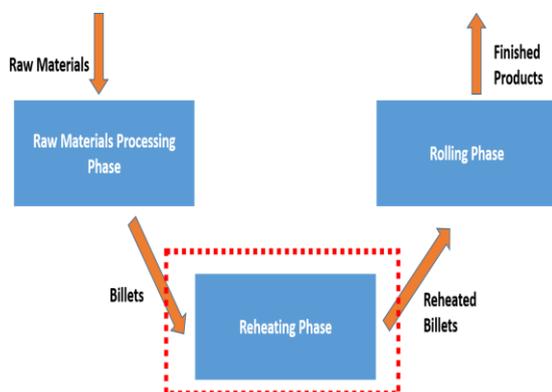
## 2.2. Steel industry billets reheating furnace

Figure 3 summarizes the main phases of the steel production: from raw materials, semi-finished products (billets in the proposed case study) are obtained; billets are reheated in a furnace in order to reach the needed temperatures for the subsequent rolling phase that is performed by rolling stands. “i.Process | Steel – RHF” APC system is focused on the reheating phase: a specific synoptic of the developed GUI (Graphical User Interface) is represented in figure 4.

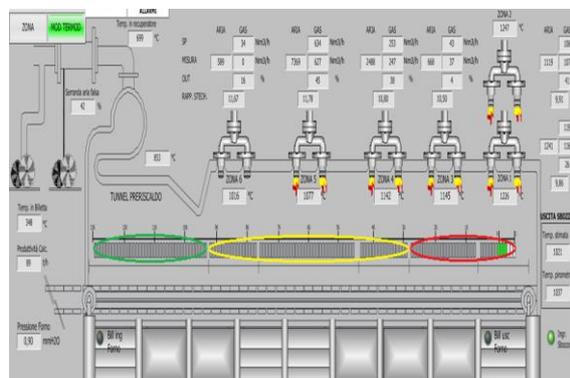
In the initial part of their path along the considered pusher type reheating furnace (movement performed by pushers according to the defined furnace production rate; maximum billets capacity: 136), billets are preheated (figure 4, “green area”: tunnel); then they are moved toward the reheating area (figure 4, “yellow area”: zone 6, zone 5, zone 4) and finally they exit the furnace from the soaking area (figure 4, “red area”: zone 3 and vertical disposition of zone 2 and zone 1). Billets can be entered in the furnace at different temperatures and the outlet specifications can vary based on the subsequent rolling phase requirements. Air/fuel burners trigger combustion reactions: a set of burners is located in each furnace zone (excluding tunnel); zone temperatures are measured by suitable thermocouples and optical pyrometers detect billets temperature at the furnace inlet and outlet.

The previous furnace management was based on local PID temperature controllers and their set-points were suitably regulated by plant operators. Plant operators were guaranteeing a correct billets reheating profile taking into account the current furnace production rate.

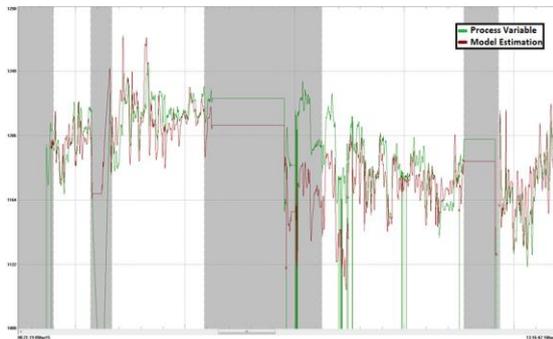
*2.2.1. “i.Process | Steel – RHF” APC system setup.* In order to set up “i.Process | Steel – RHF” APC system, two groups of CVs have been defined: zones Controlled Variables (zCVs) and billets temperature (bCVs,  $[^{\circ}\text{C}]$ ). The fuel flow rate ( $[\text{Nm}^3/\text{h}]$ ) and the stoichiometric ratio of each furnace zone equipped with a burners set have been selected as MVs. In DVs group, furnace production rate ( $[\text{t}/\text{h}]$ ), furnace pressure ( $[\text{mmH}_2\text{O}]$ ) and air pressure ( $[\text{mbar}]$ ) have been included. In the zCVs group,



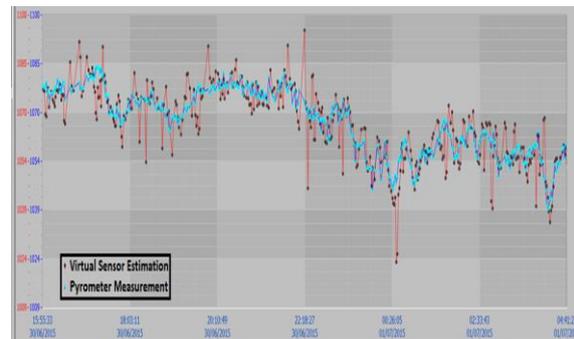
**Figure 3.** General steel industry workflow.



**Figure 4.** Billets reheating phase.



**Figure 5.** Zone 1 temperature model performances.



**Figure 6.** Virtual sensor model performances.

among other furnace process variables, zone temperatures have been introduced. In order to replace the local temperature controllers, zCVs-MVs/DVs models have been developed based on black-box identification procedures: linear time invariant asymptotically stable strictly proper minimum phase models without delays have been formulated. In figure 5, zone 1 temperature model predictions (red line) are compared to the sensors measurements (green line).

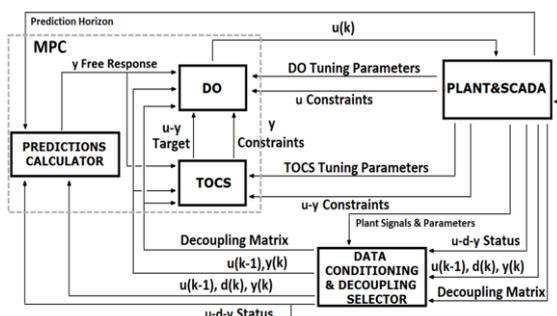
It has to be emphasized that billets temperature measurements within the furnace were not available; in order to obtain an estimation of the entire billets reheating profile, a virtual sensor has been developed. Nonlinear first principles adaptive relationships have been formulated; the model inputs consist on the first five zone temperatures (tunnel and zones 6, 5, 4, and 3) and on the mean of the last two (vertically disposed) zone temperatures (zones 2 and 1) [9]. Figure 6 shows an example of the virtual sensor model performances (red line) when compared to the pyrometer measurements in the rolling area (blue line). In order to take advantage of the estimated billets temperature (bCVs) within “i.Process | Steel – RHF” APC system framework, the virtual sensor model has been linearized and suitably cascaded with the formulated zCVs-MVs/DVs linear models.

### 3. “i.Process | Cement” and “i.Process | Steel – RHF” APC systems technology

This section reports details on the basic APC framework together with examples of customization procedures within “i.Process | Cement” and “i.Process | Steel – RHF” industrial solutions for the proposed case studies.

#### 3.1. A sketch of the basic APC architecture

Figure 7 shows the scheme of the basic APC framework architecture. A Supervisory Control and Data Acquisition (SCADA) system provides the needed parameters, e.g. updated MVs ( $u$ ), DVs ( $d$ ) and CVs ( $y$ ) plant measurements. *Data Conditioning & Decoupling Selector (DC&DS)* block processes field data, eventually performing bad detection procedures and data conditioning.



**Figure 7.** Basic APC architecture.

VARIABLES MANIPOLATE															
ABILITAZIONE	STATUS	TAG	DESCRIZIONE	EV	LOW	HIGH	MIN	MAX	TARGET	PREL	MODA	RESP	DEVI	BUSCA	BUSCA
ON	OFF	PCL_MCR_F1	Portata forno Schmelz 2	ON	10.00	120.00	10.00	120.00	10.00	10.00	10.00	10.00	10.00	●	●
ON	OFF	PCL_MCR_F2	Portata forno Schmelz 1	ON	10.00	120.00	10.00	120.00	10.00	10.00	10.00	10.00	10.00	●	●
ON	OFF	PCL_MCR_F3	Portata polverino Indica	High	300	300.0	400	400.0	400.0	400.00	400.00	400.00	400.00	●	●
ON	OFF	PCL_MCR_F4	Portata polverino precalcinatore	High	300	300.0	400	400.0	400.0	400.00	400.00	400.00	400.00	●	●
ON	OFF	PCL_MCR_S1	Gas caudante forno	Low	80.0	870.0	80.0	870.0	87.0	87.0	87.000	87.000	87.000	●	●

VARIABLES CONTROLLATE PRINCIPALI																
ABILITAZIONE	STATUS	TAG	DESCRIZIONE	EV	LOW	HIGH	MIN	MAX	PRESIDIO	TARGET	PREL	MODA	RESP	DEVI	BUSCA	BUSCA
ON	OFF	PCL_SDA_AL_02	Calore di zona	%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	●	●
ON	OFF	PCL_SDA_AL_02	Calore affollatore	%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	●	●
ON	OFF	PCL_SDA_ML_02	NCl di forno	Ann	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	●	●
ON	OFF	PCL_SDA_AL_02	NCl affollatore	Ann	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	●	●
ON	ON	PCL_SDA_AL_02	Cl in forno	%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	●	●
ON	OFF	PCL_TDR1A	Temp. 1° stadio del forno	°C	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	●	●
ON	OFF	PCL_TDR1A	Temp. 1° stadio del forno	°C	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	●	●
ON	OFF	PCL_TDR1A	Temp. 2° stadio del forno	°C	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	●	●
ON	OFF	PCL_TDR1A	Temp. 3° stadio del forno	°C	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	●	●
ON	OFF	PCL_MCR_S1	Pressione motore forno	bar	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	●	●
ON	OFF	PCL_T0	Temp. di bilanciamento	°C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	●	●

**Figure 8.** APC GUI page example.

*DC&DS* block, through an interactive Graphical User Interface (GUI) (see figure 8), determines the subset of process variables to be included in the control problem at each control instant (definition of a status value for each MV, DV and CV). All the information is forwarded to the *MPC* block, constituted by two layers that strictly cooperate and that are supported by a *Predictions Calculator* module [10, 11]. The overall MPC strategy is based on a *receding horizon* strategy [8]. The upper layer, denoted *Targets Optimizing and Constraints Softening (TOCS)*, computes the steady-state optimal configuration of MVs and CVs, solving a Linear Programming (LP) problem. A linear cost function is minimized, subject to linear constraints:

$$V_{TOCS}(k) = c_u^T \cdot \Delta \hat{u}_{TOCS}(k) + \rho_{y_{TOCS}}^T \cdot \varepsilon_{y_{TOCS}}(k) \quad (1)$$

subject to

$$\begin{aligned} \text{i.} \quad & lb_{du_{TOCS}} \leq \Delta \hat{u}_{TOCS}(k) \leq ub_{du_{TOCS}} \\ \text{ii.} \quad & lb_{u_{TOCS}} \leq \hat{u}_{TOCS}(k) \leq ub_{u_{TOCS}} \\ \text{iii.} \quad & lb_{y_{TOCS}} - \gamma_{lby_{TOCS}} \cdot \varepsilon_{y_{TOCS}}(k) \leq \hat{y}_{TOCS}(k) \leq ub_{y_{TOCS}} + \gamma_{uby_{TOCS}} \cdot \varepsilon_{y_{TOCS}}(k) \\ \text{iv.} \quad & \varepsilon_{y_{TOCS}}(k) \geq 0 \end{aligned} \quad (2)$$

The computed steady-state optimal configuration (targets and constraints) is then supplied to the *MPC* lower layer, denoted *Dynamic Optimizer (DO)* module. This module computes  $u(k)$ , i.e. the MVs value that has to be sent to the plant (see figure 7). The *DO* is based on the minimization of a quadratic cost function, subject to linear constraints:

$$V_{DO}(k) = \sum_{i=1}^{H_p} \|\hat{u}(k+i-1|k) - u_t(k+i-1|k)\|_{S(i)}^2 + \sum_{i=1}^{H_u} \|\Delta \hat{u}(k+M_i|k)\|_{R(i)}^2 + \sum_{i=1}^{H_p} \|\hat{y}(k+i|k) - y_t(k+i|k)\|_{Q(i)}^2 + \|\varepsilon_{y_{DO}}(k)\|_{\rho_{y_{DO}}}^2 \quad (3)$$

subject to

$$\begin{aligned} \text{i.} \quad & lb_{du_{DO}}(i) \leq \Delta \hat{u}(k+M_i|k) \leq ub_{du_{DO}}(i), \quad i = 1, \dots, H_u \\ \text{ii.} \quad & lb_{u_{DO}}(i) \leq \hat{u}(k+M_i|k) \leq ub_{u_{DO}}(i), \quad i = 1, \dots, H_u \\ \text{iii.} \quad & lb_{y_{DO}}(i) - \gamma_{lby_{DO}}(i) \cdot \varepsilon_{y_{DO}}(k) \leq \hat{y}(k+i|k) \leq ub_{uby_{DO}}(i) + \gamma_{uby_{DO}}(i) \cdot \varepsilon_{y_{DO}}(k), \\ & \quad \quad \quad i = 1, \dots, H_p \\ \text{iv.} \quad & \varepsilon_{y_{DO}}(k) \geq 0 \end{aligned} \quad (4)$$

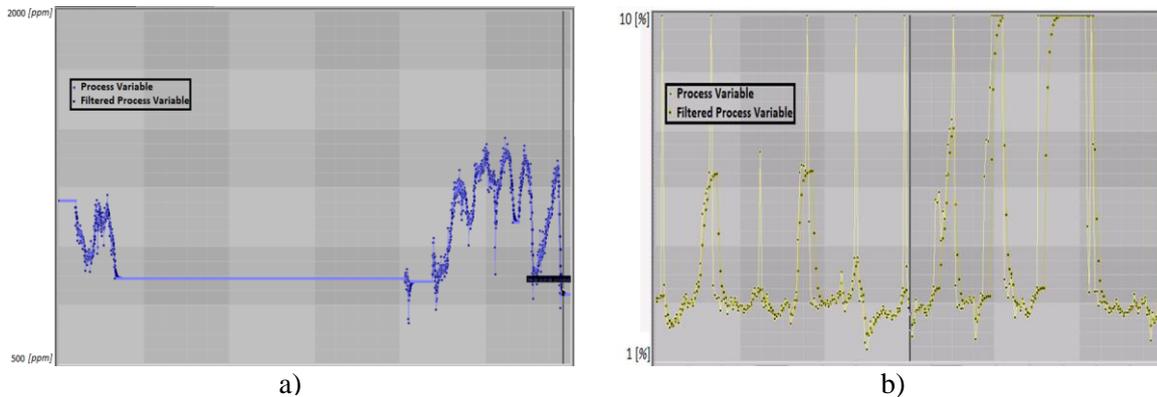
For further details on the above optimization problems, see [10, 11].

### 3.2. Example of customization in “i.Process | Cement” APC system

“i.Process | Cement” APC system has been based on the described MPC paradigm and it has been equipped with tailored customization procedures: considering, for example, the clinker production phase described in section 2 (see figure 2), redundancy on some variables can be observed. Among the main CVs, both kiln and fan nitrogen oxides have been included. The main level to be kept under APC system control is the kiln nitrogen oxides. It could happen that the related analyzer is subject to malfunctions (figure 9.a); in these cases, the option of replacing kiln nitrogen oxides control by controlling another nitrogen oxides level, e.g. fan nitrogen oxides, has been introduced. Thanks to *DC&DS* block, this option has been straight implemented in “i.Process | Cement” APC framework. A similar redundancy has been designed for oxygens concentrations (figure 9.b).

### 3.3. Example of customization in “i.Process | Steel – RHF” APC system

A customization example of the basic APC framework described in subsection 3.1, related to “i.Process | Steel – RHF” APC system, consisted in the formulation of two main control modes. The main control mode, denoted *adaptive* control mode, exploits both zCVs-MVs/DVs and bCVs-MVs/DVs linear models. In specific process conditions, e.g. virtual sensor bad estimations, “i.Process | Steel – RHF” APC system switches to *zones* control mode, exploiting only zCVs-MVs/DVs models.



**Figure 9.** Malfunction example on kiln nitrogen oxides (a) and cyclones oxygen (b) analyzers.

When in *zones* control mode, the MPC optimization problems are those reported in (1)-(4). When in *adaptive* control mode, both zCVs ( $y$ ) and bCVs terms are present in expressions (3)-(4) [12].

**4. Field results**

In this section, field results related to the described industrial APC systems are presented.

*4.1. “i.Process | Cement” APC system results*

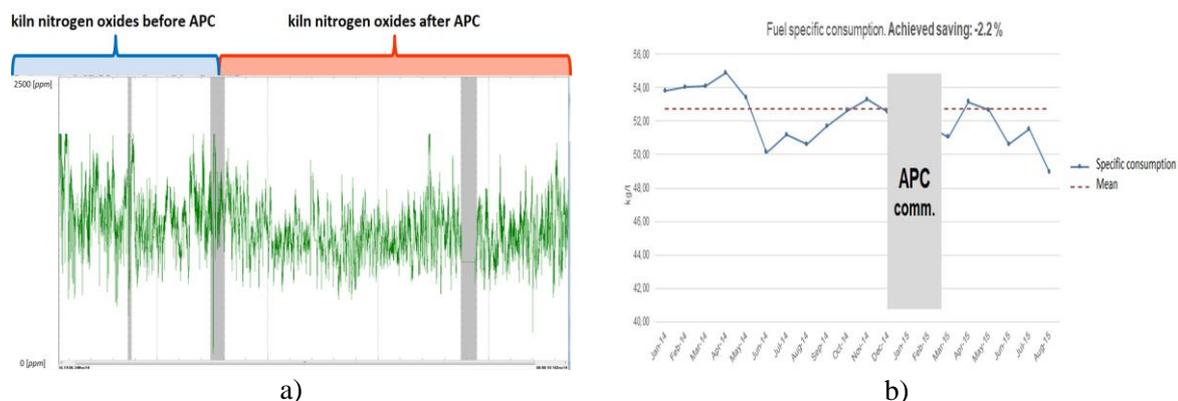
“i.Process | Cement” APC system has been installed on the clinker production phase (Italian cement plant) described in subsection 2.1 starting from December 2014/January 2015.

Figure 10.a depicts kiln nitrogen oxides trends before and after “i.Process | Cement” APC system activation (about three weeks performance test). For this crucial CV, “i.Process | Cement” APC system ensured about -32 [%] standard deviation variation together with about -15 [%] mean value variation. The improvement on critical process variables control led to a fuel specific consumption ( $[kg/t]$ ) decrease (figure 10.b): a -2.2 [%] variation has been achieved after the first eight months of “i.Process | Cement” APC system performances.

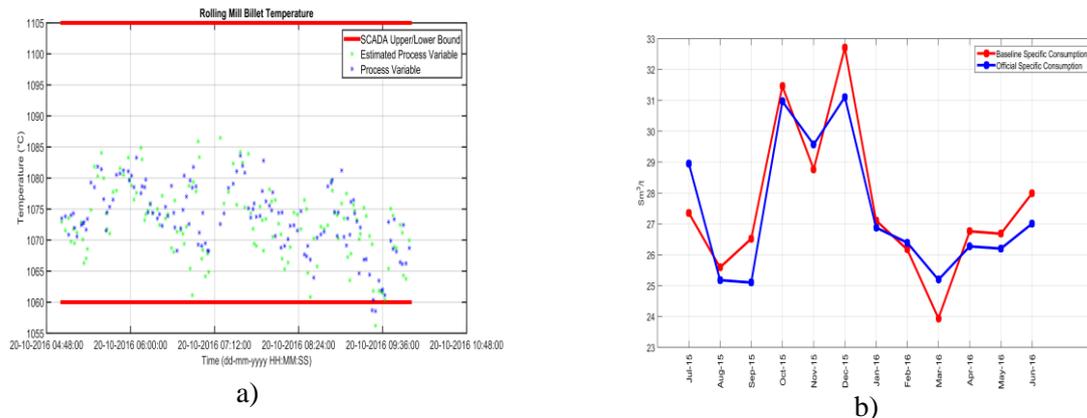
*4.2. “i.Process | Steel – RHF” APC system results*

“i.Process | Steel – RHF” APC system has been installed on the billets reheating furnace (Italian steel plant) described in subsection 2.2 in June 2015.

Figure 11.a shows an example of the controller performances: the billets temperature trends in the rolling mill area (measured by an optical pyrometer, blue stars) are compared to the virtual sensor estimations (green stars). Red lines indicate the bCVs constraints included in the MPC formulation.



**Figure 10.** Cement industry field results: kiln nitrogen oxides trends (a) and specific consumption (b) before and after “i.Process | Cement” installation.



**Figure 11.** Steel industry field results: bCVs trends (a) and comparison between baseline and official specific consumption after “i.Process | Steel – RHF” installation (b).

Thanks to the developed control strategy (Italian patent [9]), the billets temperature approaches to the required lower constraint, obtaining energy saving and environmental impact decreasing. This result can be observed from the official fuel specific consumption when compared to the defined project baseline (figure 11.b, first year of controller performances). The specific consumption has been lowered of about 2 [%] after about two years, with a service factor of about 95 [%].

## 5. Conclusions

In this paper, two proprietary industrial APC solutions, denoted “i.Process | Cement” and “i.Process | Steel – RHF”, have been described. They are oriented to improve process control and energy efficiency performances in cement industry clinker rotary kilns (clinker production phase) and steel industry billets reheating furnaces. Thanks to the installation of the developed controllers on cement and steel plants, process control and energy efficiency improvements with respect to the previous control systems (local controllers and/or operators manual conduction) have been obtained. In the two case studies of the present paper, energy efficiency certificates (Italian acronym TEE, also called “white certificates”) have been achieved.

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