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Optimization of the management of the process gas network in the integrated steelworks

(GASNET)

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Research and Innovation

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Final Report

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2 FINAL SUMMARY

2.1 WP 1: Preliminary investigations required for the development of solutions for resource efficiency

The objectives of WP1 are:

- To determine the key processes and factors affecting the off gases management in the steelwork
- To identify the techno-economic, engineering and legislative constraints that affect the off-gases and related energy management;
- To identify the main objectives to be optimized within the project

2.1.1 Task 1.1: Preparatory organisation of processes inventory

An overview of the gas and steam (where relevant) networks of the industrial partners have been provided and a representation of the gas network management policy has been given.
Limitations and drawbacks of current industrial practices for off gases management and re-use have been analyzed including the rules for gas distribution between the different sub-plants.
A preliminary analysis of the factors affecting the management of process gases have been carried out in order to point out technical gaps and non-technical barriers existing in current operations.

2.1.2 Task 1.2: Determination of process constraints

In order to pursue a deep analysis of the main technical and non-technical constraints which prevent gas network optimal management in the steelworks, a questionnaire has been prepared and sent to the three steelmaking companies involved in the project (ABG, TATA and ILVA/AMI). The questionnaire has been compiled by the industrial partners through a team work of technical and research personnel.
The outcome of such collection of information has been analyzed in order to formalize the constraints in such a way that they can be handled and accounted within the different levels of optimization problems that have been faced within the project. All the process constraints have been described in a unified and structured way and have been formalized through a series of tables.

2.1.3 Task 1.3: Selection/Definition of Key Performance Indicators

All the partners contributed to a preliminary selection and definition of a list of meaningful KPIs which was circulated among the industrial partners. In order to reduce the KPIs list, a further distinction was proposed among actual KPIs (i.e. the most feasible and relevant indexes for monitoring of the off-gases management system performances and are measurable for all the industrial partners), and the so-called Extra Performance Indicators (EPIs), which were useful indicators adopted by some of the industrial partners. The selected KPIs are common for all the industrial partners and they are calculated for all the 3 steelmaking plants. Technical, environmental and economic factors have been taken into consideration for the KPIs selection. All the other indexes, where at least one company expressed interest, are computed as well, even if they are included in the list of EPIs. The selected EPIs are calculated for each industrial plant according to their choice. KPI No. 6, namely **Econom_balance_total**, represents the objective function for the optimization task.

2.2 WP 2: Data Collection and analysis

The objectives of WP2 are:

- To design a suitable database for off- and -on line plant data collection;
- To collect plant data to be exploited for tools and models development and for the simulations.

2.2.1 Task 2.1: Analysis of measurement points

The list of measurement points for the three companies involved in the project has been compiled and reported in an Excel File.
For <u>AM Bremen</u> the main measurement equipment concerning the process off-gases, external fuels, steam and electricity is installed and most of its data are available in the current Energy Management System (EMS). In some cases, it was necessary to carry out on-site inspections together with workers of the corresponding production facilities to verify that the EMS information matches the installation or to clear out uncertainties if the information sources concerning the same measurement disagree.
The gas and steam networks of <u>Tata Steel in IJmuiden</u> are equipped with various measurements, mainly being flow meters. Some flows are not measured but calculated from other measurements. Information regarding gas quality, pressures and temperatures of gases is also available for the points for which this is relevant. All these energy data are collected as a function of time in an OSIsoft PI database. The database enables to lookup actual values online and also contains historical data. Generally, it can be concluded that all information currently used by the internal Energy Department was available and that the database could also be used for analysis work, also in the framework of this project.
At <u>ILVA/AMI</u> the list of the measurement points has been compiled, with the descriptions of the measurements, unit of measures, sampling rates, plant system and others. However, due to the difficult

conditions of the steelwork, the flowmeters, which were originally foreseen at the proposal stage, could not be installed

2.2.2 Task 2.2: Database organization

As far as the choice of which DataBase Management System (DBMS) to use is concerned, the system on the industrial partner's side (e.g. on the *GasNet bridge server*) was selected by industrial partners and is a traditional SQL DBMS (e.g. Oracle, MS SQL Server, etc.).
SSSA defined a structure for the SQL database, which was conceived merging from one side the data that comes from the plant and from the other side the data knowledge represented electronically by the Excel sheet. From a modelling definition point of view, the most convenient way to gather the data is according to the gas networks they belong to. The database structure has been revised and finalized after the completion of the models development, according to the project schedule and by considering the software architecture, which has been designed in WP4.

2.2.3 Task 2.3: Interfaces with existing information systems

The industrial partners agreed on establishing an interface layer between the GASNET system and the IT system of the plant, in order to allow safe testing of the system as well as a flexible adaptation to other facilities. The developed software application implementing the GASNET system application is basically composed of three independent modules. A server developed in C# receives TCP-IP requests from two clients: the graphical user interface (GUI) and the models simulation. Thanks to this infrastructure, the whole application can run on several machines located in different places. The interfaces with existing information systems have been finalised in order to allow real data loading and exchanging and running the different modules. Data are exchanged by means of two databases: the database of historical data and the database of current data.

2.2.4 Task 2.4: Data collection

In the first stages of the project, data collection was off-line pursued by exploiting historical data, while, in a later stage, it was pursued by directly exploiting the GASNET database.
The data provided in the first stage have been exploited to design and tune the models, which were developed in WP3. After the models development, new data were collected by all the industrial partners in order to validate and test the models themselves. Some additional data were asked by the developers to increase the model performance. The performances of some models have been improved by adding the data from the production scheduling, when available.

2.2.5 Task 2.5: Data preparation, analysis, interpretation and reconciliation

A suitable data preparation procedure has been established. The developed tools provide a number of different ways to resolve missing, duplicate, or non-uniform times, and to resample or aggregate data to regular row times. Moreover, general purpose procedures have been developed and implemented for outliers removal and dimensional data reduction.

2.3 WP 3: Interactions among gas network, process schedule and electricity and gas demand

The objectives of WP3 are:

- to investigate and model the gas behaviour inside the network;
- to investigate the effects of gas availability depending upon process scheduling;
- to predict of electricity and natural gas demand from the suppliers.

2.3.1 Task 3.1 Gas and steam behaviour inside the network.

The ABG gas (BFG and BOFG) and steam networks were modeled in Flowmaster by BFI based on drawings of the pipes and P&IDs, while SSSA modelled the off-gas network of ILVA/AMI Taranto.
A massive preliminary work has been done in order to collect the information required by the software. AutoCAD plant maps allowed the measurement of piping length and diameters, bends angles, and the placement of flow-conditioning major valves. A strict collaboration with plant staff has been fundamental. Incorrect data could affect negatively the simulation (e.g. errors in pressure drop). In addition, technical sheets of valves and boosters have been provided by contacting the constructors. When possible, customized parameters curves have been manually created, by exploiting the information supplied. In all other cases, appropriate values and curves have been assumed, by mathematical calculations and equivalent equipment comparison. According to the different gas types involved in the plants, new material templates have been created, by setting up the appropriate composition and properties.
As an overall outcome of the Flowmaster modelling work, the developed models of the gas and steam networks can be used to give evidence to the volume flow and pressure distribution for different scenarios and operating conditions. The influence e.g. of single gas/steam consumers or suppliers on the whole network can be evaluated. Further the duration of periods can be identified, in which rapid changes, e.g. triggered by an emergency shut down of a plant, have an influence on the network. With all these

information it has been possible to decide, whether the impact of consumers/suppliers and sudden changes on the overall network behaviour was relevant or not for the control models.
The following simplifications appeared reasonable for both control model and gas network simulation:

- The dominant time constant of the networks is determined by the dynamic of the gas storage. It is here in the range of 10 -20 minutes for the BOF and BF gas network.
- The balancing oscillations in the network caused by fast switching events do not need to be modelled, as they disappear in less than 1 minute.

2.3.2 Task 3.2 Process models for considering the effects of scheduling on gas and steam production/consumption.

Within this task a library of process models has been developed, which forecast the main quantitative and “qualitative” features of the off-gases produced by the producing processes as well as the demand of the main off-gas consumers processes. A detailed literature analysis related to the state of the art highlighted, for instance, that no linear correlations exist between the BF gas (BFG) variations and the most relevant process parameters. On the contrary, complex nonlinear relationships link the BFG quantity and quality to the different affecting factors. According to this result, the models design has been mostly carried out by following a hybrid data-driven approach, which considered some aspects related to the physical and chemical process features, through a suitable selection and management of data. NN-based models, for the most complex and highly non-linear processes, have been selected, while equation-based models (based e.g. on piecewise linear and Hammerstein – Wiener Models) have been applied for other processes showing simpler dynamic behaviour.

2.3.3 Task 3.3 Models of energy transformation equipment

In this task, a library of models for the relevant energy transformation equipments have been developed. To this aim, standard FeedForward Neural Networks (FFNN) and linear regression models proved to be sufficient to achieve adequate accuracy, although also ESN-based models have been tested. The models have been validated with real data not used for their tuning.

2.4 WP 4: Interactions among gas network, process schedule and electricity and gas demand

The objective of WP4 is the development of an integrated software tool for gas network modelling and optimization handling different aspects of gas management which are relevant for the steelworks and which can be easily used by plant operators.

2.4.1 Task 4.1 Software architecture.

The software architecture of the GASNET system has been designed by taking into account the following main pre-requisites:

- <u>Flexibility</u>, in order to allow future improvements and extensions (e.g. new units, improved models, etc..). This requirement implies the adoption of a modular design and the need to provide the possibility to select the optimization procedure.
- <u>Adaptability</u> to different networks and different steelworks. This requisite demand for the availability of Basic elements which can be adapted to a wide variety of gas producers and consumers, provided that a model of production and consumption is available
- <u>Easy use and configuration</u>. This aspect implies that the main basic processes need to be available together with a plain and codified procedure to create and customize new processes. Moreover, a user-friendly graphical interface needs to be provided.
- <u>License free software</u>. This requirement implies that the available commercial softwares, which comes equipped with well tested user interfaces, cannot be used and a standalone code must be developed, which will necessary have a simpler and more schematic approach to modelling.
- <u>Open source code</u>. Such as clearly written in the proposal, all the code must be available for all the partners of the project, in order to face future maintenance issue.

2.4.2 Task 4.2 Gas and steam network structure simulation and derived simplified network models.

A steam and gas network is modeled as a digraph, where the vertices are the processes and the mixing nodes; the arcs are the pipes connecting the different nodes and are oriented according to the gas flow direction.
The producers are those processes producing gas and have a given negative demand (the amount of gas/energy that is produced). The consumers have a positive demand (the required amount of gas that must be sent to the consumer). A gasholder is a vertex whose demand depends on the current filling level and it is in the range determined by its minimum and maximum possible filling level.

Both producers and consumers have an energetic demand, while the gasholder demand (filling level) refers to the amount of Nm^3 of gas it can contain.
For each vertex an energetic balance must be formulated. Torches and consumers have a non-negative balance; natural gas providers and other producers must have a non-negative balance; gasholders balance must respect the minimum and maximum range, while all connection nodes must have a zero balance (all the gas that flows in must flow out).
There are volumetric lower and upper bounds on the amount of gas that must flow in every pipe.
A cost function is then established, taking into account the revenues obtained from selling gas to consumers and the costs of burning gas into torches or buying from natural gas providers and the cost of structural changes in the network like build or demolition of pipes.
This network structure with its constraints and the minimization of the cost function can be formulated as an optimization problem, which falls under the category of QCQP quadratic constrained quadratic programming.
This kind of representation has been adopted also for the graphical representation of the network.

2.4.3 Task 4.3 Constraints implementation

A mathematical formulation has been provided for all the constraints affecting the off-gas management, starting from the equations of the energetic balance of producers, consumers and gasholders. Torches must have a non-negative balance, while natural gas sources must have a non-positive balance. The lower and upper capacities of each pipe have also been considered among the constraints.
Given that different type of gases are possibly mixing into the same pipes, the concentration of gas in the mixed flow entering a node must be the same concentration is flowing out on every pipe. These equations introduce non-linearity in the constraints, more precisely the constraints are quadratic and non-convex. This inevitably slows down the computation of an optimal solution.
In order to have a model that accounts for the possibility of pipe constructions/deletions, activation variables have been added to the model. The upper and lower bounds constraints are thus consequently extended to all possible connections. Moreover, three types of cost for the pipes are considered: maintenance cost, demolition cost (for pipes already in the original network) and building cost (for pipes not in the original network). These quantities are assumed as amortized over the used time unit.

2.4.4 Task 4.4 Framework for optimization strategies

Within the project, several optimization strategies have been formulated for the distribution of process off-gas, relating to applications aimed at improving the structure of the gas and steam networks, simulating the gas mixing behavior and application related to control systems for the long, medium and short-term optimization. In general, the simulation of the gas network can be seen as a constraint linear or nonlinear programming problem. As each network can be represented in the form of a digraph consisting of vertices and nodes, for which a state space model has been formulated. Gas flows are divided or joined together in the nodes and the Kirchhoff node equation for flows can be applied. Obviously, the volume flows, pressures or storage volume/fill level are limited and a suitable formulation for such constraint to the in and out sizes and inner states has been elaborated. The control system based on online optimization strategies are formulated as linear programming problem for the long and medium-term, as mixed integer linear programming problems for the short term online control.

2.4.5 Task 4.5 Development of a user-friendly interface

A user-friendly interface has been developed in order to support network simulation and optimal management as well as visualization of the different real and forecasted variables and of the different KPIs. Such interface is part of **Deliverable D4.2.**
The software component of the GASNET system, which is devoted to forecasting for KPI monitoring and optimization is basically composed of 3 independent modules: a server, a Graphical User Interface (GUI) and the models simulation module.
The server, which has been developed in C#, receives TCP-IP requests from the GUI and the models simulation module. Thanks to this infrastructure, the whole application can run on several machines located in different places.
The models simulation module, that was initially developed in Matlab and then translated in C#, runs continuously. Each time the simulation ends, the output is stored into a CSV file and it will be uploaded to the database.
The GUI is organised by Plant and System Unit and shows, for each forecasted variable, the current and the forecasted values for the two hours ahead prediction, according to the outcomes of the model simulations module.

2.5 WP 5: Multi-period and multi-objective optimization models

The objectives of WP5 are:
- To develop and implement optimization strategies to be embedded in the decision support tool;
- To make first tests using off-line data coming from the industrial partners' sites.

2.5.1 Task 5.1 Development of the overall structure of the optimisation system.

An approach based on the Economic Model Predictive Control (EMPC) has been developed, which combines the static econometric optimization and the dynamic control into one concept.
The term Economic MPC directly hints at the distinctive feature of this MPC formulation, namely that it allows for an arbitrary, possibly economic, cost function to be minimized by the controller. This makes it particularly attractive for applications in which the primary objective is not stabilization of some setpoint, but rather optimal operation with respect to a real economic performance criterion.
Furthermore, the economic long-term optimization can be approximated by iterative economic short-term optimization. The state of equilibrium the performance of the iterative economic short-term optimization is equal to the economic long-term optimization. Therefore, the control system has been extended to include economic costs and the costs for the purchase of natural gas, electricity and the revenue from the sale of electricity has been explicitly considered.
The final implementation of the control strategy is based on the concept of hierarchical control systems. With respect to the initial idea for the implementation of the control strategy, the concept has been modified in order to deal with the real availability of the production scheduling. It is possible to widen the horizon of prediction and scheduling of POG distribution according to the future horizon of data related to production scheduling. Therefore, it was preferred to combine tasks 5.3 and 5.4, which have been finally carried out as a single task, in which the time horizon depends on the availability of data.
In order to keep the control problem manageable, the control problem has been divided in two main subproblems:

- The HL EMPC, the High Level EMPC for long term overall network optimisation
- The DEMPC, the distributed EMPC for short term optimization of each subnetwork (POG and steam)

The HL Optimizer is scheduled with a control period of 15 minutes, while the DEMPC low-level controller is scheduled every 1 minute. The two layers are executed in parallel with a multirate approach.
The DEMPC consists of three distributed economic model predictive controller, each aimed at optimizing the own gas or steam subnetwork for a horizon of 2 hours. In particular, the DEMPC consists of three subnetwork controllers:

- The MPC 1, which control the BOFG network
- The MPC 2, which control the BFG network and the power plant
- The MPC 3, which control the steam network.

2.5.2 Task 5.2 Off line structure optimisation of the gas network.

The problem of optimizing the gas network structurehas been translated into the minimization of the previously introduced objective function, corresponding to the sum of all costs, minus the sum of all the revenues. The problem of minimizing scuh function subject to all the constraints formalised in WP4 is a non-convex Quadratically Constrained Quadratic Problem (QCQP) belonging to the category of NP-complete problems and it is computationally hard to find an optimal solution to such problem.
A number of free license QCQP solvers have been tested on data from a real case scenario, but the results were unsuccessful: given the magnitude of the problem a solution could not be found. Therefore, initially the problem has been implemented in MatLab and solved through its routines from the optimization package. In order to avoid expensive license software, a novel non-linear optimizer has also been designed, which is based on the well known algorithm of Sequential Quadratic Programming (SQP). The basic idea of SQP is to form easier subproblems and solve them iteratively in order to converge to a solution of the global problem. The number of subproblems to be solved is generally exponential in the number of activation variables, therefore, in order to avoid a computational explosion, the number of subproblems that can be solved is limited. When this limit is reached, the best solution is selected among the integral approximations of the solutions obtained in the active branches.

2.5.3 Task 5.3 Multi-objective long term (set up) strategy planning optimisation considering demand and process uncertainty (multiple long term period) and Task 5.4 Scheduling for power generation optimisation

The main objectives of the two tasks are related to the optimization of the electric energy generation in a daily basis and the optimal distribution of the POG within the other users. The module takes into account the influence of the scheduling of each main process on the capability of the byproducts gases networks (such as BFG, BOFG and COG) to store the gas in the gasholder. In addition, it predicts possible issues related to their shortage and finally reacts accordingly, planning the optimal distribution of the use of BFG, BOFG and COG in the various processes, including the electrical power plants and the main consumers.
More in detail, the objectives can be summarized as follows:

- The optimization of the distribuition of byproduct gases;
- The maximization of the energy efficiency conversion in the powerplants;
- Minimization of the use of NG in each main consumer (powerplants, HSM, Steam boilers);
- Minimization of the byproduct gases flaring in torches and consequently the minimization of the environmental impact in the long term.

As a result of the optimization strategy, the module produces suitable references for the lower level optimization of each gas and steam network, starting from the predictions of production and consumption of each byproduct gases, through models designed with a lower time level detail, in which the only time dependencies are related to the dynamic of the gasholders and the steam stored in the accumulators. The steam network dynamics are considered istantaneus, as its mass flow and pressure dynamics fall within 15 seconds - 1 minute time ranges, that are sampling times not suitable for a daily/weekly optimization.
The optimization problem can be described starting from given data and assumptions:

1) Byproduct gases, suitable production units, boilers and other byproduct gas users, generation rate at a time and demand profiles in production units as forecasted by the models;
2) Dedicated gasholders, their minimum and maximum capacities, normal inventory levels, high and low inventory levels for safe operational regions;
3) Boilers, suitable fuels that can be fed, suitable steams that can be generated, maximum inlet flow rates of byproduct gases, thermal efficiency, minimum and maximum steam generation rates, and minimum heating values;
4) Burners, suitable byproduct gases, initial status and feed rates at a time;
5) Energy generation equipment (e.g. steam turbines, etc.), suitable steams that can be fed, suitable steams that can be generated, minimum and maximum feed rates, thermal efficiency, minimum and maximum generation rates, and minimum and maximum power generation rates;
6) Steam and electricity demand profiles with time, steam enthalpy, electricity energy content, maximum imported power from the grid, and maximum exported power to the grid;
7) Economic data: natural gas purchase cost, electricity sale price and purchase cost, penalty coefficients for by-product gas flaring and burner switching operations, penalty coefficients for deviations from normal inventory levels in gasholders and violations of low and high inventory levels of the safe operational region in a gasholder;
8) Planning horizon.

The solution of the optimization problem determines:

1) The optimal distribution of byproduct gases among the users in a daily/weekly basis;
2) The profiles of gasholders level in the time horizon;
3) The future optimized objective function, related to Specific Economic Balance between costs and revenues.

2.6 WP 6: Industrial tests and validation

The objectives of WP6 are:

- To perform extensive tests of the developed advisory tool and evaluate the achieved results.
- To develop general guidelines for the analysis and optimization of gas networks inside the steelworks and for the application of the developed decision support tool
- To disseminate the project results in the scientific and industrial community

2.6.1 Task 6.1 Preliminary off-line tests exploiting the historical databases.

A substantial part of the offline test work was carried out on the process models developed during WP3, during which a set of models were developed and are part of the final library of the GASNET software. The models aim at predicting the most important quantities involved in the various optimization systems. The models forecast volumetric flow and energy contents of off-gasses, steam production and consumption of each main process, gasholder levels, dynamic behaviour of the steam network and electric power production and consumption within the steelworks.
Moreover, at the end of the development, some final off-line tests of the strategy planning have been developed before the final implementation stage, which are here shown and discussed.

2.6.2 Task 6.2 Industrial tests of the decision support tool on the different plants.

The off-line optimization tool has been tested by considering the neworks of all the three involved industrial steelworks to the aim of verifying its main functionalities. The simulation of the ABG network actually has been already investigated as a benchmark in the development stages of the tool, therefore deeper simulation have been performed concerning the networks of Tata Steel Ijmuden and AMI/ILVA. The optimization algorithm proved its capability to find realistic solutions in a reasonable time by respecting all the constraints. Moreover interesting suggestion are provided in one case relating to the possibility to improving the network efficiency by building some new pipes. Such results have some value even if the investigation has been performed using fictitious costs for building, demolition and maintenance of the selected piping.
The functionalities of the on-line monitoring and decision support tool have been tested only by ABG, while ILVA, the subcontractor of SSSA, could not develop the onsite test due to its particular internal situation.
The tool appears to be user-friendly, the models provided forecasted values whose accuracy is in-line with the expectations and suitable for the optimization purposes. It is possible to efficiently on-line monitor the performance of the network management through on-line visualization of both relevant variables and KPIs.
The effectiveness of the HL optimizers have been tested by exploiting information and data coming from ABG. The test of such functionality has been possible only in an off-line way, through a comparison of the actual outcome of the management of the gas network and what could be achieved if the HL optimization had been exploited. Such functionality is tested over a series of missions composed of several days. Such

performance is evaluated through a series of Key Performance Indicators (KPIs) related to: the economic savings that can be obtained through the application of the references calculated by the high-level control system in comparison to the real case; the increase of electric energy production that can be achieved through an optimized consumption scheduling of the POG in the internal power plant; the decrease of energy waste in the torches with respect to the real case; the decrease in the consumption of NG in the controllable systems. The reults are very encouraging and show that considerable advantages in terms of economic and environmental costs can be achieved.

2.6.3 Task 6.3 Evaluation and validation

The results achieved in the industrial tests have been deeply analysed by all the partners in order to outline the advantages of the developed approach with respect to current gas network management strategies, by also quantifying the performance in terms of the KPIs.
The developed tools proved to be easy to use and capable of providing interesting hints and elements for an optimal management of the off-gas and steam networks. In particular, the off-line optimization tool provides meaningful although very preliminary indications on the potentials for improvements of the networks management. As such module provides a stationary optimized distribution of gas (or steam) inside the network, it can or suggest the convenience or viability of layout modifications (i.e. pipe dismantling or construiction). Moreover, such tool can be exploited in the first step of the deployment of the overall system, in order to highlight bottlenecks and critical issues in the gas network management and to define a list of priorities, issues to be solved or improvements to be reached.

The related to the overall test show that the economic costs can be significantly reduced by adopting the proposed optimization tool. A greater internal production of electricity with respect to the standard management can be obtained, thanks to the optimized distribution of POGs. Moreover, a significant reduction in the NG consumption can be achieved as well as a clear reduction in the use of torches, as the developed control system is capable to synchronize and balance the energy demands of the users of the system and the production of the required energy, with greater efficiency and a considerable reduction in waste. Considerable advantages are also observed as far as the management of the steam network is concerned. Huge savings in the steam production can be achieved thanks to an almost total reduction of the condensed steam in the network.

2.6.4 Task 6.4 Transferability issues and dissemination

Based on the poutcomes of the tests, some general guidelines have been developed for the analysis and optimization of gas networks inside integrated steelworks and for the application of the developed decision support tool. Moreover, a user manual for the developed software tool has been developed by SSSA
As far as the dissemination is concerned, the partners have been deeply committed to publish the outcomes of the project through papers published in international journals as well as through presentations in international conferences and workshops. In particular, 3 papers have been published in International Journal (indexed both on ISI and on SCOPUS), 11 paper have been published on proceedings of international conferences and 2 further presentations have been given within relevant international Workshops.
The GASNET Workshop has been organised as a Special Session of the European Steel Days 2019 (ESTAD 2019), which took place in Dusseldorf on June 24-28, In order to widen the audience and ensure a higher level of visibility to the project outcomes. This special session, which was entitled: *"Efficiency increase and CO_2 mitigation in iron and steelmaking: Efficient and safe management and expoitation of off-gases in the steel sector"*, has been held on June 27 and included five papers which presented different aspects of the work developed within the project. The papers presented in this special session have been collected in a volume of Proceedings of the GASNET workshop
A group named "GASNET" has been established by SSSA on the ResearchGate platform at the beginning of the project to the aim of coming into discussion with other interested researchers and increasing the visibility of publications produced throughout the project.
Finally a logo has been elaborated for the GasNet system, to be used in future communication and dissemination activities, and a flyer depicting the GasNet DSS.

2.7 WP 7: Coordination and Reporting

The objectives of WP7 are:

- Coordination of project activities, control of project progress;
- Preparation and presentation of progress and final reports.

2.7.1 Task 7.1: Coordination work and meetings

A fruitful and continuous information exchange has been established among the project partners via email exchange and many conference calls. Moreover 10 physical partners' meetings have been organised. Furthermore, SSSA's personeel was hosted at ABG and ILVA/AMI for extensive periods both during the development phase and for the intermediate and final tests of the system, and BFI personnel organised regular visits to ABG during the models development phase.

2.7.2 Task 7.2: Documentation

The minutes of all the Partners' meeting and conference calls were sent via email. Tables and documents were shared by the partners in order to exchange useful information for the completion of the different activities.

2.7.3 Task 7.3: Reporting

All the periodic reports have been issued in due time. The Final Report is being delivered by 31/03/2020.

3 LIST OF DELIVERABLES

No.	Description	Form (location)	Due date	Final. date
D1.1	List of process constraints	List (in MTR)	31/3/2016	Delivered
D1.2	List of KPIs	List (in MTR)	31/3/2016	Delivered
D2.1	List of measurement points	List (in MTR)	31/3/2016	Delivered (separated Excel file on CIRCABC)
D2.2	Structured database	List (in MTR)	31/3/2016	Delivered
D2.3	Software for data filtering	Description (in MTR)	31/3/2016	Delivered
D3.1	Implementable models to consider gas behaviour inside the network	Description (in SAR)	31/9/2017	Delivered
D3.2	Implementable models to take into account the effect of process scheduling on gas production and demands	Description (in SAR)	31/9/2017	Delivered
D3.3	Implementable models for prediction of steam demands from consumers	Description (in SAR)	31/9/2017	Delivered
D3.4	Implementable models of energy transformation equipment	Description (in SAR)	31/9/2017	Delivered
D4.1	Software architecture of the decision support tool	Description (in SAR)	31/9/2017	Delivered
D 4.2	First version of decision support tool	Description (in TAR)	30/06/2018	Delivered
D5.1	Software for off-line structure optimization ready for integration in the decision support tool	Description (in TAR)	31/05/2018	Delivered
D5.2	Software for multi-object long-term strategy planning ready for integration in the decision support tool	Description (in TAR)	31/05/2018	Delivered
D5.3	Software for short term planning and rescheduling optimisation ready for integration in the decision support tool	Description (in TAR)	31/05/2018	Delivered
D5.4	Software for short term continuous online unit control ready for integration in the decision support tool	Description (in TAR)	31/05/2018	Delivered
D6.1	Final version of the decision support tool	Description (in FR)	30/06/2019	Delivered
D6.2	Proceedings of the GASNET workshop	Book	30/06/2019	Delivered
D6.3	Guidelines for exploitation of the integrated DSS	Description (in FR)	30/06/2019	Delivered
D6.4	User manual of the integrated simulation and decision support tool	Book	30/06/2019	Delivered
D6.5	Dissemination material, such as leaflets and demo versions of the software	Leaflet and logo (in FR)	30/06/2019	Delivered
D7.1	Minute of the meetings	Documents (deliv. via email to the partners, available for the RFCS officers)	≈ Each six months	Delivered
D7.2	First annual progress report	Report/Pres. (CIRCA)	31/3/2016	Delivered
D7.3	Mid-term report	Report/Pres. (CIRCA)	31/3/2017	Delivered
D7.4	Second annual progress report	Report/Pres. (CIRCA)	31/3/2018	Delivered
D7.5	Third annual progress report	Report/Pres. (CIRCA)	31/3/2019	Delivered
D7.5	Final report	Report/Pres. (CIRCA)	31/3/2020	Delivered

4 WORK UNDERTAKEN

4.1 WP 1: Preliminary investigations required for the development of solutions for resource efficiency

The objectives of WP1 are:

- To determine the key processes and factors affecting the off gases management in the steelwork
- To identify the techno-economic, engineering and legislative constraints that affect the off-gases and related energy management;
- To identify the main objectives to be optimized within the project

4.1.1 Task 1.1: Preparatory organisation of processes inventory

An overview of the gas and steam (where relevant) networks of the industrial partners have been provided and a representation of the gas network management policy has been given.
A detailed inventory of the available measurements (including sampling rates, units and storage policies) related to off-gas and steam networks has been pursued. Schemes and maps of the concerned networks have been collected. The technical personnel of the different plants provided information to SSSA, BFI and AMMR during dedicated restricted meetings.
Limitations and drawbacks of current industrial practices for off gases management and re-use have been analysed, including the rules for gas distribution between the different sub-plants.
A preliminary analysis of the factors affecting the management of process gases have been carried out in order to point out issues, technical gaps and non-technical barriers existing in current operations.
Errore. L'origine riferimento non è stata trovata. and **Errore. L'origine riferimento non è stata trovata.** show the steam and gas network at ArcelorMittal Bremen and Tata Steel Ijmuiden, while **Figure 3** depicts the off-gas network of ILVA/AMI Taranto.

4.1.2 Task 1.2: Determination of process constraints

In order to pursue a deep analysis of the main technical and non-technical constraints which prevent gas network optimal management in the steelworks, a questionnaire has been prepared and sent to the three steelmaking companies involved in the project (ABG, TATA and ILVA/AMI). The questionnaire consisted of the following main parts:

1. Gas networks which provide composition, average production, LCV and its variations, dust content, sulfur, quality and environmental problems for Natural Gas, COG, BOFG and BFG of all the three industrial partners;
2. Process and Networks Technical Information and Constraints, where the list of gas users and type of gas used are shown for all the three industrial partners;
3. The lists of the additional equipment and characteristics;
4. Constraints Description;
5. Contract Description.

The questionnaire has been compiled by the industrial partners through a team work of technical and research personnel.
The outcome of such collection of information has been analyzed in order to formalize the constraints in such a way that they can be handled and accounted within the different levels of optimization problems that have been faced within the project.
All the process constraints have been described in a unified and structured way and have been formalized through a series of tables, which represent **Deliverable 1.1**, which was included in the Mid-Term Report.

4.1.3 Task 1.3: Selection/Definition of Key Performance Indicators

All the partners contributed to a preliminary selection and definition of a list of meaningful KPIs which was circulated among the industrial partners. In order to reduce the KPIs list, a further distinction was proposed among actual KPIs (i.e. the most feasible and relevant indexes for monitoring of the off-gases management system performances and are measurable for all the industrial partners), and the so-called Extra Performance Indicators (EPIs), which were useful indicators adopted by some of the industrial partners. Such list is summarized in **Table 1** (see **Deliverable 1.2** for further details). The selected KPIs are common for all the industrial partners and they are calculated for all the 3 steelmaking plants. Technical, environmental and economic factors have been taken into consideration for the KPIs selection. All the other indexes, where at least one company expressed interest, are computed as well, even if they are included in the list of EPIs. The selected EPIs are calculated for each industrial plant according to their choice. KPI No. 6, namely **Econom_balance_total**, also represents the objective function for the optimization task. The detailed list of KPIs and EPIs represents **Deliverable 1.2**, which was included in the Mid-Term Report.

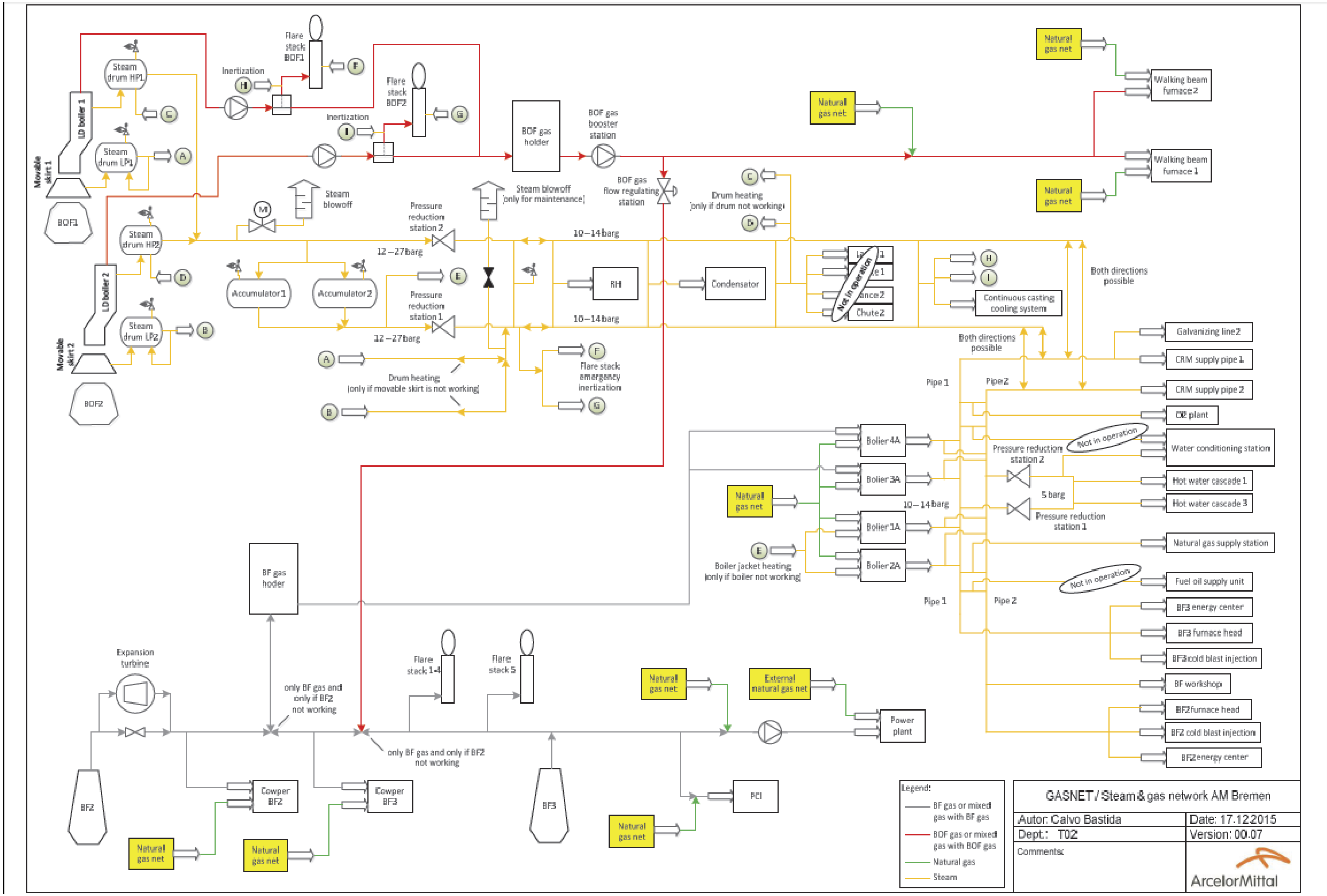


Figure 1: Steam and gas Networks at AM Bremen

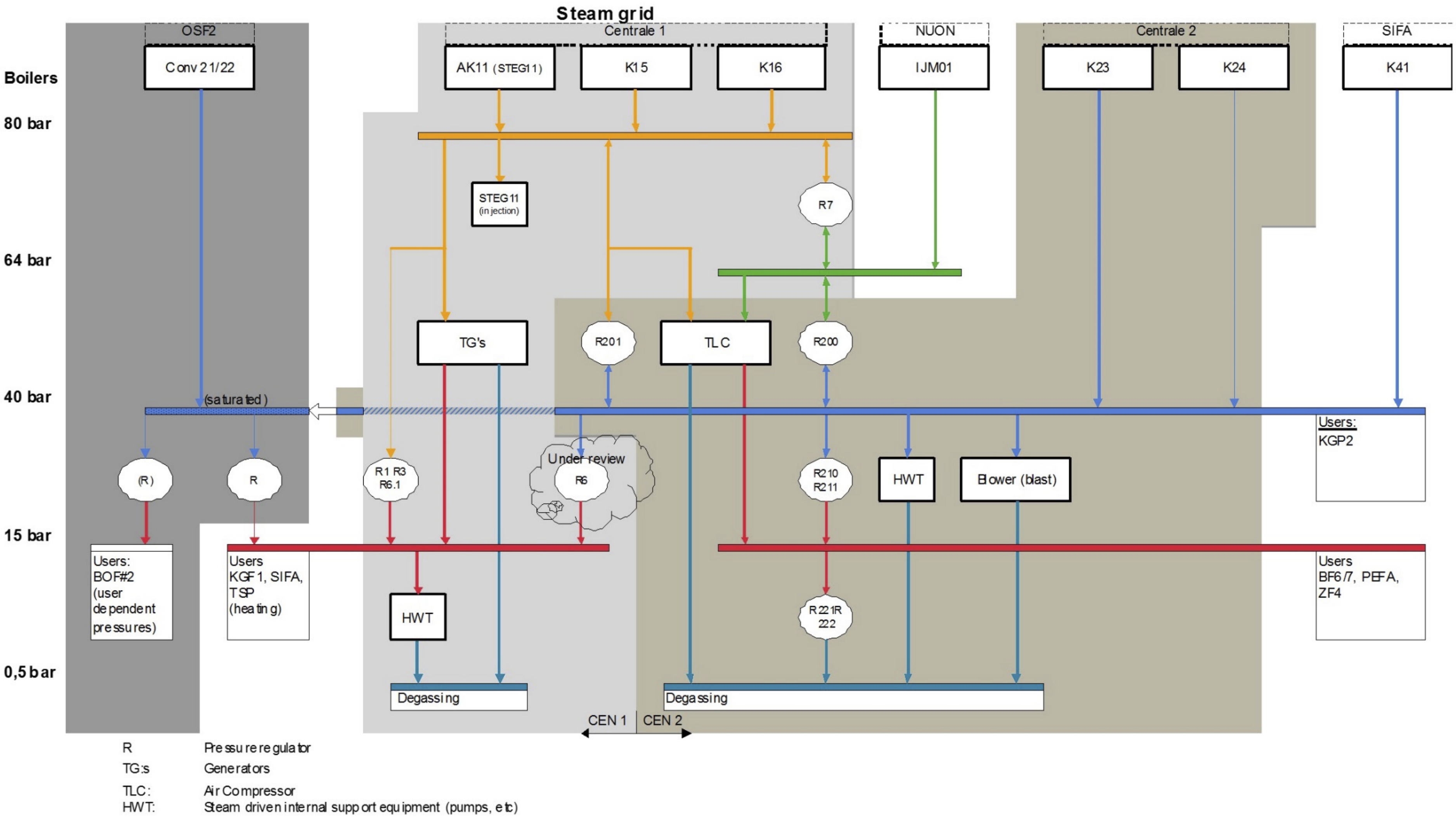


Figure 2. Steam and gas Networks at Tata Steel Ijmuiden

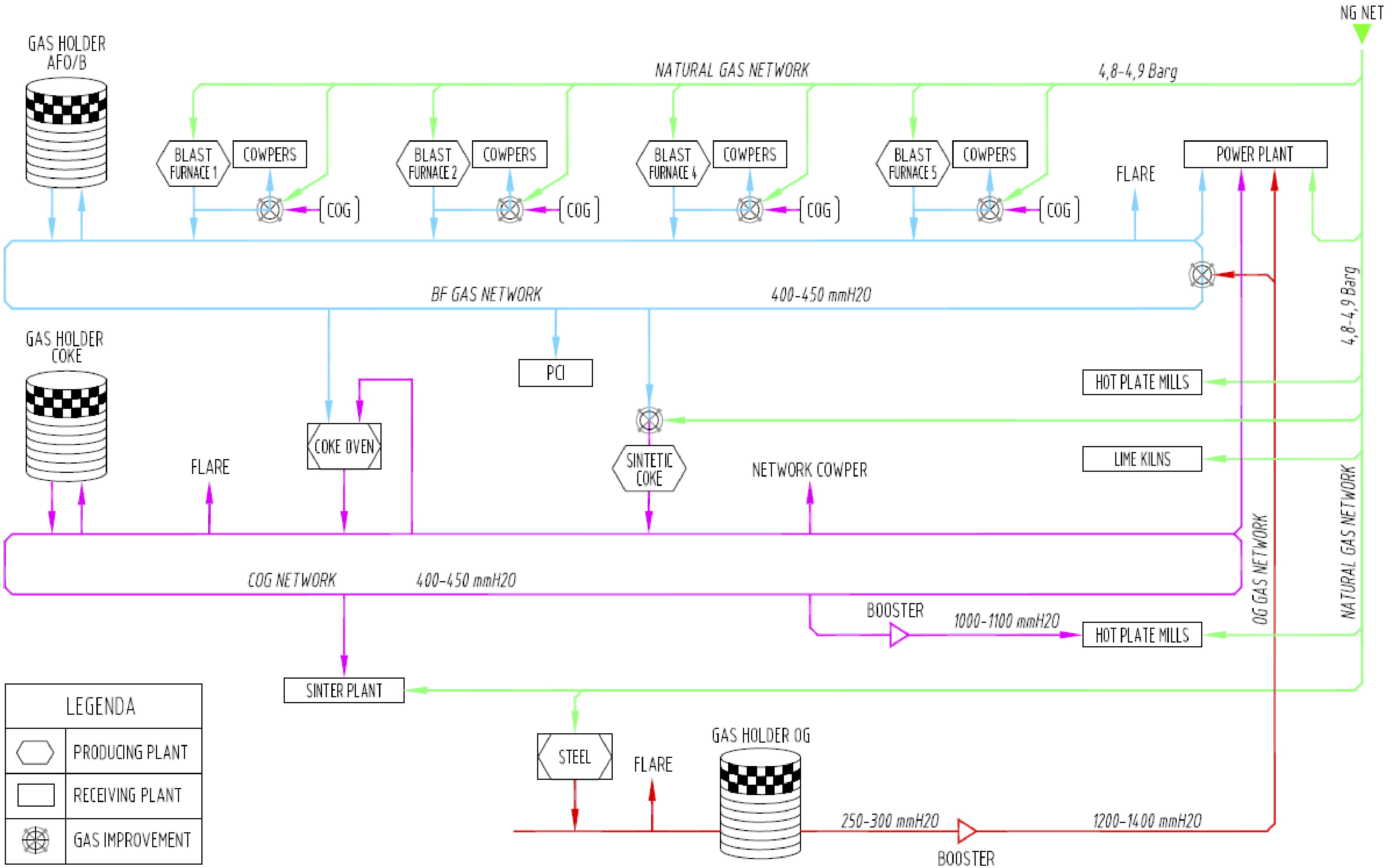


Figure 3. ILVA/AMI Taranto off-gas network: Natural gas network (green), COG network (magenta), BFG network (blue), BOFG network (red).

Group	N.	KPI Name	Description	U.M.	Scope-Facilities
STEAM	**1**	Overall Steam losses	Ratio between the mass amount of steam losses and the total mass amount of steam produced in the integrated steelworks	%	Integrated steelworks
FLARES	**2**[1]	Flare losses	Ratio between the energy amount of off-gas flaring and the overall recoverable energy amount from off-gas produced in each area of integrated steelworks (CO, BF, BOF)	GJ/GJ %	CO, BF, BOF
PROCESS OFF GAS	**3**	Total normalized energy from recovered off-gas	Amount of energy from recovered off-gas for unit of produced steel (as raw slab)	GJ/ton crude steel	Integrated steelworks
	4	Percentage of used energy produced with process off-gases	Ratio between the used energy produced with process off-gases and the total used energy	GJ/GJ, %	Integrated steelworks
ECONOMICAL	**5**	Specific economic balance for used energy	Economic balance for energy management concerning process off-gases per GJ of used energy of the internal and external consumers	€/ GJ delivered	Steelworks
	6	Specific economic balance of process off-gas management	Economic balance for energy management concerning process off-gases related to the crude steel production	€/ ton crude steel	Steelworks

Table 1: Summary of the selected KPIs

4.2 WP 2: Data Collection and analysis

The objectives of WP2 are:

- To design a suitable database for off- and -on line plant data collection;
- To collect plant data to be exploited for tools and models development and for the simulations.

4.2.1 Task 2.1: Analysis of measurement points

The list of measurement points for the three companies involved in the project has been compiled and reported in an Excel File, which has been upload on CIRCABC (it represents **Deliverable D2.1**). In the sheets of this Excel File, for each industrial partner and for each used medium (steam, gas, electricity, condensate), the following information is included:

- data description
- measurement unit
- corresponding plant system and plant unit
- range/typical value
- datum name for GASNET
- name of source data and the data source
- magnitude type
- sampling frequency.

4.2.2 Task 2.2: Database organization

As far as the choice of which DataBase Management System (DBMS) to use is concerned, the system on the industrial partner's side (e.g. on the *GasNet bridge server*) was selected by industrial partners and is a traditional SQL DBMS (e.g. Oracle, MS SQL Server, etc.).

SSSA defined a structure for the SQL database, which was conceived merging from one side the data that comes from the plant and from the other side the data knowledge represented electronically by the Excel sheet. From a modelling definition point of view, the most convenient way to gather the data is according to the gas networks they belong to. The database structure has been revised and finalized after the completion of the models development, according to the project schedule and by considering

[1] ILVA/AMI is not allowed to flare useful gas: the production cycle is currently adapted to this constraint upon indication of the Integrated Environmental Authorization (AIA) released from the Italian Government in 2013

the software architecture, which has been designed in WP4. In particular, two types of database are required, which differ from each other in the specific purpose, as schematically depicted in **Figure 4**:

- The datatabase of the current data that has the purpose to feed the models for predicting 2 hours ahead the behavior of specific process involved in the optimization strategy;
- A database for past (historical) data that is useful to adjust the parameters of the models in the event that the performance of these falls below a certain threshold.

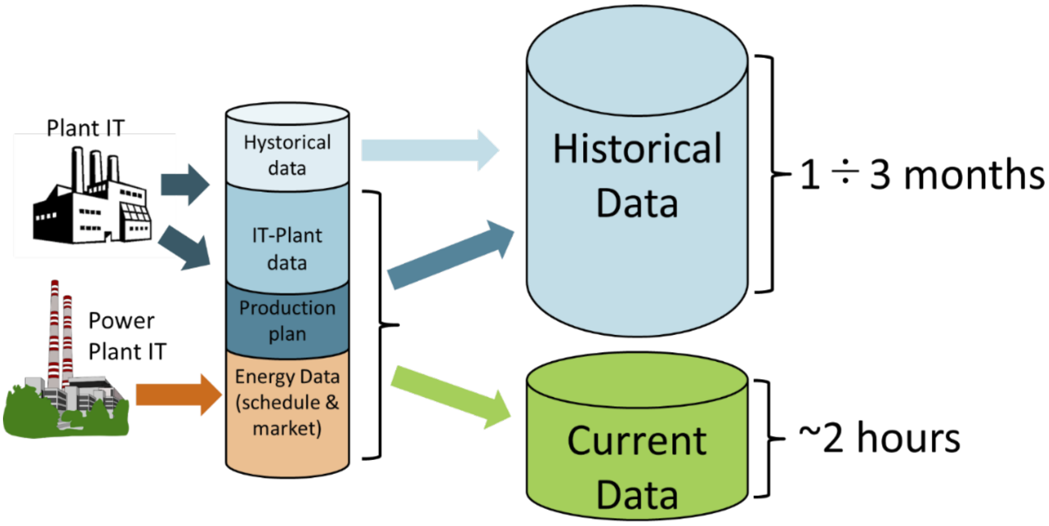


Figure 4: Historical and current databases

In general, the architecture of each of these databases is composed of 2 different layers (see **Figure 5**), the first one (Layer 1) holds all the view names and measurements with the same names available in the specific plant. The second layer (Layer 2) receives the data from Layer 1 and, after a series of transformations, makes available the data of each measured variable organized in viewnames and with names translation defined during WP 2 and the successive work. Here the standardization procedures for the viewnames and variables names stored in Layer 2 of the GASNET database are summarized.

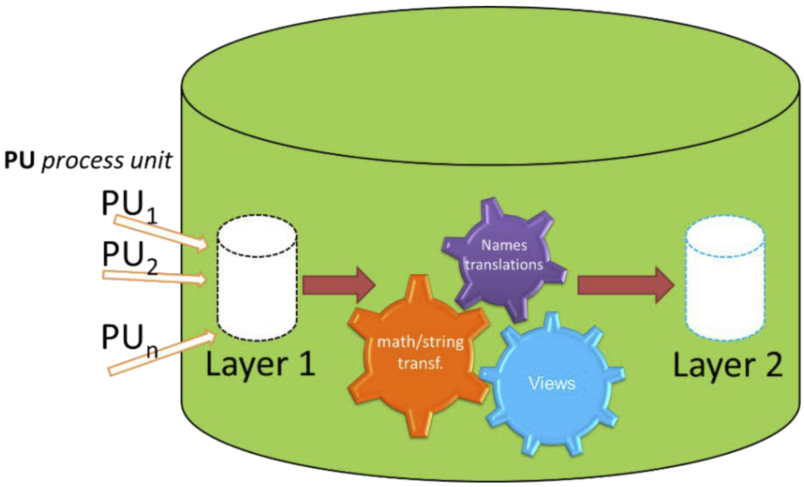


Figure 5: Architecture of each database

Views and Variables Names

The data, which are available in this view, are delivered for the model interface only each 15 sec, 1 min, 5 min, 15 min, according to the required performance. In order to standardize as much as possible the names of measured variables, it is essential to follow some naming methodologies. The following rule has been defined to obtain a standard composition of the name of variables:

MAGNITUDE_PSMS_UNITS_AUX (R.1)

where each piece has been stored in single view (such as IF_Magnitudes_V, IF_PSMS_V and so on). The list is intended as an example and has to be completed with specific needs of each partner plant; the list cannot be exhaustive, as many names may be specific to the specific plant.
The designed database structure and the relative interface is organized in several views that allows describing in detail all the measurement points, the models in the GASNET software and all the relations between them. All the relations are shown in **Figure 6,** which depicts the structure of the Layer 2 of GASNET database interface. Based on the interface tables, the data are ordered in the different views. The views deliver the measured values with certain time stamps, units and the time ranges.

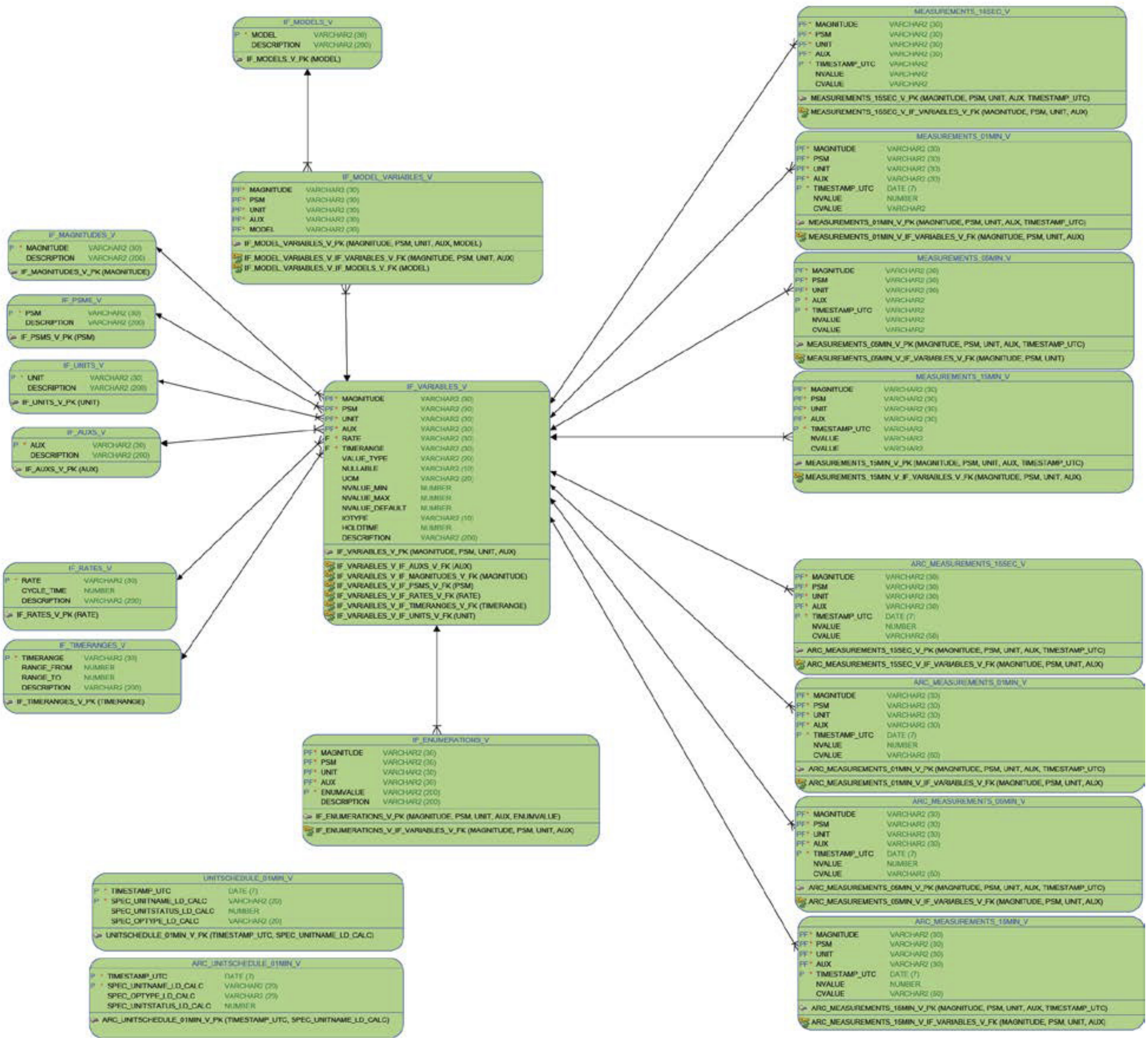


Figure 6: Structure of the Layer 2 of GASNET database interface

Database of current data

The objective of this database is to feed the GASNET models to forecast the future production and consumption of the main variables of interest. The basic specifications for this database (measurements names) are defined in the previous section.
The number of timestamps of each view has to be defined in function of the samples needed for the inputs of specific models.

In this database, the **Layer 2** is composed of several different views (tables). The rule for the naming of the views can be summarized as follows:

MEASUREMENTS_**"SAMPLINGTIME"**_V (R.2)

Database of historical data

This subsection presents the final specification for the Database of historical data. As mentioned in the previous section of this document, the objective of this database is to store a dataset useful for re-tuning the parameters of the models or for re-training the models in function of their current real accuracy.
The basic specifications for this database (measurements names) are defined in the previous section. The number of timestamps of each view has to be defined in function of the samples needed for the re-tuning of specific models and has to be designed also in function of database performances. As rule of thumb, the number of samples have to include 1-3 months of historical data.
In this database, the **Layer 2** is composed of several different views (tables). The rule for the naming of the views can be summarized as follows:

ARC_MEASUREMENTS_**"SamplingTime"**_V (R.3)

4.2.3 Task 2.3: Interfaces with existing information systems

The industrial partners agreed on establishing an interface layer between the GASNET system and the IT system of the plant, in order to allow safe testing of the system as well as a flexible adaptation to other facilities. **Figure 7** depicts the exemplar case of ABG, where an interface will be established with ProDISS. ProDISS is a databank-based communication interface, which exchanges messages with other ProDISS systems (usually plants).

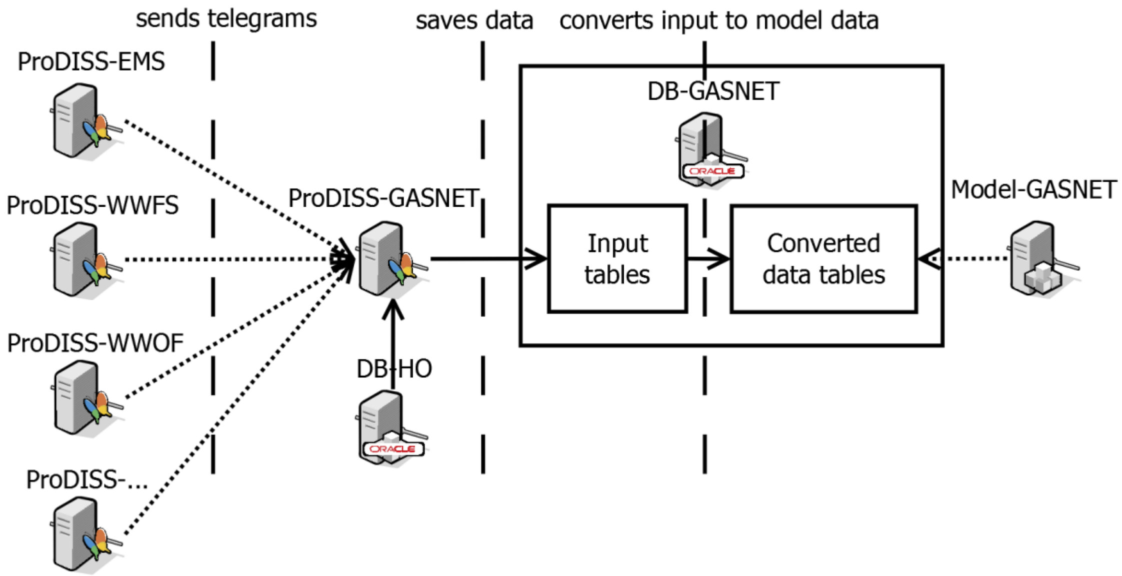


Figure 7: Database and interface structure at ABG

The following procedure is provided:
1. ProDISS–GASNET receives from a plant a message with required data for the GasNet model.
2. ProDISS–GASNET stores the data in an input layer in the database. The data have the same structure as in the received messages.
3. ProDiss-GASNET starts with a PL/SQL package in the database, which reads the data from the input layer and brings in a structure as required by the GASNET model. The data are stored in a separate layer.
4. The GASNET model reads the data from the separate layer (if required).

Thanks to this procedure the GASNET model can read the processed data from the separate layer at any time and can directly access the data in the required format, so further calculations are not needed.
The developed software application implementing the GASNET system application is basically composed of three independent modules. A server developed in C# receives TCP-IP requests from two clients: the graphical user interface (GUI) and the models simulation. Thanks to this infrastructure, the whole

application can run on several machines located in different places. The interfaces with existing information systems have been finalised in order to allow real data loading and exchanging and running the different modules. Data are exchanged by means of the two above-described databases: the database of historical data and the database of current data.

4.2.4 Task 2.4: Data collection

In the first stages of the project, data collection was off-line pursued by exploiting historical data, while, in a later stage, it was pursued by directly exploiting the GASNET dataset.
In particular, in the case of AM Bremen, the data collection in the first phase was done using historical data from 01/07/2015 until 30/06/2016. The data listed in the List of Measurement were collected from the data base of the Energy Management System and from other databases of the production units and delivered to the developers. In the case of Tata Steel, most of the required data for the GASNET project was available from a OSISOFT PI database. Tata Steel started the collection of datasets for a number of days of operation of the IJmuiden site. ILVA/AMI Taranto, in the first stage of the project provided about 2'000'000 of samples, which belong to 391 parameters related to the off-gas network management and monitoring system. Such data are related to the acquired signals for the parameters of steam and gas involved in the several plant units of the gas/steam networks that are: BFs and related cowpers and services, coke ovens, sinter plants, mills, steeshops, heat recovery lines, boilers, gasholders, oxygen and hydrogen plants, power plants, flares, etc. The biggest amount of measured and collected parameters are mass and volume flows, pressures and temperatures but also gasholder levels, gas calorific values. The calculated molecular weights of BFG, COG and BOFG are also acquired.
The data provided in the first stage have been exploited to design and tune the models, which were developed in WP3. After the models development, new data were collected by all the industrial partners in order to validate and test the models themselves. Some additional data were asked by the developers to increase the model performance. The performances of some models have been improved by adding the data from the production scheduling, when available.

4.2.5 Task 2.5: Data preparation, analysis, interpretation and reconciliation

A suitable data preparation procedure has been established. **Figure 8** shows how to create a regular timed dataset from one that has missing, duplicate, or non-uniform times. A timed dataset is a type of table that associates a time-stamp, or *row time*, with each row of data. In a regular timed dataset, the row times are sorted and unique, and differ by the same regular time step. Timed dataset can be irregular. They can contain rows that are not sorted by their row times. Timed data can contain multiple rows with the same row time, though the rows can have different data values. Even when row times are sorted and unique, they can differ by time steps of different sizes. Timed dataset can even contain NaT or NaN values to indicate missing row times.
The developed tools provide a number of different ways to resolve missing, duplicate, or non-uniform times, and to resample or aggregate data to regular row times.
The work flow consists of following steps:

- find missing row times,
- remove missing times and data,
- sort the timed data-set by its row times
- make a unique and sorted row timed data-set,
- remove duplicate times, specify a unique time vector.
- make a regular timetable, specify a regular time vector.

Futhermore data preparation concerned, firstly an analysis aimed at detecting the so—called *outliers* and afterwards an analysis aimed at reducing the dimension of the data to be considered for the development of the models within WP3.
Outliers are observations that can be considered anomalous due to several reasons, such as: wrong measurements, faulty sensors, sensor breakdown and so on.

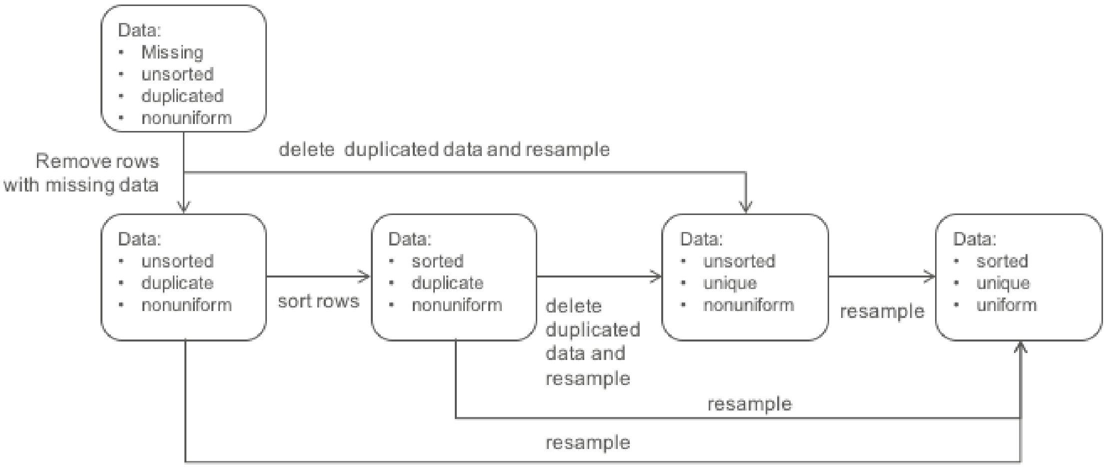


Figure 8: Flow diagram of the data preparation

The analysis can follow two different branches or methods: supervised or unsupervised.

- **Supervised methods**: employed when an a-priori classification of a comprehensive dataset is available for the training of the model;
- **Unsupervised methods**: employed when no information is available but the data themselves.

SSSA focused its efforts exploiting principally 3 unsupervised methods and aggregates their results by means of a Fuzzy Inference System (FIS). The 3 techniques are evaluated at once and a number between zero and one is the result, proportional to the probability that a particular input pattern is an outlier.

Dimensional data reduction consists in transforming a wide dataset into a more reduced one by retaining most of the relevant information content of the original dataset. In the proposed analysis the dimensional data reduction is performed through two main steps: elimination of redundant variables and selection of the variables which mostly affect the considered target. **Figure 9** depicts a scheme of the overall data reduction procedure which has been implemented. The proposed approach is general, can be applied to any kind of data-driven model and has been intensively applied in WP3.

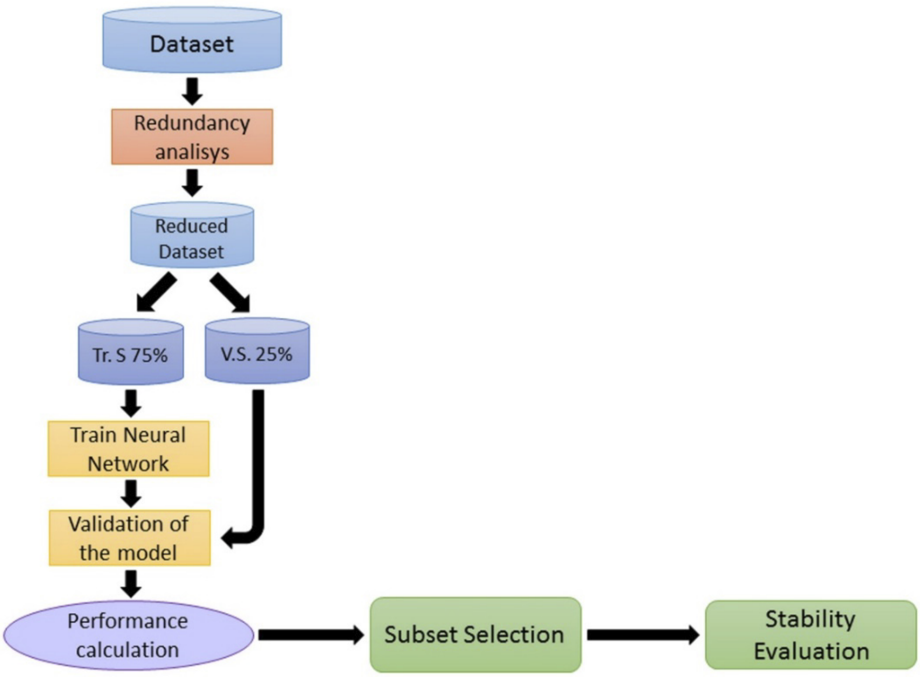


Figure 9. Block diagram of the proposed approach

The details of the general-purpose software procedures which have been implemented for outliers detection and data dimensionality reduction are described in **Deliverable 2.3**.

4.3 WP 3: Interactions among gas network, process schedule and electricity and gas demand

The objectives of WP3 are:

- to investigate and model the gas behaviour inside the network;
- to investigate the effects of gas availability depending upon process scheduling;
- to predict electricity and natural gas demand from the suppliers.

4.3.1 Task 3.1 Gas and steam behaviour inside the network.

The ABG gas (BFG and BOFG) and steam networks were modeled in Flowmaster by BFI based on drawings of the pipes and P&IDs, while SSSA modelled the off-gas network of ILVA/AMI Taranto.
The Flowmaster software allows modeling and analyzing pipe flows in complex systems through steady state and transient simulations of complex networks and it is based on the one dimensional Bernoulli's principle along a stream line. It is thus useful to study the effects of process events like the closing of a valve, the sudden shut down of a furnace or other process changing at eventual limiting conditions.
A massive preliminary work has been done in order to collect the information required by the software. AutoCAD plant maps allowed the measurement of piping length and diameters, bends angles, and the placement of flow-conditioning major valves. A strict collaboration with plant staff has been fundamental. Incorrect data could affect negatively the simulation (e.g. errors in pressure drop). In addition, technical sheets of valves and boosters have been provided by contacting the constructors. When possible, customized parameters curves have been manually created, by exploiting the information supplied. In all other cases, appropriate values and curves have been assumed, by mathematical calculations and equivalent equipment comparison. According to the different gas types involved in the plants, new material templates have been created, by setting up the appropriate composition and properties.
According to the preliminary analysis carried out within WP1, the huge and very complex gas network of ILVA/AMI has been subdivided into interconnected subnetworks. In particular, SSSA carried out the definition of Flowmaster multifluid steady state models of the following three ILVA/AMI gas sub-networks: BOFG network, BFG network and COG network.
A detailed description of the developed models is reported in **Deliverable 3.1**. Here, as an example, the model of ABG gas and steam network is reported (see **Figure 10**).

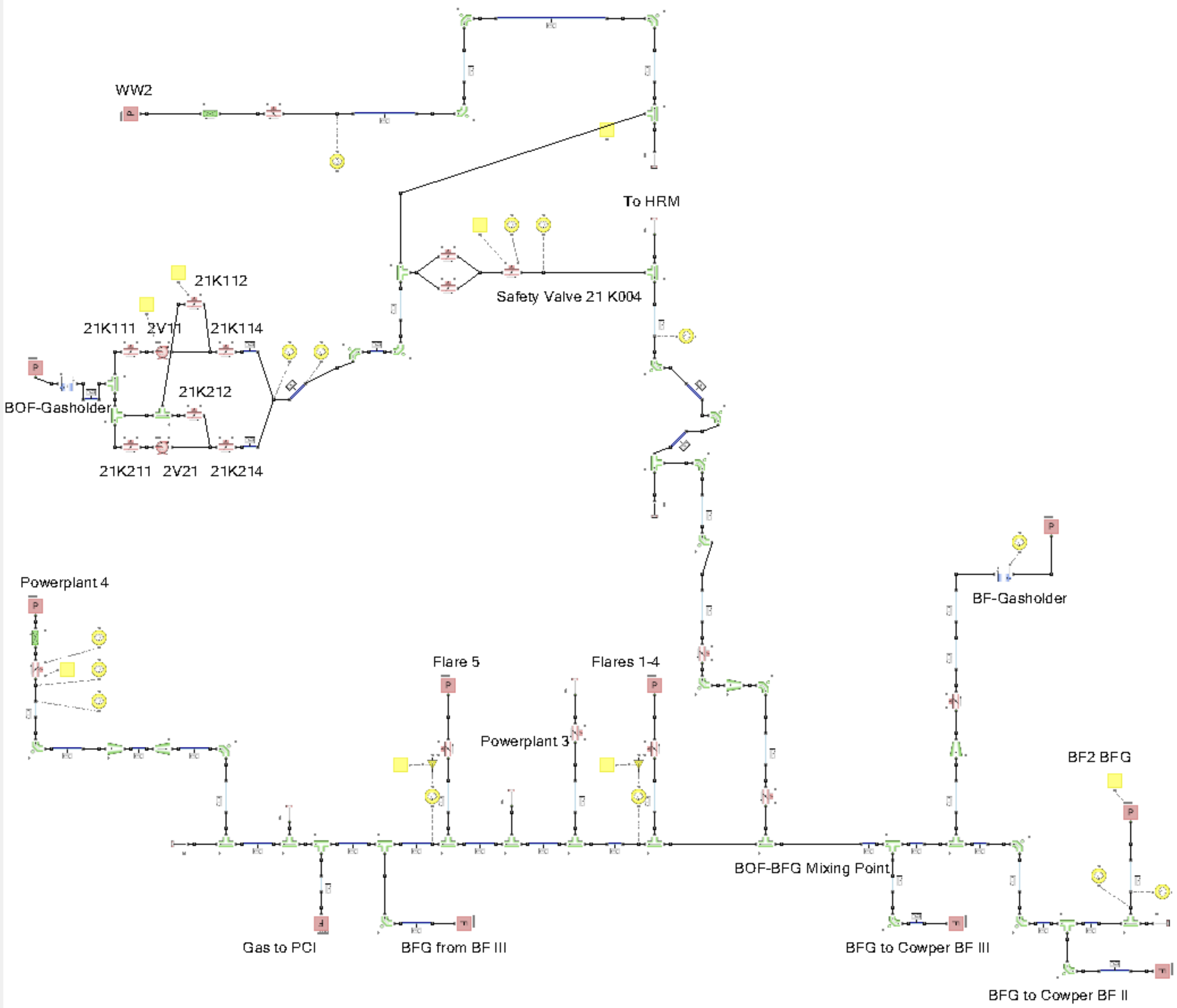


Figure 10: Scheme of the Flowmaster model of the ABG gas network

Table 2 summarizes the gas consumers and sources considered in the model. To enable a correct calculation of gas flows and pressure distribution some consumers are defined as flow sinks while the other consumers and the gas sources are defined by their pressure. First component in the BOFG network is the gasholder, since the BOF cannot be modelled in Flowmaster. The fans in the BOFG network (2V11, 2V12) are defined according to data from the supplier. The roughness of the pipes was assumed with 0.5 mm, due to the fact that the pipes are long standing and that deposits are likely. However, the influence of the pipe roughness to the pressure distribution is minimal due to the big diameter of the pipes (between 1 and 3 m).

Consumers	**Sources**
Hot rolling mill (WW2)	BOF
Cowper BF 2	BF 2
Cowper BF 3	BF 3
Flares 1 - 4	
Flare 5	
Pulverized coal injection (PCI)	
Power plant 4	

Table 2: Considered gas consumers and sources in the Flowmaster model

After implementation of the network the model was validated according to measured process data from ABG. **Table 3** shows the validation results. Yellow marked values are process data from ABG and grey marked values are calculated data of the Flowmaster model. It can be seen that the accuracy of the model is quiet good for most of the parameters. Improvements of the model accuracy are necessary in terms of cases with high BOFG gas flows. Nevertheless, the conclusion is that the model can be used to give evidence to the gas flow and pressure distribution for different scenarios and operation conditions. Thus, it was used to create a data basis for the prediction models (see following chapters), in case of lack of measured data.
As an overall outcome of the Flowmaster modelling work, the developed models of the gas and steam networks can be used to give evidence to the volume flow and pressure distribution for different scenarios and operating conditions. The influence e.g. of single gas/steam consumers or suppliers on the whole network can be evaluated. Further the duration of periods can be identified, in which rapid changes, e.g. triggered by an emergency shut down of a plant, have an influence on the network. With all this information it has been possible to decide, whether the impact of consumers/suppliers and sudden changes on the overall network behaviour was relevant or not for the control models.
The following simplifications appeared reasonable for both control model and gas network simulation:

- The dominant time constant of the networks is determined by the dynamic of the gas storage. It is here in the range of 10 - 20 minutes for the BOF and BF gas network.
- The balancing oscillations in the network caused by fast switching events do not need to be modelled, as they disappear in less than 1 minute.

		01.05.2016 00:03	01.05.2016 00:42	05.05.2016 15:00	07.05.2016 14:31	10.05.2016 17:04	19.05.2016 00:57	19.05.2016 01:38	26.05.2016 15:12	26.05.2016 15:13	28.05.2016 03:30
p_BOFG_trans_meas	mbar	105,940	103,970	102,863	102,902	21,525	104,478	106,260	107,676	110,666	105,928
p after fan 2V11	mbar	103,340	103,660	99,210	100,450	21,740	103,210	107,720	106,430	105,920	102,440
p_BOFG_pipeBFG_meas	mbar	47,651	45,874	56,078	43,597	48,408	64,870	61,844	56,482	55,350	53,757
p BOFG supply (BOFG pipe)	mbar	49,800	49,680	50,180	50,100	48,180	53,040	46,550	51,190	50,820	50,540
p_MG_pipeHSM_meas	mbar	97,425	96,215	96,288	96,071	16,304	98,147	98,951	95,919	99,119	98,367
p pipe to WW2	mbar	99,850	100,010	95,660	98,630	21,740	102,350	104,470	99,850	99,360	99,050
p_BFG-MG_trans_meas	mbar	50,280	49,353	50,268	46,544	51,341	55,533	50,510	52,446	51,655	51,498
p BFG net	mbar	49,750	49,720	49,400	50,720	48,180	53,310	47,180	50,710	50,340	50,060
vF_BOFG_trans_meas	kg/s	23,088	18,233	18,060	13,439	0,000	9,777	16,944	34,890	34,501	21,960
BOFG mass flow after gasholder	kg/s	18,599	18,528	19,720	13,015	0,000	8,932	17,483	26,443	26,387	19,148
vF_BOFG_pipeBFG_meas	kg/s	3,551	0,000	13,111	0,000	0,000	0,000	0,000	11,550	11,268	10,357
BOFG mass flow to BFG net	kg/s	2,485	0,000	13,698	0,000	0,000	0,000	0,000	10,366	10,353	10,370
vF_BOFG_pipeHSM_calc	kg/s	19,475	18,204	4,158	12,707	0,000	10,965	17,331	23,832	23,310	10,743
BOFG mass flow WW2	kg/s	16,114	18,528	6,022	13,015	0,000	8,932	17,483	16,076	16,035	8,777
vF_BFG_flare5_meas	kg/s	0,000	0,000	0,000	0,000	0,000	114,005	111,978	0,000	0,000	0,000
Gas mass flow flare 5	kg/s	0,000	0,000	0,000	0,000	0,000	115,866	111,699	0,000	0,000	0,000
vF_BFG_flares1to4_meas	kg/s	0,000	0,000	0,000	122,849	0,000	32,009	74,253	0,000	0,000	0,000
Gas mass flow flare 1-4	kg/s	0,000	0,000	0,000	124,593	0,000	33,731	74,050	0,000	0,000	0,000

Table 3: Validation results of the Flowmaster model of the ABG gas network

4.3.2 Task 3.2 Process models for considering the effects of scheduling on gas and steam production/consumption.

The overall aim of this task is the development of process models forecasting the main quantitative and "qualitative" features of the off-gases produced by the producing processes as well as the demand of the main off-gas consumers processes. A detailed literature analysis related to the state of the art highlighted, for instance, that no linear correlations exist between the BF gas (BFG) variations and the most relevant process parameters. On the contrary, complex nonlinear relationships link the BFG quantity and quality to the different affecting factors. According to this result, the models design has been mostly carried out by following a hybrid data-driven approach, which considered some aspects related to the physical and chemical process features, through a suitable selection and management of data. NN-based models, for the most complex and highly non-linear processes, have been selected, while equation-based models (based e.g. on piecewise linear and Hammerstein – Wiener Models) have been applied for other processes showing simpler dynamic behaviour.

Most of the NN-based models have been developed by using Echo State Neural Networks (ESN) through an ad-hoc developed Matlab® based toolbox. An ESN (**Figure 11**) is a recurrent NN with a sparsely connected hidden layer that exhibits dynamic temporal behaviour [1-4].

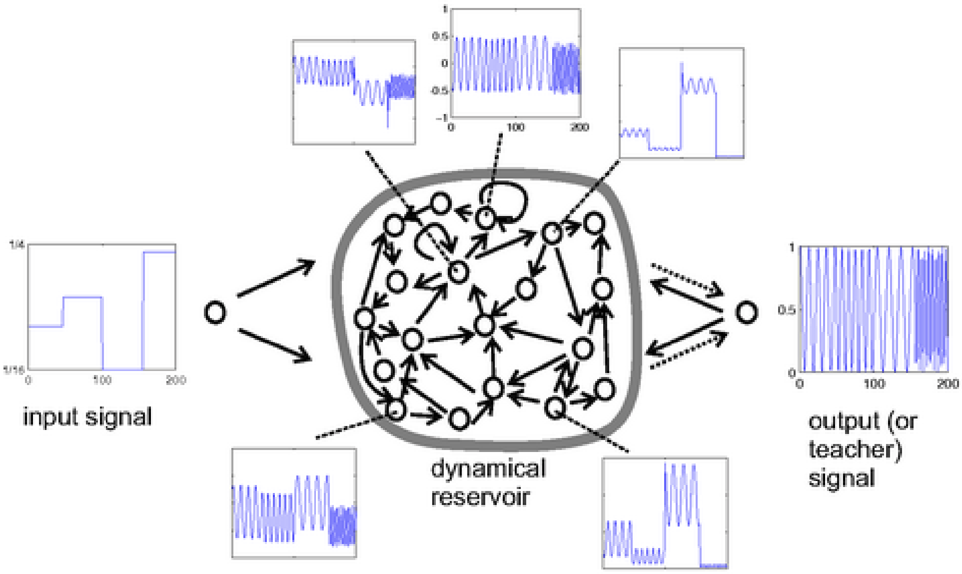


Figure 11. Basic ESN structure [1]

The main idea of ESN network can be summarized as follows:

1. Driving a random, large, fixed recurrent NN (dynamical reservoir) with the input signal and considering the output feedback (if required by the task);
2. Inducing a nonlinear response signal in each neuron within the reservoir network;
3. Reconstructing a desired output signal by a trainable linear combination of all the response signals.

The selection of this kind of NN derives from the very good results, which have been found in literature and according to their features. ESN are suitable when system states (related to the system/process changes during time) have to be taken into account. Moreover, they have a sort of internal dynamic memory that takes into account the internal response of correlated and past states.

The procedures to tune all the models are available for all the partners, by thus allowing them to autonomously maintain and update the models after the project completion without the need to acquire further software licences. Such approach is intended to improve the transferability of the models outcome throughout the EU steel industry.

The developed models are related to off-gases and steam production and demands and to the energy consumption by taking into account the effect of process scheduling. In the choice of the main units to be modelled, the need and the request of the industrial partners have been considered. Moreover, according to the requirement and specifications provided by the industrial partners themselves, the required forecasting time horizon is 2 hours with a frequency of prediction between 1 and 15 minutes depending on the process or the plant unit.

The accuracy of the NN-based models has been evaluated by considering several error indicators. Among such indicators, the Percentage Error Err_3 is computed as follows (considering that FOt and ROt are respectively the forecasted and real outputs):

$$Err_3 = \overline{\left(\frac{|FOt - \mathrm{ROt}|}{\overline{ROt}}\right)} \cdot 100$$

This index is computed under request of the industrial partners, as it is simpler to visualize and understand by the operators with respect other ones. In addition, the index *NMAE* is useful for assessing the performance of models related to discontinuous processes, as the average error is normalised by the whole range of variation of the target variable.
All the developed models have been described in details in **Deliverable 3.2**. In the following, as exemplar cases, the models of the BOF gas production and of the consumption of mixed gas, BOFG and NG in the HSM are presented.

BOF gas production

The conversion of pig iron in steel is a very dynamic process and is characterised by a highly non-linear relationship between process parameters and amount and quality of produced off-gas. Therefore, a complex model has been developed, by exploiting the features of multiple ESNs, in order to obtain a quantitative prediction of the recoverable gas in terms of volume and heating power and a qualitative idea of flareable and total volume flows and heating power with a frequency of 1 minute and for the next two hours. The qualitative feature of the prediction of flareable and total BOF gas (BOFG) volume flows and heating powers depends from the accuracy of data available for the flared gas, which is not comparable to the accuracy of the data related to the recovered gas. The model has been conceived as a single model independently from the number of converters, but it can be converted into separated models by just adding as input data the "Converter use program" (which converter is used in the next 2 hours). Five separated ESNs need to be tuned in order to individually predict recoverable, flareable and total BOFG and CO and H_2 contents in the gas. So doing, each neural network is specialised and the computational burden in the training phase is not excessive (almost 1 hour by using 450000 data with a frequency of sample of 1 minute and by exploiting for the training phase 70% of the available data, while 30% of the data are used for the validation). The CO and H_2 content are the variables, which are exploited to compute the NCV; then such value is combined with BOFG volume flows to obtain its heating power. Most of the inputs (including the BOF plant unit states) are common among the different ESNs but other additional inputs related, for instance, to some materials of the charge are used only in some ESNs. These are the most correlated parameters with respect to the related targets and they have been selected both through a preliminary correlation analysis and by discussing with the technical personnel of industrial partner.
The structure of the BOFG production model is illustrated in **Figure 12**.

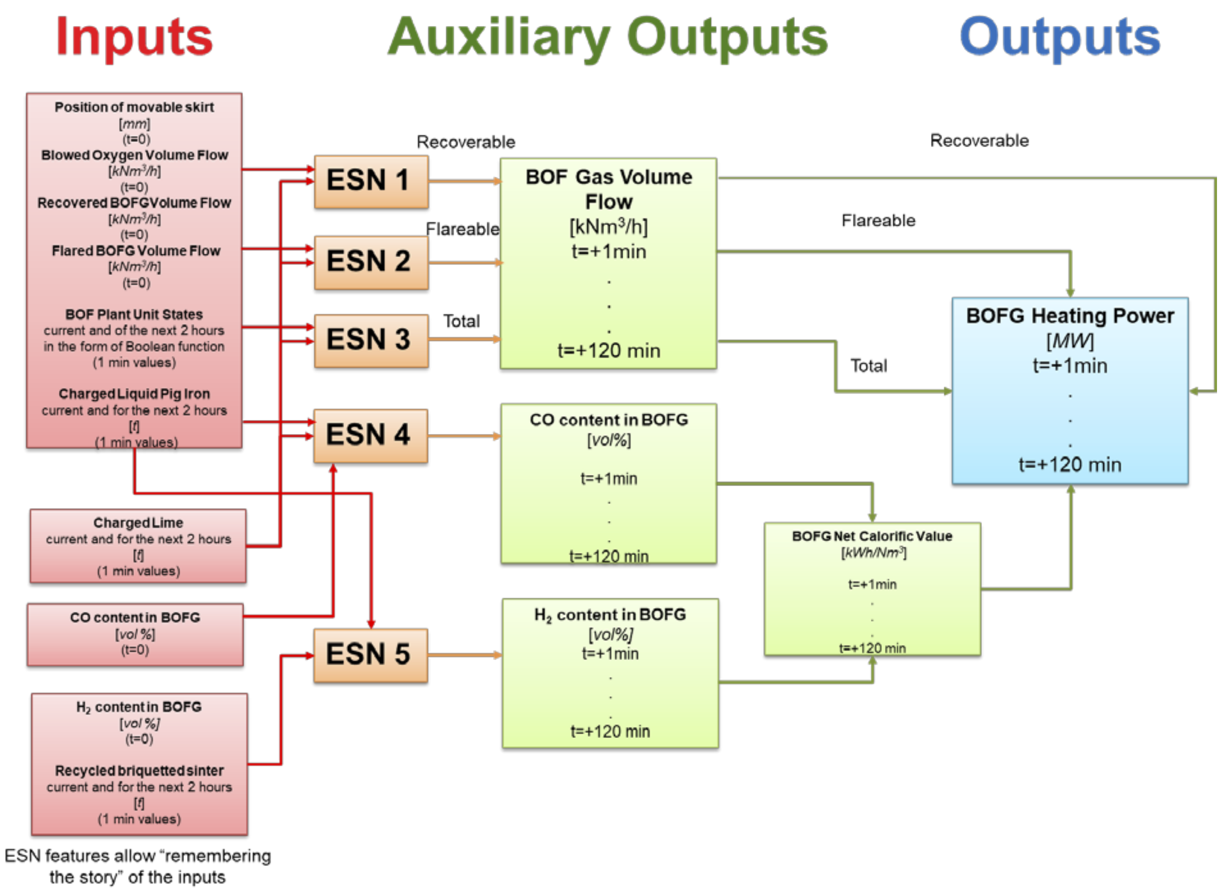


Figure 12: Structure of the model developed to forecast BOFG production

All the exploited ESN are standard Echo State Network without target feedback (such as described in the Mid Term Report), having a connectivity parameter (percentage of connection number between reservoir units) defined as the minimum between $\frac{10}{reservoir\ units}$ and 1. They exploit hyperbolic tangent and identity respectively as reservoir and target activation functions.
There are 7 parameters to be tuned/optimized for each ESN:

- Reservoir Units (number of state neurons)
- Spectral Radius
- Input Scaling
- Teacher Scaling
- Noise Level
- Input Shifting
- Teacher Shifting

Training of the ESNs is carried out offline by exploiting a training set containing 70 % of the whole dataset (the other fraction of the dataset is used for validation); 10 month of data are sufficient in the training procedure. During the training, the Reservoir-Target Weights (Output Weights) are computed. The training is carried out by following the Pseudoinverse Weight calculation method (see Midterm report for more details). The tuning of the model is manual and the objective is the minimization of the previously defined errors. In particular, preliminary analyses show that a suitable range of number of neurons is 400-600.
The model has been offline trained and tested by exploiting real data, which have been provided by the industrial partners and are related to some months of production (450000 data related to a period of 10 months). **Figure 13** shows the prediction error for BOF recoverable gas volume flow and heating power. The model is considered suitable for the purposes because it is able to give a good indication of the BOFG production in the considered time horizon, as depicted in the example of prediction in **Figure 14**. The data have been normalized because of confidentiality reason.

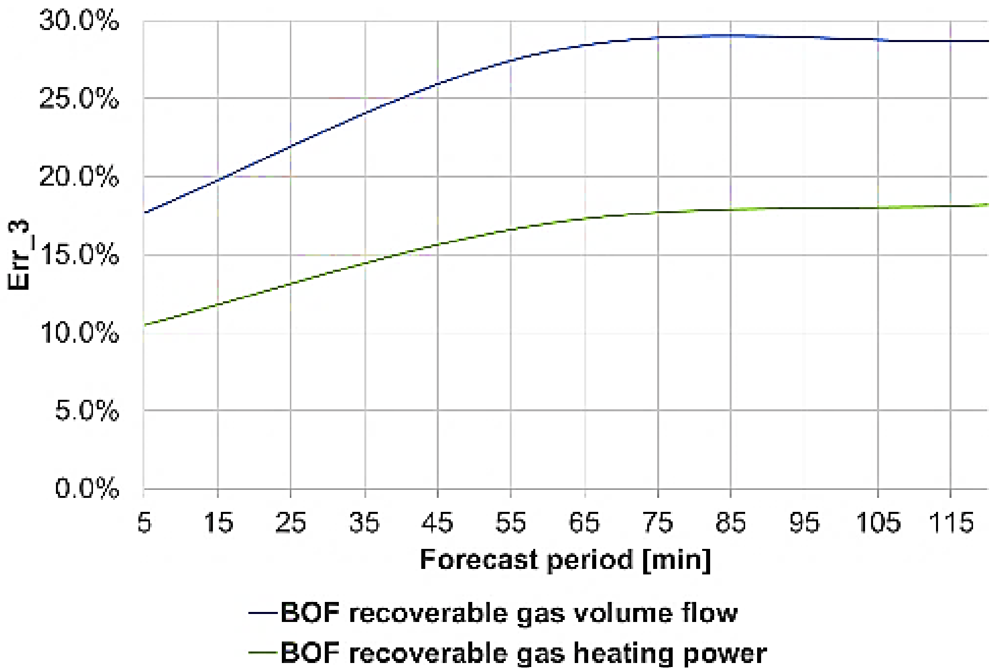


Figure 13: Error trends of BOFG production model for recoverable gas volume flow and heating power

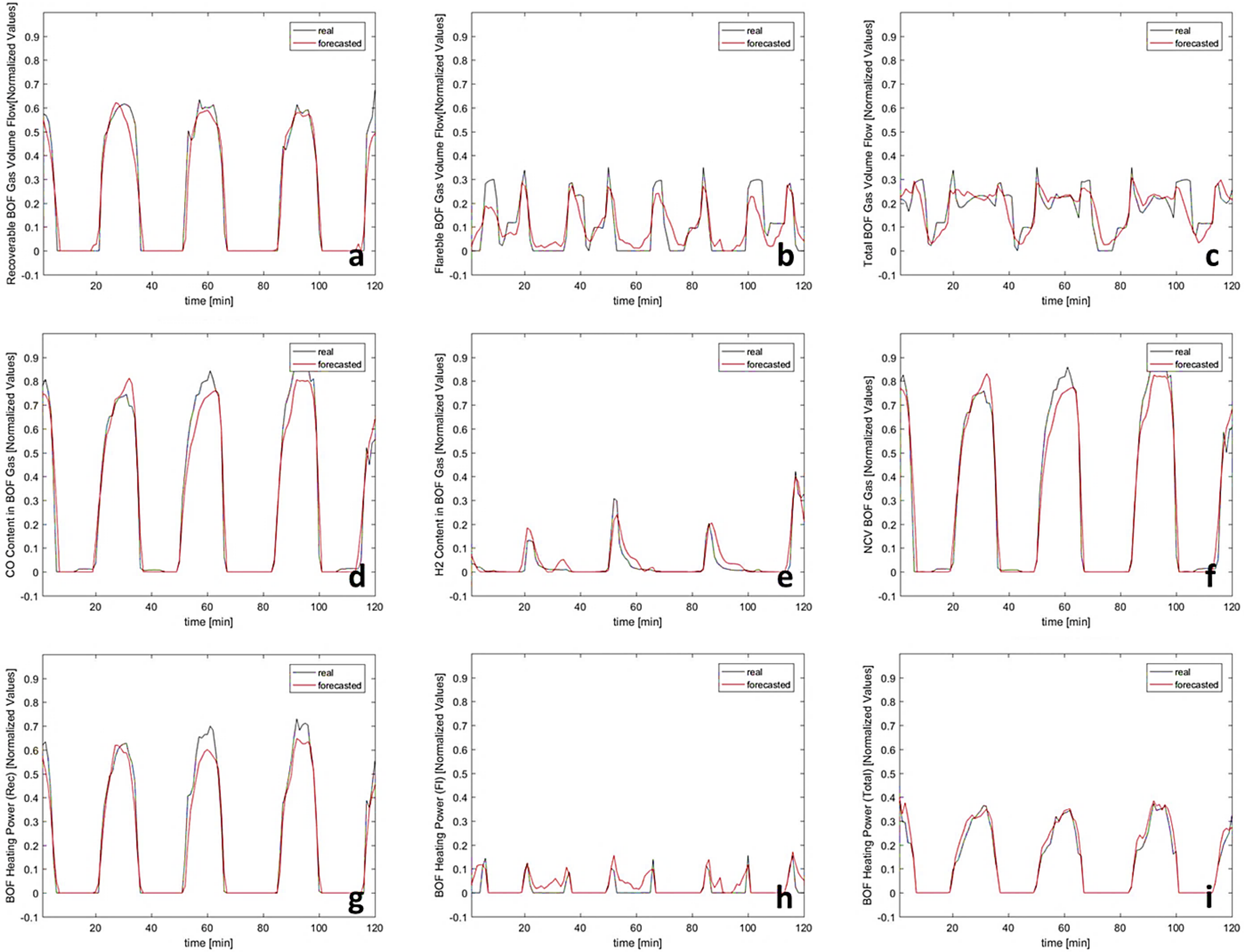


Figure 14: Comparison between real and forecasted values of BOFG production model for: a) recoverable gas volume flow; b) flareable gas volume flow; c) total gas volume flow; d) CO content; e) H_2 content; f) NCV; g) recoverable gas heating power; h) flareable gas heating power; i) total gas heating power.

Hot Strip mill

The NG consumption is calculated according to the production plans of the hot strip mill. **Figure 15** schematically shows the material flow in the hot strip mill. Slabs are heated in parallel in three walking beam furnaces. From there, the slabs enter the roughing mill and the finishing mill. Finally, the strip is coiled up. The cycle time for the furnaces is determined by the time it takes to roll a finished strip from a slab. The next slab is thus basically triggered by when the finished strip leaves the HSM.

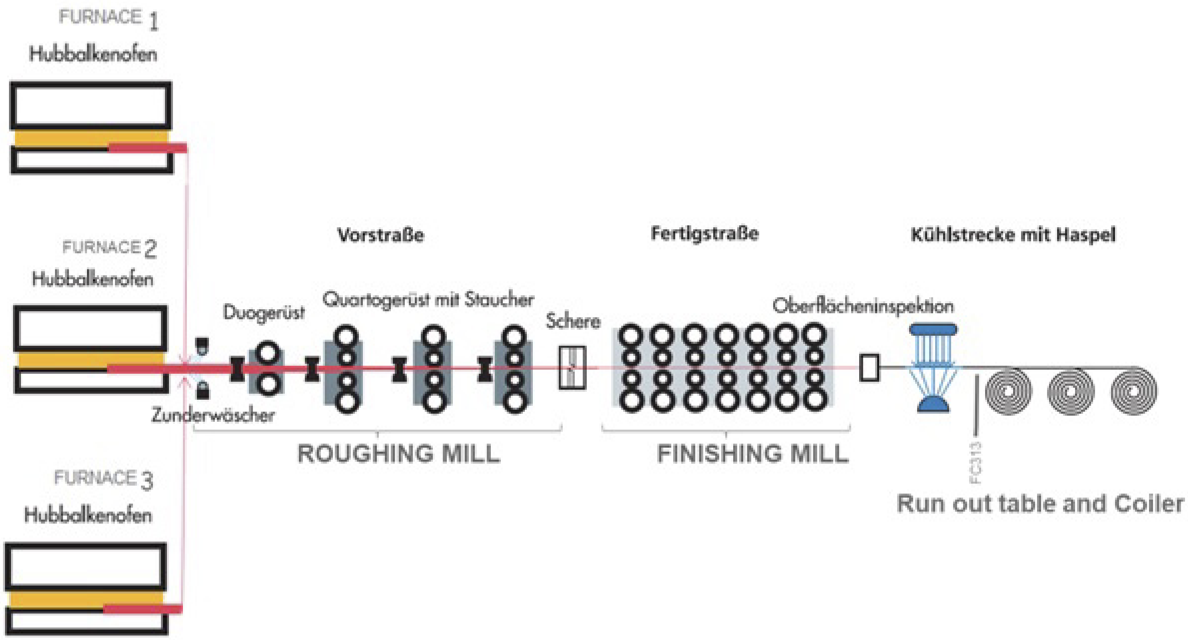
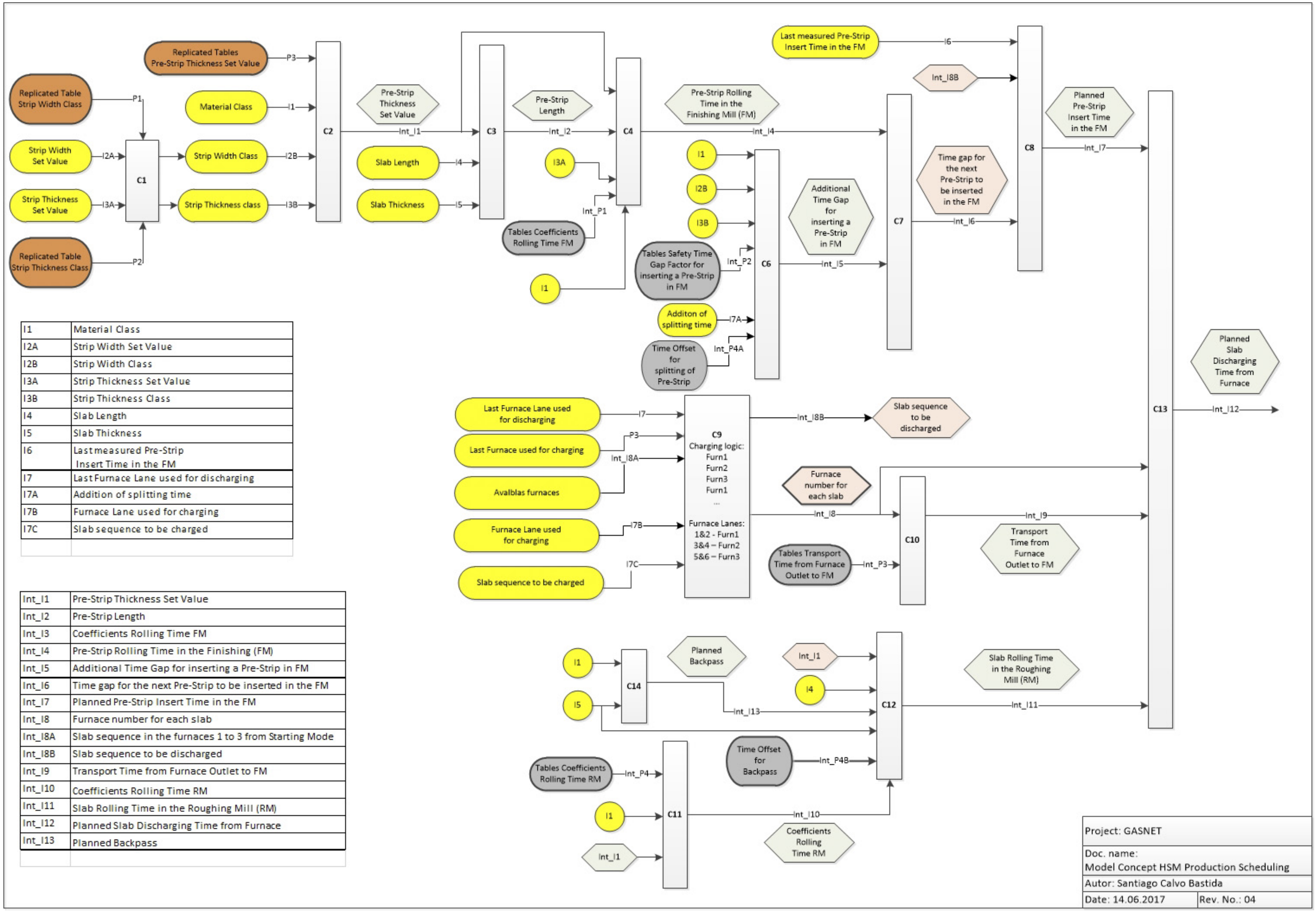


Figure 15: Overview of material flow in the hot strip mill

Figures 16 and 17 show the structure of the prediction model. In particular, **Figure 16** depicts the calculation of the "Planned Slab Discharing time form Furnace". This information is then used, such as depicted in **Figure 17**, for the calculation of natural gas and mixed gas consumption, as it essentially triggers the material flow in the individual walking beam furnaces. The Planned Slab Discharging time form Furnace is composed of the following part-times:

- Planned pre strip entering time in Finishing Mill (C1 - C8).
- Transport time form furnace outlet to Finishing mill (C9 - C10)
- Slab Rolling time in the Roughing Mill (C12 - C14).

Figure 16 shows that the gas consumption in C20 is calculated individually for each furnace zone and then combined in module C21 to form the total volume flow of natural gas and BOFG. Then block C22 calculates the volumetric flow of the natural gas and BOFG under the LCV of NG, BOF, and MIX gases.
Finally, **Figure 18** shows the structure of the model for predicting electrical energy.



I1	Material Class
I2A	Strip Width Set Value
I2B	Strip Width Class
I3A	Strip Thickness Set Value
I3B	Strip Thickness Class
I4	Slab Length
I5	Slab Thickness
I6	Last measured Pre-Strip Insert Time in the FM
I7	Last Furnace Lane used for discharging
I7A	Addition of splitting time
I7B	Furnace Lane used for charging
I7C	Slab sequence to be charged

Int_I1	Pre-Strip Thickness Set Value
Int_I2	Pre-Strip Length
Int_I3	Coefficients Rolling Time FM
Int_I4	Pre-Strip Rolling Time in the Finishing (FM)
Int_I5	Additional Time Gap for inserting a Pre-Strip in FM
Int_I6	Time gap for the next Pre-Strip to be inserted in the FM
Int_I7	Planned Pre-Strip Insert Time in the FM
Int_I8	Furnace number for each slab
Int_I8A	Slab sequence in the furnaces 1 to 3 from Starting Mode
Int_I8B	Slab sequence to be discharged
Int_I9	Transport Time from Furnace Outlet to FM
Int_I10	Coefficients Rolling Time RM
Int_I11	Slab Rolling Time in the Roughing Mill (RM)
Int_I12	Planned Slab Discharging Time from Furnace
Int_I13	Planned Backpass

Figure 16: Model structure for predicting charging times in HMS

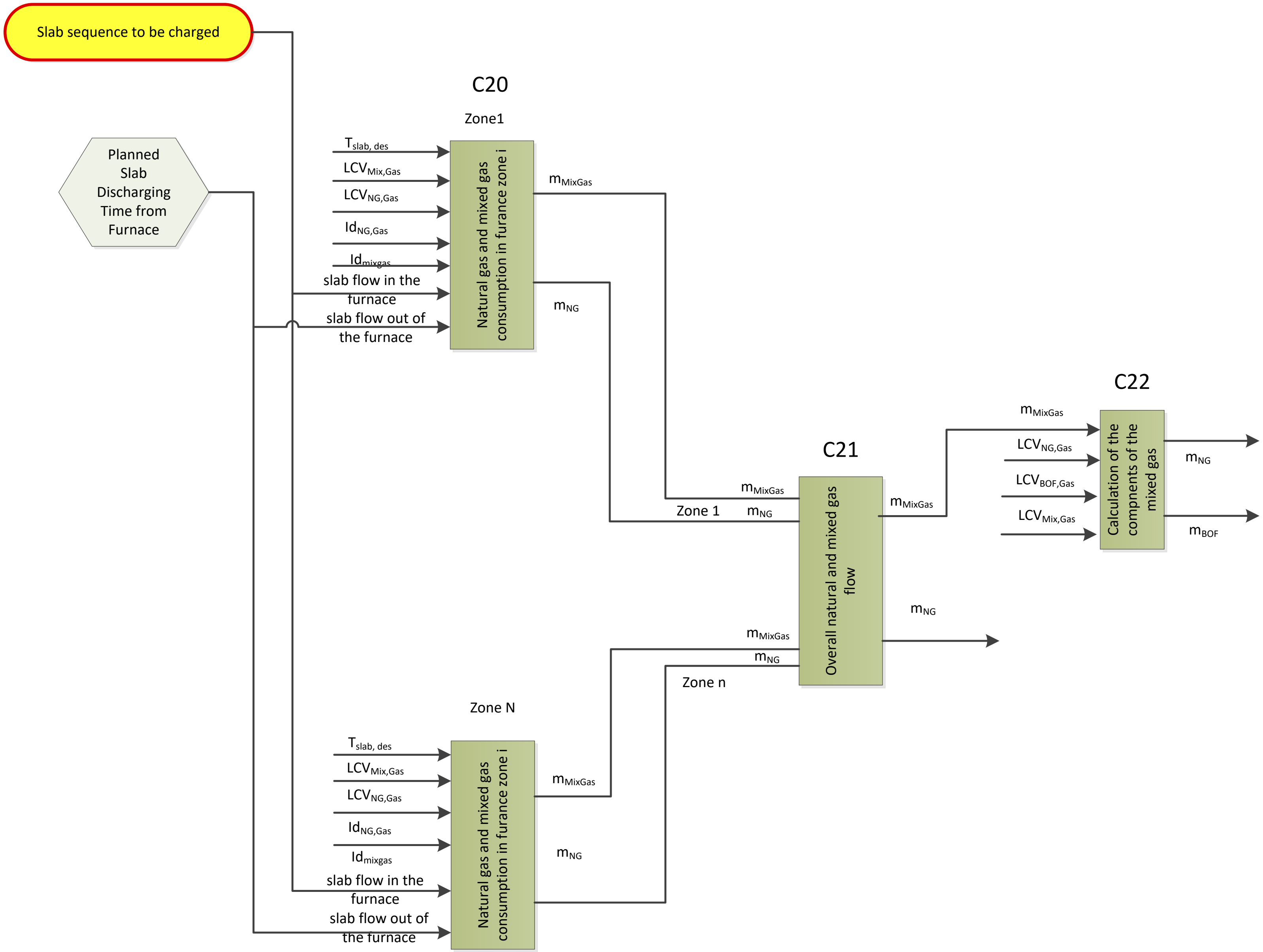


Figure 17: Structure of the model for mixed gas, BOFG and NG consumption in the HSM

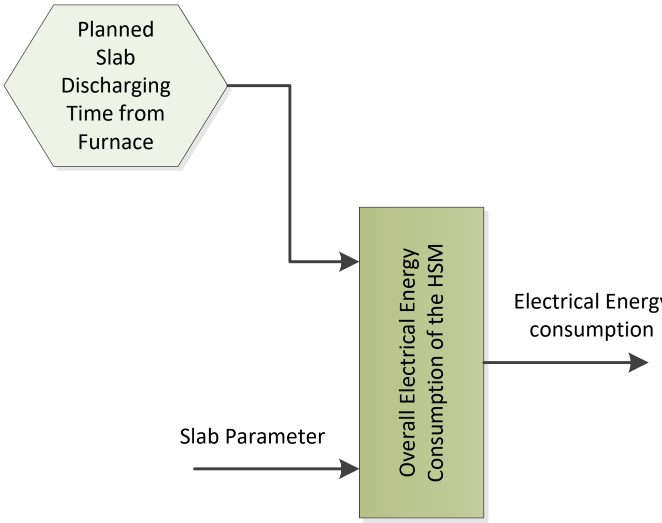
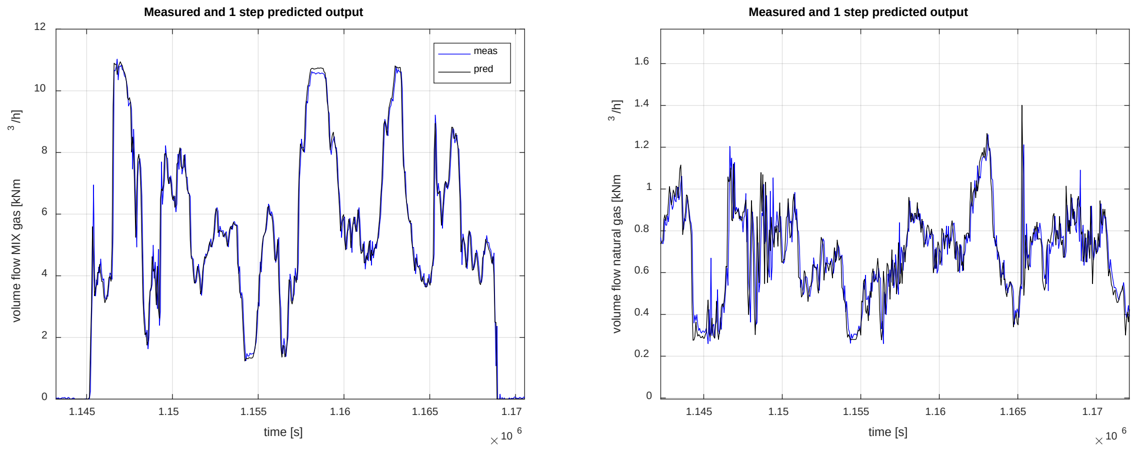


Figure 18: Model of the Electrical Energy Consumption

The accuracy of the model is sufficient for the controller design in WP5 because the accuracy of the one-step head prediction is essential here. These mode deviations only have to be less than 20-30 %. However, the accuracy of the model decreases significantly if prediction have to be made further into the future. Therefore, depending on the achieved control results, the model accuracy may have to be improved.
One reason for the inaccuracy is the following: oven is essentially a low-pass filter. If we want to identify the inverse function, we usually have to deal with a high pass filter with a very abrupt changes. This is difficult to identify with high accuracy. An alternative approach would be to identify the model in a forward direction. In this case, however, measurement of the furnace temperature is necessary. And then use optimization to estimate energy consumption (the so-called regulator problem).
If the walking beam furnaces are controlled by a Model Predictive Controller (MPC), it should be checked whether the prediction of this controller can be used as a prediction of energy consumption.
Due to the model inaccuracy, WP4 and WP5 take into account approaches from the field of robust MPC, which are excellent at dealing with these inaccuracies. This fact can limit the modelling effort.
The accuracy of the models is calculated as follows:

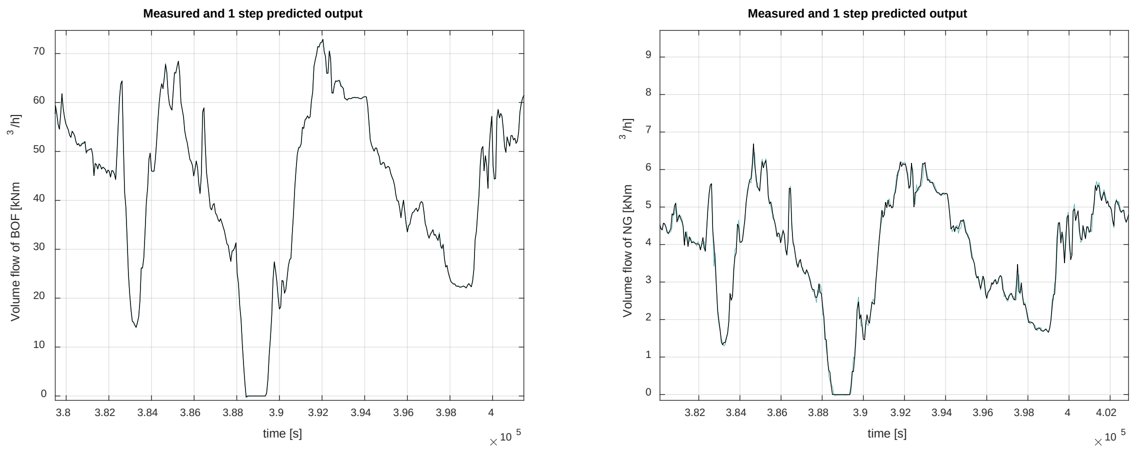
$$Fit = \frac{1 - \|\boldsymbol{y} - \hat{\boldsymbol{y}}\|}{\|\boldsymbol{y} - \bar{\boldsymbol{y}}\|} * 100\%$$

where $\boldsymbol{y}$ describes the measured value, $\hat{\boldsymbol{y}}$ describes the estimate and $\bar{\boldsymbol{y}}$ represents the average over time value of the measurement.
Two examples of prediction accuracy are provided in **Figure 19** and **Figure 20** related to the 1 step head prediction for the mix gas consumption and the BOF consumption, respectively. In the first case, the value of *Fit* for 1 step ahead prediction is between 80 - 95 % and decreases with increasing prediction width. For the design of the controller, this is sufficient in the first step and may need to be improved for the disturbance prediction. In the second case, the value of Fit for 1 step ahead prediction is between 98,3 %, which is very high.



a) b)

Figure 19: a) 1 step ahead prediction for the mix gas consumption; b) the consumption for the natural gases in zone 2 of the furnace 1.



a) b)

Figure 20: a) 1 step ahead prediction for the BOF consumption; b) the consumption for the natural gases in zone in the mixing station.

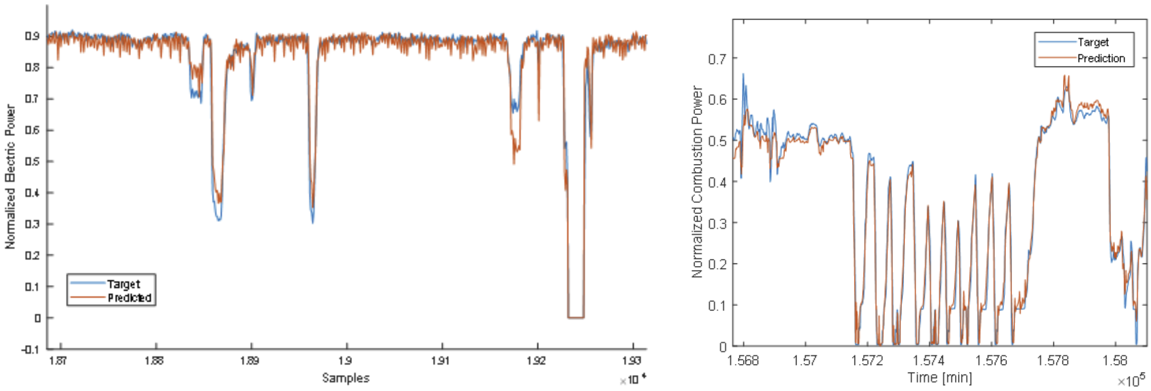
4.3.3 Task 3.3 Models of energy transformation equipment

In this task, a library of models for the relevant energy transformation equipment have been developed. To this aim, standard FeedForward Neural Networks (FFNN) and linear regression models proved to be sufficient to achieve adequate accuracy, although also ESN-based models have been tested. The models have been validated with real data not used for their tuning. In the following, the main developed models are briefly presented. The detailed models descriptions are provided in **Deliverable 3.4**.

Expansion Turbine

An efficient way to recover energy from off-gas production is to use the gases into expansion turbines, that allow, through an electric generator, to produce electricity. In metal manufacturing it is possible to expand BFG production, obtaining electric power and also allowing the outlet gas pressure to be controlled before being sent to relative gas network.

In this case, the electrical power generation could be forecasted using the produced volume flow of BFG expanded in the turbine. The turbine efficiency depends also on the volume flow. For these reasons, it was sufficient to model the nonlinear function of the turbine efficiency. A fast and efficient way to model this relationship is the use of simple neural networks; in particular the Feedforward Neural Networks (FFNNs) was used in this case of study. The model has been trained and tested by exploiting real data, which have been provided by the industrial partners. An example of the prediction accuracy is provided in **Figure 21.a**, where predicted and real values are compared. The prediction is acceptable for the quantitative forecasting.



(a) (b)

Figure 21: Comparison between real and simulated data for: (a) electrical power generation of the expansion turbine; (b) combustion power of the auxiliary boilers.

Auxiliary Boilers

In metal manufacturing the main producers of steam are typically the BOF LD plants and the electric power plants, but it is common to balance the steam demand through auxiliary steam generators that have fast start-up dynamics. Auxiliary boilers typically have different burners that allow producing steam through the exploitation of off-gas (e.g. BFG) and natural gas (NG).

In this case, the main modelled behaviour is the thermal power required for the production of a demand of steam mass flow. The thermal power is computed as follows:

$$W_{\text{thermal}} = \sum_{i=1}^{n} \dot{m}_i \cdot NCV_i$$

where *i* is the *i-th* type of gas, NCV_i is the Net Calorific Value of the *i-th* gas type and $\dot{m}_i$ is the gas flow used during the combustion.

According to this objective, it is sufficient to model the nonlinear behavior of the combustion efficiency. A fast and efficient way to model this relationship is the use of simple neural networks; in particular the Feedforward Neural Networks (FFNNs) was used in this case of study. The model has been trained and tested by exploiting real data, which have been provided by the industrial partners. The prediction is acceptable for the quantitative forecasting. An example of the prediction accuracy is provided in **Figure 21.b,** where predicted and real values are compared.

Forecasting of electrical power generation from power plant

The aim of the model is to forecast every 15 minutes for the next 2 hours the electricity generated by the power plant burning a mix of steel gases. This model is a simple model based on a regression between the gas heating power burnt into the power plant and the resulting generated electricity.

4.4 WP 4: Interactions among gas network, process schedule and electricity and gas demand

The objective of WP4 is the development of an integrated software tool for gas network modelling and optimization, handling different aspects of gas management which are relevant for the steelworks and which can be easily used by plant operators.

4.4.1 Task 4.1 Software architecture.

The software architecture of the GASNET system has been designed by taking into account the following main pre-requisites:

- Flexibility, in order to allow future improvements and extensions (e.g. new units, improved models, etc..). This requirement implies the adoption of a modular design and the need to provide the possibility to select the optimization procedure.
- Adaptability to different networks and different steelworks. This requisite demand for the availability of Basic elements which can be adapted to a wide variety of gas producers and consumers, provided that a model of production and consumption is available

- Easy use and configuration. This aspect implies that the main basic processes need to be available together with a plain and codified procedure to create and customize new processes. Moreover, a user-friendly graphical interface needs to be provided.
- License free software. This requirement implies that the available commercial softwares, which comes equipped with well tested user interfaces, cannot be used and a standalone code must be developed, which will necessary have a simpler and more schematic approach to modelling.
- Open source code. Such as clearly written in the proposal, all the code must be available for all the partners of the project, in order to face future maintenance issue.

Actually the GASNET dB helps collecting all the information required by the GASNET system for the off-gas distribution optimization, such as depicted in **Figure 22**.

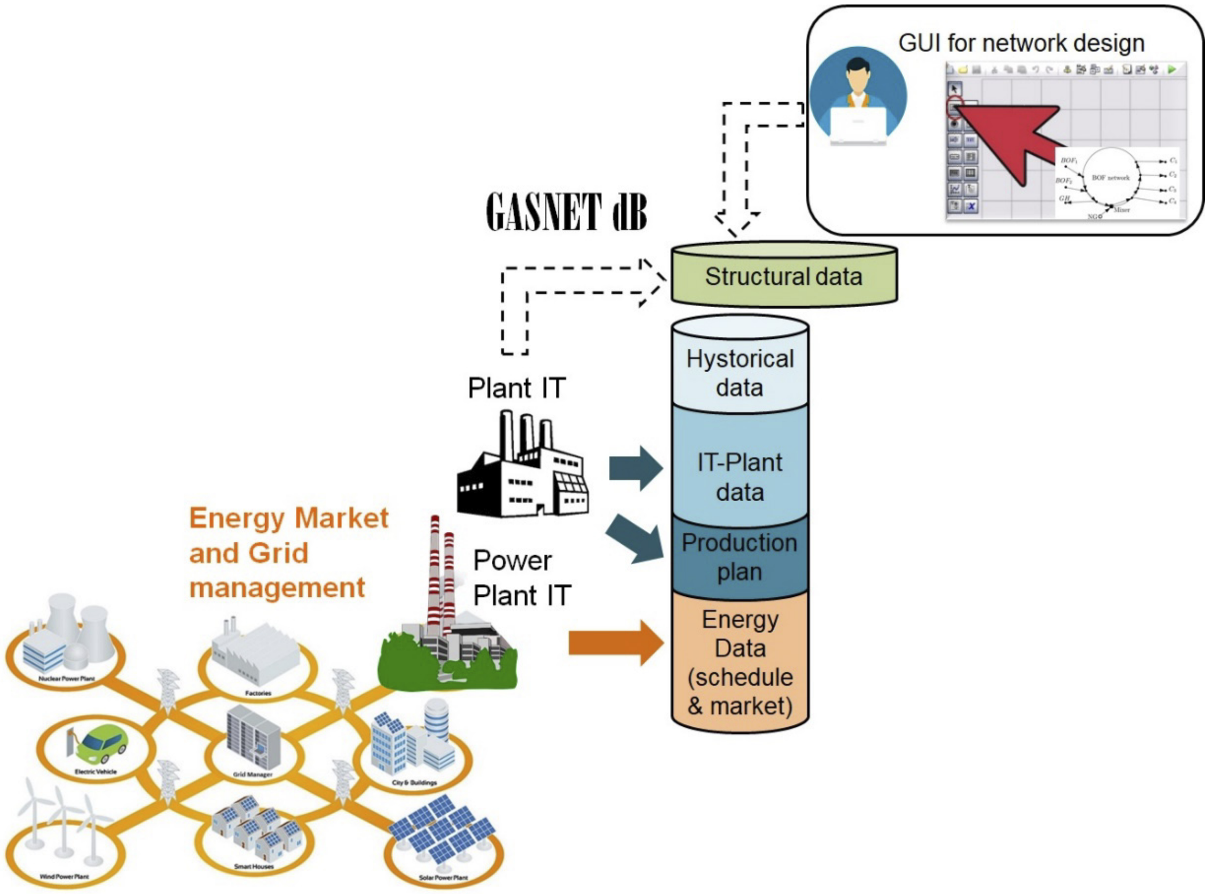


Figure 22: Summary of the information that needs to be conveyed to the GasNet tool

In particular, the database includes the overall structure of the off-gas and steam network, in order to customize the tool with respect to the specific needing of each plant. The database is also continuously fed by the data coming from the IT system of the plant, according to the study developed in the first period of the project within WP2. Among such data, the production schedule is also provided, which is fundamental in order to forecast the production of the off-gases and steam from the producers as well as the demand from the different consumers. This database also conveys the information coming from the Power Plants and from the energy market (e.g. the price of Natural Gas and possibly the price of electricity in the incoming period), as it is linked to the external energy grid manager.
The overall structure of the optimization tool is depicted in **Figure 23**: based on the data, which are continuously acquired from the plant, and on the most updated version of the production schedule (which is also coming from the IT system of the plant), some of the forecasting models developed in WP3 provide a prediction of the future off-gases and steam production (e.g. in next 2 hours). Such predictions take into account the variability due to the process schedule and are an input for the power generation scheduling and optimization tool. Such optimization layer exploits the information coming from the power plant and from the energy market in order to establish the best trade-off between the internal and

external demand of energy, considering also the price of Natural Gas (NG) and of electricity. This layer provides to the lower levels the target consumption of off-gases and Natural gas and receives from them an updated version of the amount of off-gases which could be actually sent to the power plants in the next 2 hours, as well as the total NG demand as coming from the consumers included in the different subnetworks.

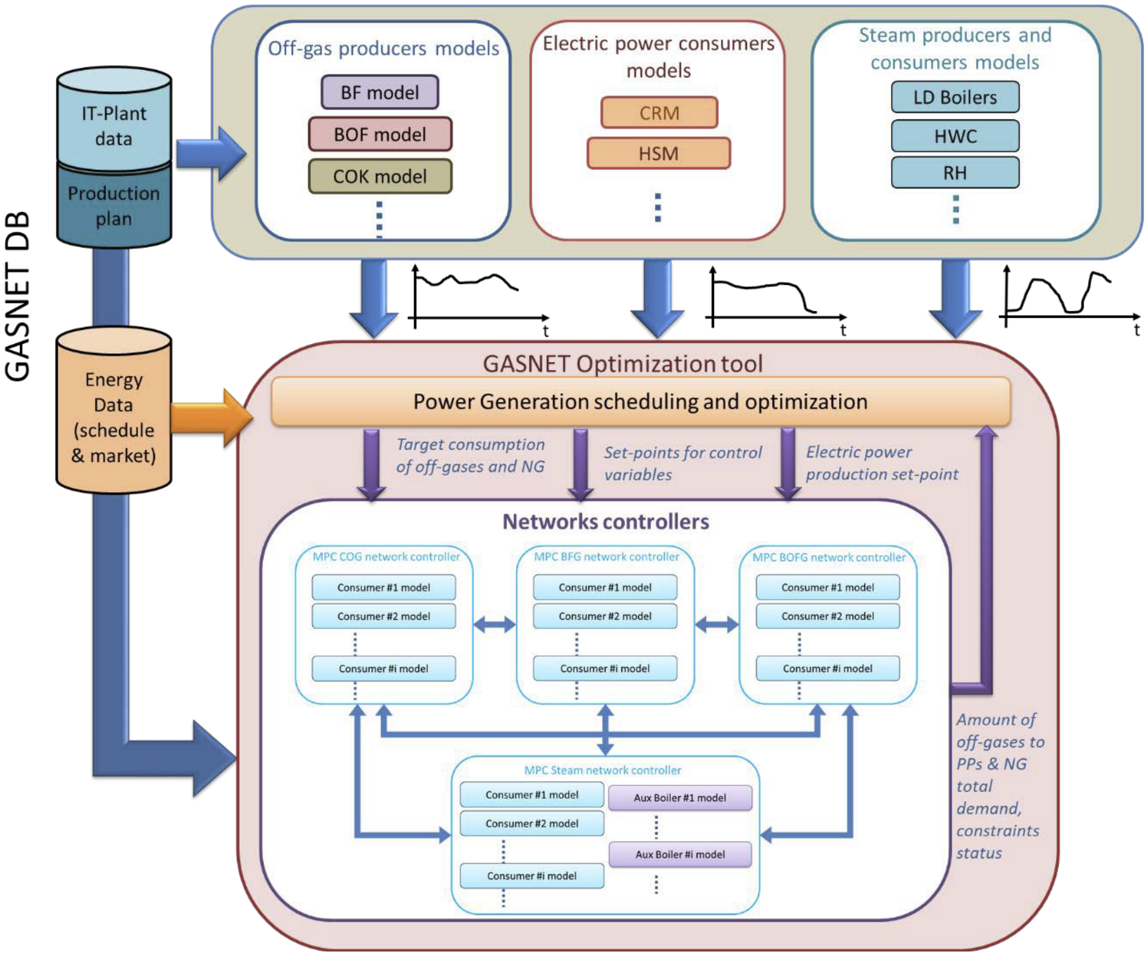


Figure 23: Overview of the GasNet Optimization tool

The GasNet tool also comes equipped with a Graphical User Interface (GUI) allowing easy and user-friendly exploitation of the different forecasting models and optimization levels, by also monitoring the performance of the GasNet tool itself. The GUI is articulated in different sub-units representing interfaces to the different components of the GasNet tool, according to the architecture schematically depicted in **Figure 24**.

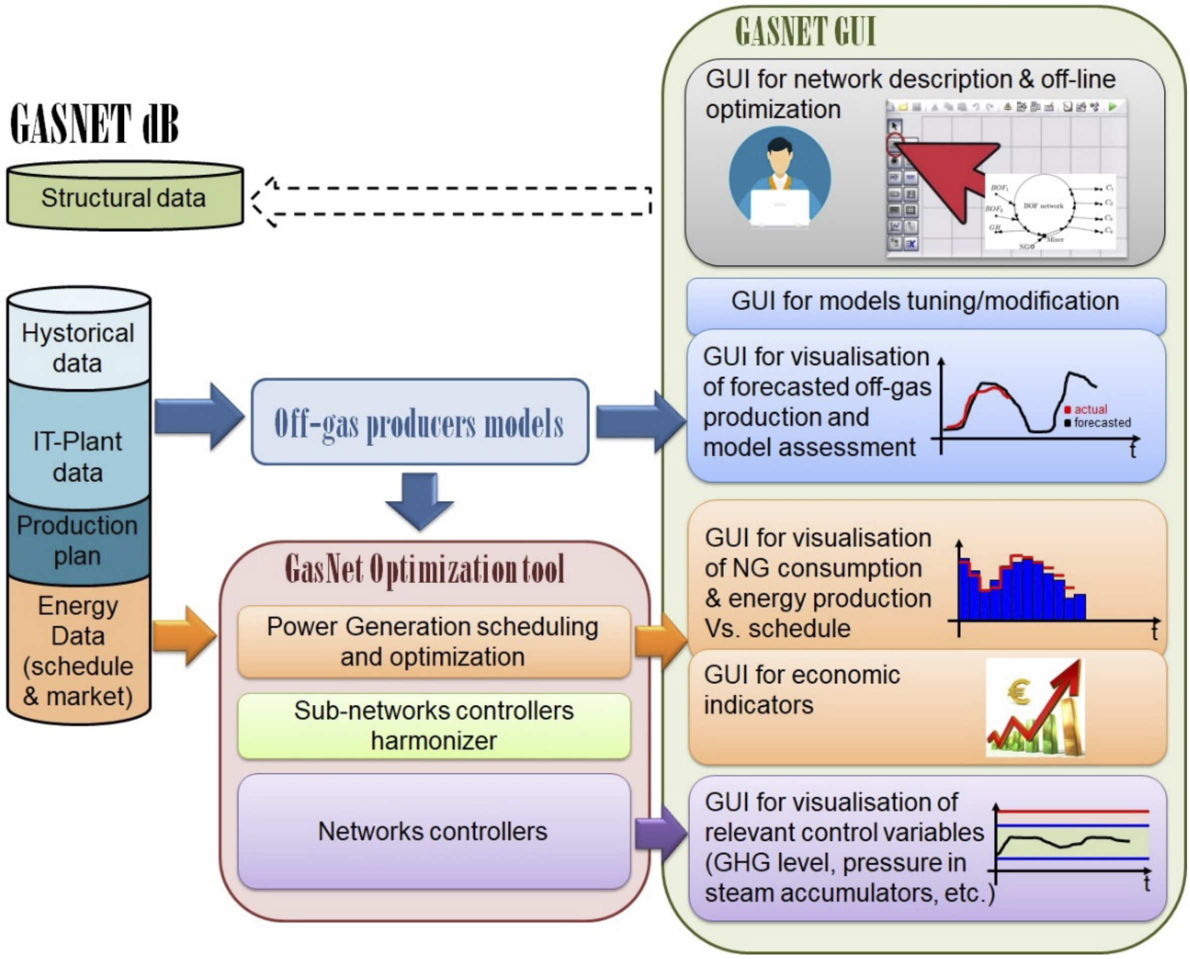


Figure 24: GasNet overall architecture and interaction between the optimization tool and the GasNet GUI

4.4.2 Task 4.2 Gas and steam network structure simulation and derived simplified network models

A steam and gas network is modeled as a digraph, where the vertices are the processes and the mixing nodes; the arcs are the pipes connecting the different nodes and are oriented according to the gas flow direction.

The producers are those processes producing gas and have a given negative demand (the amount of gas/energy that is produced). The consumers have a negative demand (the required amount of gas that must be sent to the consumer). A gasholder h is a vertex whose demand depends on the current filling level and it is in the range $[GHLmin(h), GHLmax(h)]$, where $GHLmin(h)$ and $GHLmax(h)$ are respectively the minimum and maximum possible filling level for the gasholder h.

Note that both producers and consumers have an energetic demand, while the gasholder demand (filling level) refers to the amount of $Nm^3$of gas it can contain.

When a mixture of more gases is flowing into the same pipe, the energy of the mixture is calculated as $\sum_g x_g \cdot LHV(g)$ where x_g is the amount of Nm^3 of gas g that is flowing and $LHV(g)$ is the lower heating value of gas g.

For each vertex an energetic balance must be formulated. Torches and consumers have a non-negative balance; natural gas providers and other producers must have a non-negative balance; gasholders balance must respect the minimum and maximum range, while all connection nodes must have a zero balance (all the gas that flows in must flow out).

There are volumetric lower and upper bounds on the amount of gas that must flow in every pipe.

A cost function is then established, taking into account the revenues obtained from selling gas to consumers and the costs of burning gas into torches or buying from natural gas providers and the cost of structural changes in the network like build or demolition of pipes.

This network structure with its constraints and the minimization of the cost function can be formulated as an optimization problem that falls under the category of QCQP quadratic constrained quadratic programming.
This kind of representation has been adopted also for the graphical representation of the network.
A graphic interface has been designed in order to provide all the parameters. The appearance of such interface is depicted in **Figure A.9**, which is a simplified representation of the ABG network. For confidentiality constraints, the parameters indicated in the **Figure A.9** (such as gasholders filling level or energetic demands) do not correspond to real data, but represent fictitious data of the same order of magnitude.
Through this interface, it is possible to manually build the network digraph and insert the needed values such as node numbers of consumers, producers, torches, gasholders, natural gas providers; energetic demands, costs and revenues for the objective functions, etc..
The interface displays the solution such as exemplarily depicted in **Figure A.10**. The amount of each gas type flowing in a pipe is displayed on the corresponding arc.
On the right side all the numeric values are reported: the *X* values represent the volumetric flow: *X(i,j)* is the volumetric flow from node *i* to node *j*, which is reported for each gas; the Y binary values are the activation values: *Y(i,j)=0,* if the pipe *ij* must be demolished (or not built) and *Y(i,j)=1* if the pipe *ij* must be kept in the network (or built).
A more detailed description of such interface as part of the off-line network optimization tool is provided in **Deliverable 6.1**, which is included in **Appendix A**.

4.4.3 Task 4.3 Constraints implementation

Let x_{ij}^g be the amount of Nm^3 of gas g that is flowing through the pipe starting from node i and connecting it with node j. The equation for the energetic balance of producers is the following:

$$\sum_{g,j}(x_{pj}^g - x_{jp}^g) \cdot LHV(g) = Eb(p)$$

Where $Eb(p)$ is the (negative) energetic demand for producer p.
Similarly, the equation for the energetic balance of consumers is the following:

$$\sum_{g,i}(x_{ci}^g - x_{ic}^g) \cdot LHV(g) = Eb(c)$$

where $Eb(c)$ is the (positive) energetic demand of consumer d.
Torches must have a non-negative balance, while natural gas (nitrogen) sources must have a non-positive balance. Thus

$$\sum_{g,j}(x_{tj}^g - x_{jt}^g) \geq 0$$

$$\sum_{g,j}(x_{nj}^g - x_{jn}^g) \leq 0$$

For every torch t and every natural gas (nitrogen) provider n.
Consumers might have lower (upper) bound for the inflow of a specific gas. Let $LowGasDemand(c,g), UpGasDemand(c,g)$ be the bounds for consumer c related to gas g, the following constraints are added:

$$LowGasDemand(c,g) \leq \sum_i x_{ic}^g \leq UpGasDemand(c,g)$$

Gasholders h have a current filling level $GHL(h)$ and a minimum (maximum) filling level $GHLmin(h), GHLmax(h)$ respectively. Therefore, the balance at every gasholder h is the following:

$$GHLmin(h) - GHL(h) \leq \sum_{g,j}(x_{hj}^g - x_{jh}^g) \leq GHLmax(h) - GHL(h)$$

There are lower and upper capacities l_{ij}, u_{ij} for each pipe from i to j. Therefore $l_{ij} \leq x_{ij}^g \leq u_{ij}$ for every g,i,j such that there is a pipe from i to j, and $x_{ij}^g = 0$ for every g and every i,j such that there is no pipe from i to j.

Given that different type of gases are possibly mixing into the same pipes, the concentration of gas $\bar{g}$ in the mixed flow entering a node $\bar{\iota}$ must be the same concentration is flowing out of $\bar{\iota}$ on every pipe $\bar{\iota}\bar{\jmath}$. Therefore, for every $\bar{\iota}, \bar{\jmath}, \bar{g}$

$$\sum_j x_{j\bar{\iota}}^{\bar{g}} \cdot \sum_g x_{\bar{\iota}\bar{\jmath}}^{g} = x_{\bar{\iota}\bar{\jmath}}^{\bar{g}} \cdot \sum_{j,g} x_{j\bar{\iota}}^{g}$$

These equations introduce non-linearity in the constraints, more precisely the constraints are quadratic and non-convex. This inevitably slows down the computation of an optimal solution.
When the node $\bar{\iota}$ is a gasholder containing multiple gases, let $GHL(\bar{\iota}, g)$ be the level of gas g contained in the gasholder $\bar{\iota}$, the mixing equations become, for every $\bar{\jmath}$,

$$\left(\sum_j x_{j\bar{\iota}}^{\bar{g}} + GHL(\bar{\iota}, \bar{g})\right) \cdot \sum_g x_{\bar{\iota}\bar{\jmath}}^{g} = x_{\bar{\iota}\bar{\jmath}}^{\bar{g}} \cdot \left(\sum_{j,g} (x_{j\bar{\iota}}^{g} + GHL(\bar{\iota}, g))\right)$$

Some nodes $\bar{\iota}$ can have a lower (upper) bound on the concentration of a gas $\bar{g}$. Let $lmix(\bar{\iota}, \bar{g})$ and $umix(\bar{\iota}, \bar{g})$ be these bounds. The following equations are added:

$$lmix(\bar{\iota}, \bar{g}) \cdot \sum_{j,g} x_{\bar{\iota}j}^{g} \leq \sum_j x_{\bar{\iota}j}^{\bar{g}} \leq umix(\bar{\iota}, \bar{g}) \cdot \sum_{j,g} x_{\bar{\iota}j}^{g}$$

Finally, some consumers might have a minimum or maximum lower wobbe index $Wobbemin(c), Wobbemax(c)$ of the inflow gas mix. Let $r_c(g)$ be the concentration of the gas $\bar{g}$ flowing to consumer c, namely
$r_c(\bar{g}) = \sum_j x_{jc}^{\bar{g}} \Big/ \sum_{j,g} x_{jc}^{g}$; the lower heating value of the mix at c is $LHV_{mix}(c) = \sum_g r_c(g) \cdot LHV(g)$; the specific gravity of the mix at is c is $Gravity_{mix}(c) = \sum_g r_c(g) \cdot Gravity(g)$. The lower wobbe index of a gas is defined as the ratio between the LHV of the gas and the square root of its specific gravity. Thus, at consumer c:

$$MinWobbe(c) \leq \frac{LHV_{mix}(c)}{\sqrt{Gravity_{mix}(c)}} = MaxWobbe(c)$$

Let P_{ng} be the price of purchasing one Nm^3 of natural gas. Let P_t be the price of burning one $Nm^3$of gas into a torch t and let P_{E_c} be the revenue from selling one MJ of energy to consumer c.
The function to minimize is the sum of all costs, minus the revenues

$$F(x) = \sum_{n \in NG, g} x_{ni}^{g} \cdot P_{ng} + \sum_{t \in TT, j, g} x_{jt}^{g} \cdot P_t - \sum_{c \in C, j, g} x_{jc}^{g} \cdot LHV(g) \cdot P_{E_c}$$

The problem of minimizing $F(x)$ subject to all the above constraints is a non-convex QCQP (Quadratically Constrained Quadratic Problem). It belongs to the category of NP-complete problems: it is computationally hard to find an optimal solution.
Once the network structure is formulated and all parameters are provided to the algorithm, the constraints are implemented as described above. The inequalities are linear and they can be represented in a matrix form $A \cdot x - b \leq 0$.
For example the inequalities related to the energetic demands of a node c are obtained as a scalar product of the vectors $A^c \cdot x$, where the row vector A^c is such that the entry related to x_{cj}^{g} equals $-LHV(g)$ if there is an arc from c to j, $LHV(g)$ if there is an arc from j to c, and 0 otherwise. The term b^c is simply the energetic demand of node c.
Similarly it is possible to implement all the linear equalities, inequalities and the objective function. In this way, once the adjacency structure is given, it is simple to construct the matrix for the linear constraints. The non linear (equality) constrains are implemented through a function that computes the quadratic terms as described in the equation for the mixing of gases. More precisely for every $\bar{\iota}, \bar{\jmath}, \bar{g}$

$$h_{\bar{\iota},\bar{\jmath},\bar{g}}(x) = \sum_j x_{j\bar{\iota}}^{\bar{g}} \cdot \sum_g x_{\bar{\jmath}\bar{\iota}}^{g} - x_{\bar{\jmath}\bar{\iota}}^{\bar{g}} \cdot \sum_{j,g} x_{j\bar{\iota}}^{g}$$

If the variables y_{ij} are added to the problem they are binary, so the problem falls in the class of integer problems. To keep the problem only in the class of non linear problems and avoid integrality constraints, the constraints $h_{ij}(y) = y_{ij} \cdot (1 - y_{ij}) = 0$ can be added: these equations force the variables y_{ij} being binary.
Once f, g, h are implemented they are given as input to the optimization algorithm that finds a solution of the problem.

4.4.4 Task 4.4 Framework for optimization strategies

Task 4.4 involved the development of a framework for solving the various optimization problems addressed. The developed framework consists of a series of libraries made up of free license software and algorithms developed internally during the project for specific applications. In particular, as regards the Linear Programming (LP) and Mixed Integer Linear Programming (MILP) problems, the open source libraries developed within the Google OR-Tools project were used, which incorporate a series of algorithms, commercial and non-commercial for the solution of the mentioned problems. Of the complex library mentioned, only the open-source algorithms that allow the development of industrial commercial applications, such as CBC (Coin-or branch and cut), have been exploited.
As regards the formulation of LP and MILP problems, reference can be made to the specific applications developed respectively within task 5.3/5.4 and 5.5.
As each network can be represented in the form of a digraph consisting of vertices and nodes, the following state space model applies to each vertex *i*:

$$\boldsymbol{P}_i := \begin{cases} \boldsymbol{x}_{k+1}^i = \boldsymbol{A}^i \boldsymbol{x}_k^i + \boldsymbol{B}^i \boldsymbol{u}_k^i + \boldsymbol{E}_k^i \boldsymbol{d}_k^i \\ \boldsymbol{y}_k^i = \boldsymbol{C}_k^i \boldsymbol{x}_k^i + \boldsymbol{D}^i \boldsymbol{u}_k^i + \boldsymbol{F}_k^i \boldsymbol{d}_k^i \end{cases}$$

or in short

$$\boldsymbol{y}_k^i = \boldsymbol{P}_i \circ \begin{bmatrix} \boldsymbol{u}_k^i \\ \boldsymbol{d}_k^i \end{bmatrix}$$

These describe the storage processes in the network (gasholder) or other dynamic processes for the dynamic supply of mixed gas. The following equation applies to the nodes in the network:

$$\boldsymbol{E}\boldsymbol{u}_k + \boldsymbol{G}\boldsymbol{y}_k = 0$$

with

$$\boldsymbol{u}_k = [\boldsymbol{u}_k^1 \quad \cdots \quad \boldsymbol{u}_k^n]^T \text{ and } \boldsymbol{y}_k = [\boldsymbol{y}_k^1 \quad \cdots \quad \boldsymbol{y}_k^n]^T \text{ and } \boldsymbol{d}_k = [\boldsymbol{d}_k^1 \quad \cdots \quad \boldsymbol{d}_k^n]^T$$

whereas $\boldsymbol{u}_k^i$ is the input, $\boldsymbol{x}_k^i$ is the inner state, $\boldsymbol{y}_k^i$ is the output and $\boldsymbol{d}_k^i$ is the disturbance.
Gas flows are divided or joined together in the nodes. Therefore, the Kirchhoff node equation for flows must apply here. Furthermore, the volume flows, pressures or storage volume/fill level are limited. This constraint to the in and out sizes and inner states can be described as follows.
The constraints on the input, output and state variables can be described as follows:

Input constraints

$$\begin{bmatrix} \boldsymbol{I} \\ -\boldsymbol{I} \end{bmatrix} \boldsymbol{u}_k^i \le \begin{bmatrix} \boldsymbol{u}_{max}^i \\ -\boldsymbol{u}_{min}^i \end{bmatrix}$$

Output constraints:

$$\begin{bmatrix} \boldsymbol{I} \\ -\boldsymbol{I} \end{bmatrix} \boldsymbol{y}_k^i \le \begin{bmatrix} \boldsymbol{y}_{max}^i \\ -\boldsymbol{y}_{min}^i \end{bmatrix}$$

Constraint on the inner states:

$$\begin{bmatrix} \boldsymbol{I} \\ -\boldsymbol{I} \end{bmatrix} \boldsymbol{x}_k^i \le \begin{bmatrix} \boldsymbol{x}_{max}^i \\ -\boldsymbol{x}_{min}^i \end{bmatrix}$$

In general, the simulation of the gas network can be seen as a constraint linear or nonlinear programming problem. Whereby the constraints are the model equations described above and the objective function is to minimize the simulation error.

4.4.5 Task 4.5 Development of a user-friendly interface

A user friendly interface has been developed in order to support network simulation and optimal management as well as visualization of the different real and forecasted variables and of the different KPIs. The developed software component of the GASNET system, which is devoted to forecasting for KPI monitoring and optimization is basically composed of 3 independent modules, such as schematically depicted in **Figure 25**.

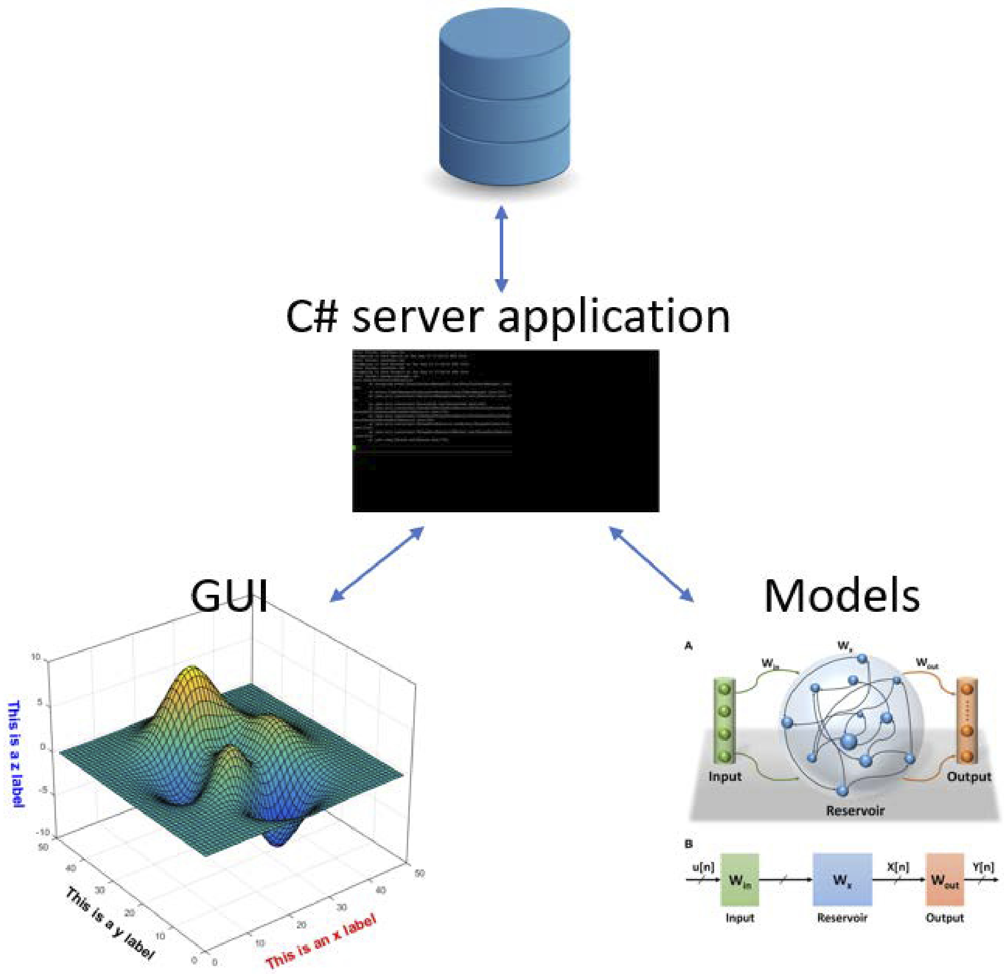


Figure 25: Overview of the developed application

A server developed in C# receives TCP-IP requests from two clients: the Graphical User Interface (GUI) and the models simulation. Thanks to this infrastructure, the whole application can run on several machines located in different places.
The C# server application performs queries to the Oracle DB and gathers the results into customized objects, which can be easily exploited by the client that made the request. In order to optimize and not to overload the database, queries are executed with different time rates depending on the input variables time rate (such as 15 seconds, 30 seconds and so on).
The GUI and the Models simulation modules are identified by the server at the beginning of the connection thanks to a unique id that will be send from the client to the server. The id 1 identifies the GUI and the id 2 identifies the models module.
The models simulation module, that was initially developed in Matlab and then translated in C#, runs continuously. Each time the simulation ends, the output is stored into a CSV file and it will be uploaded to the database. In the ABG case, SSSA does not have enough permission to perform INSERT queries into the Oracle database. For this reason, an EXE file is provided by the company, which upload the CSV files to the db.
The CSV files have a fixed and predefined structure. They are composed of three columns:

- Variable name
- Variable value
- Timestamp

Subsequently that model simulation performs a new input request to the C# server in order to go on with the next time slot simulation.

The GUI is organised by Plant and System Unit. The GUI shows for each forecasted variable the current and the forecasted values for the two hours ahead prediction, according to the outcomes of the model simulations module. **Figure 26** shows one example of comparison between actual and forecasted variable. The background and lines colors can be set according to the user's preferences.

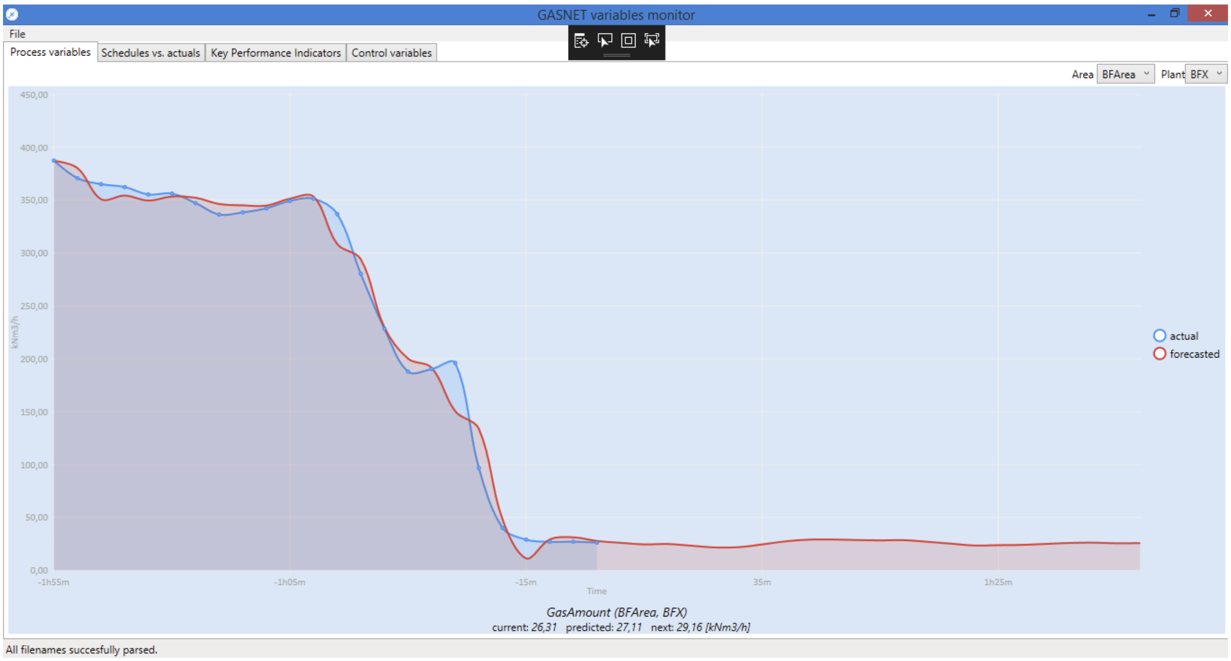


Figure 26: Exemplar screenshot of the GUI

The final version of the online decision support tool is described in **Deliverable 6.1**, which is included in **Appendix A**.
The tool also allows the joint visualization of different process variables, such as depicted in the example provided in **Figure A.4**.
In addition, the application shows also the following list of KPI:

- Overall steam losses (Steam)
- Flare losses (Flares)
- Total normalized energy from recovered off-gas (Process off-gas)
- Percentage of used energy produced with process off-gases (Process off-gas)
- Specific economic balance for used energy (Economic)
- Specific economic balance of process off-gas magagement (Economic)

Figure A.5 provides an example of the visualization of the main KPIs: the displayed values are only indicative and not taken from real data for confidentiality constraints.

4.5 WP 5: Multi-period and multi-objective optimization models

The objectives of WP5 are:

- To develop and implement optimization strategies to be embedded in the decision support tool;
- To make first tests using off-line data coming from the industrial partners' sites.

4.5.1 Task 5.1 Development of the overall structure of the optimisation system.

During the proposal preparation phase, it was planned to implement a hierarchical control concept consisting of static long-term optimization and underlying dynamic short-term optimization.
The practice in most industrial process control systems is to decompose the plant's management and optimization into tree levels, as depicted in **Figure 27.a**.

The first level deals with planning and scheduling. Long-term decisions are made here over months and days.
The second level, usually referred to as real-time optimization (RTO) takes into account all sorts of different constraints (including production, safety, or physical constraints) and essentially performs a static optimization. That is, it determines, among all feasible steady-state plant operating conditions (setpoints), those with minimal cost (long term set-up strategy).
The third level is responsible for deciding suitable dynamic control actions that steer the plant's operation to the desired steady-state operating condition within a reasonable amount of time. Since constraints are also of concern during transient operation, in many advanced industrial control systems, the dynamic operation is usually implemented with some kind of model predictive control (MPC) schemes (short-term control Task 5.4)

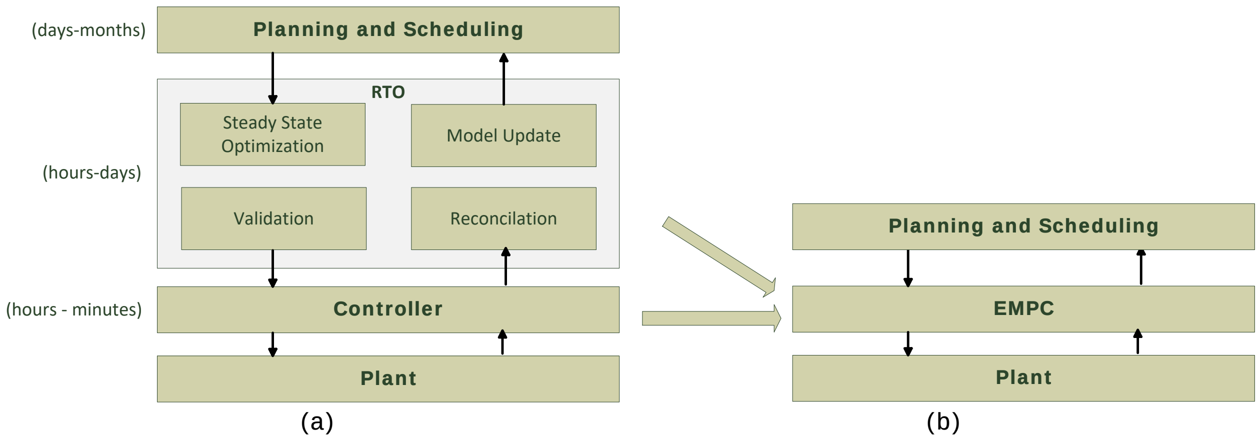


Figure 27 (a) Current industrial practice of economic optimisation consisting of two layer: a steady state layer covering the Real time optimisation (RTO) and a Dynamic layer covering the online control. (b) GASNET proposed the following structure consisting an Economic Model Predictive Control Layer (EMPC)

This structure has the following drawbacks:

- Inconsistent model
- Re-identify linear model as set point changes
- Time scale separation may not hold
- Economics unavailable in dynamic layer
- It is not clear how to choose a profitable dynamic of dynamic layer
- Sometimes a constant set point is not economically optimal or does not exist at all as for example for the control task of the gas holder in BOF network

In recovering from this disadvantage, the procedure of Economic Model Predictive Control (EMPC) has been developed in recent years. It combines the static econometric optimization and the dynamic control into one concept, as shown in **Figure 27.b**
The term Economic MPC directly hints at the distinctive feature of this MPC formulation, namely that it allows an arbitrary, possibly economic, cost function to be minimized by the controller. This makes it particularly attractive for applications in which the primary objective is not stabilization of some setpoint, but rather optimal operation with respect to a real economic performance criterion.
Furthermore, the economic long-term optimization can be approximated by iterative economic short-term optimization. In [5] it was shown that in the state of equilibrium the performance of the iterative economic short-term optimization is equal to the economic long-term optimization.
In the particular case of the management of the gas and steam network at, the control system was extended to include economic costs [5-8] and the costs for the purchase of natural gas, electricity and the revenue from the sale of electricity has been explicitly considered.
The final implementation of the control strategy is based on the concept of hierarchical control systems. With respect to the initial idea for the implementation of the control strategy, the concept has been modified in order to deal with the real availability of the production scheduling. It is possible to widen the horizon of prediction and scheduling of POG distribution according to the future horizon of data related to production scheduling. Therefore, it was preferred to combine tasks 5.3 and 5.4, which have been finally carried out as a single task, in which the time horizon depends on the availability of data.

In order to keep the control problem manageable, the control problem has been divided in two main subproblems, such as shown in **Figure 28**:

- The HL EMPC, the High Level EMPC for long term overall network optimisation
- The DEMPC, the distributed EMPC for short term optimization of each subnetwork (POG and steam)

The HL Optimizer is scheduled with a control period of 15 minutes, while the DEMPC low-level controller is scheduled every 1 minute. The two layers are executed in parallel with a multirate approach.

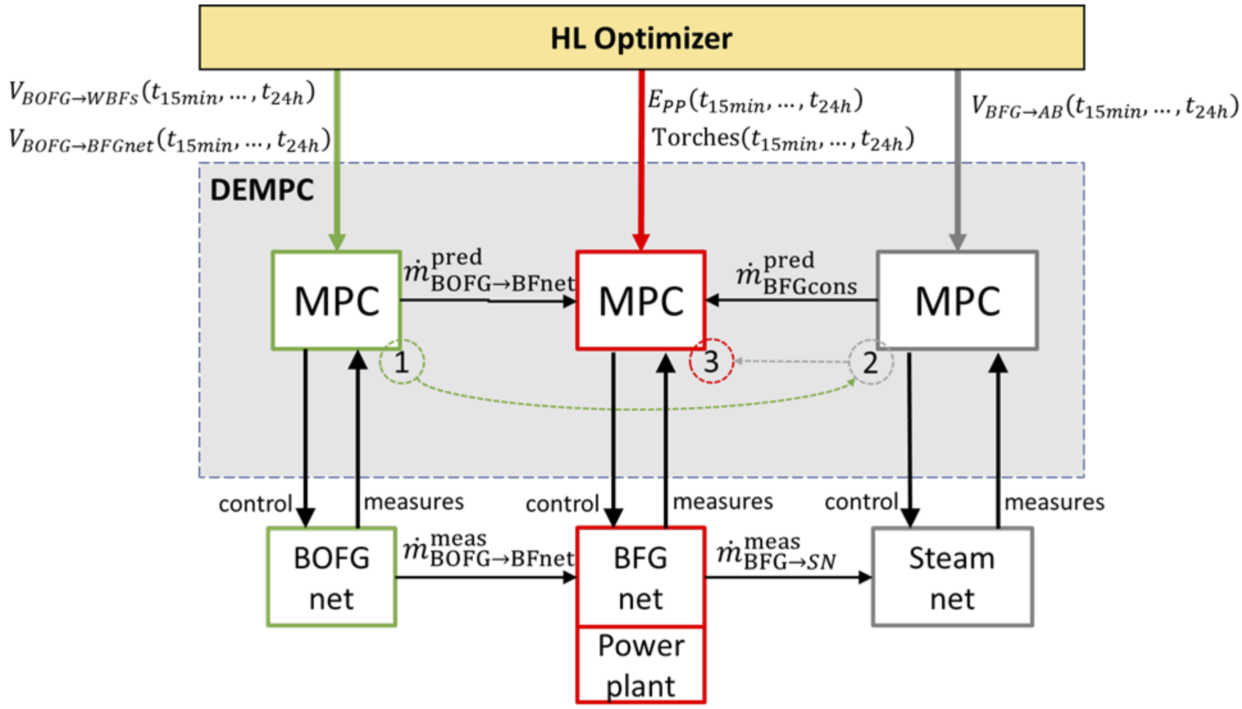


Figure 28: Structure of the hierarchical control system based on economic model Predictive control consists of two main layers, the HL economic long-term optimization and the DEMPC

The DEMPC consists of three distributed economic model predictive controller, each aimed at optimizing the own gas or steam subnetwork for a horizon of 2 hours. In particular, the DEMPC (depicted in **Figure 29**) consists of three subnetwork controllers:

- The MPC 1 (In **Figure 29** depicted in green), which control the BOFG network
- The MPC 2 (In **Figure 29** depicted in red), which control the BFG network and the power plant
- The MPC 3 (In **Figure 29** depicted in grey), which control the steam network

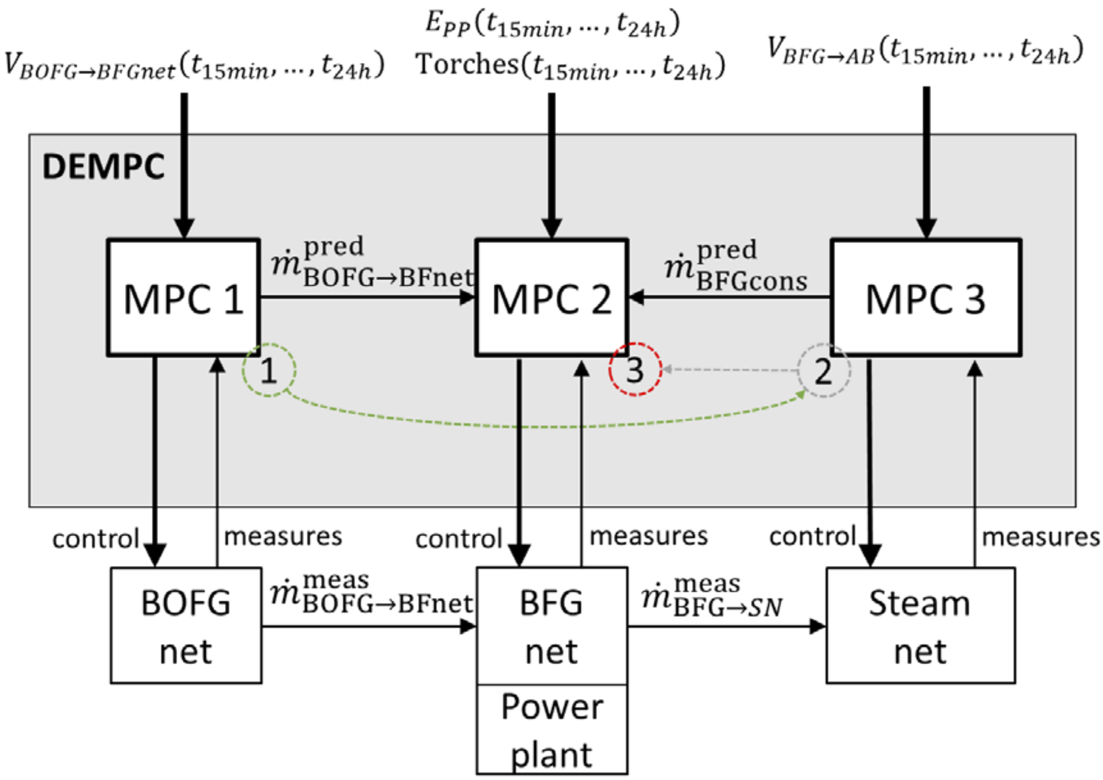


Figure 29: Structure of the low-level controller based on EMPC. The controller consists of three main MPCs, the MPC 1 that controls the BOFG network, the MPC 2 that controls the BFG network and the power plant, and the MPC 3 that controls the steam network.

The proposed implementation strategy of this hierarchical control system is as follows:

1. At each sampling time t_k, all the EMPC controllers receive the measurement from the sensors.
2. The HL Optimizer, every 15 minutes, computes the global optimization using a simplified model of the entire network for a sampling time of 15 minutes. It then sends the predicted volume exchange flows to the sub controller DEMPC, used as a reference to be followed
3. The DEMPC evaluates its future input trajectory based on the current measurement and the recommended exchange currents between BFG and BOF network recommended by the HL Optimizer. The DEMPC
   - 3.1. MPC 1 (BOFG network controller) sends the first step input value to its actuators and sends its entire future input trajectory to MPC 2 (BF network controller)
   - 3.2. The MPC 3 of the steam network calculates its future input trajectory based on the current measurement and the use of BFG gas for steam generation recommended by the HL Optimizer. The MPC 3 sends the input value of the first step to its actuators and sends its entire future input trajectory to the MPC 2.
   - 3.3. MPC 2 of BFG and electrical network receives the future input trajectories from MPC 1 and MPC 3 and evaluates its future input trajectory based on the measurments. MPC2 sends the first step input value to its actuators
   - 3.4. Go to step 3.1, until the HL is not scheduled. If the HL is scheduled, go to step 4
4. Every 15 minutes, go to step 1.

In **Subsections 5.5.3, 5.5.4 and 5.5.5,** the controllers for the individual networks are described in deeper detail.

4.5.2 Task 5.2 Off-line structure optimisation of the gas network.

The problem of optimizing the gas network structure, as introduced in Section 5.4.3, formally translates into the minimization of the previously introduced objective function, corresponding to the sum of all costs, minus the revenues:

$$F(x) = \sum_{n \in NG,g} x_{ni}^{g} \cdot P_{ng} + \sum_{t \in TT,j,g} x_{jt}^{g} \cdot P_{t} - \sum_{c \in C,j,g} x_{jc}^{g} \cdot LHV(g) \cdot P_{E_c}$$

The problem of minimizing $F(x)$ subject to all the above constraints is a non-convex Quadratically Constrained Quadratic Problem (QCQP). It belongs to the category of NP-complete problems: it is computationally hard to find an optimal solution.

In order to have a model that accounts for the possibility of pipe constructions/deletions, activation variables y_{ij} are added to the model: for every possible connection ij, $y_{ij} = 0$ if the pipe ij is not activated and $y_{ij} = 1$ otherwise. The upper and lower bounds constraints are thus consquentely extended to all possible connections ij: the constraints $y_{ij} \cdot l_{ij} \leq x_{ij}^{g} \leq y_{ij} \cdot u_{ij}$ define the activation variables, while ensuring that the flow stays within the pipe capacities.

There can be three types of cost: a maintenance cost, a demolition cost (for pipes already in the original network), and a building cost (for pipes not in the original network). These quantities are assumed as amortized over the used time unit. Let c_{ij} be the difference between maintenance cost and demolition cost related to a pipe ij that is in the original network and let c_{ij} be the sum of maintenance cost and building cost related to a pipe ij that is not in the network. The component that must be added to the objective function is the sum over all possible connections ij of $y_{ij} \cdot c_{ij}$. Therefore, the objective function becomes as follows:

$$G(x, y) = F(x) + \sum_{i,j} y_{ij} \cdot c_{ij}$$

A number of free license QCQP solvers have been tested on data from a real case scenario, but the results were unsuccessful: given the magnitude of the problem a solution could not be found. Therefore, initially the problem has been implemented in MatLab and solved through its routines from the optimization package. In order to avoid expensive license software, a novel non-linear optimizer has also been designed, which is based on the well-known algorithm of Sequential Quadratic Programming (SQP). The SQP algorithm is a general algorithm that solves problems of the form

$$\begin{aligned} &\min f(x) \\ &s.t.\ g(x) \leq 0 \\ &\quad\ h(x) = 0 \end{aligned}$$

where x is the vector of decision variables, $f(x)$ is the objective function and $g(x), h(x)$ are the constraint vectorial functions representing inequality and equality constraints respectively. Here $f(x), g(x), h(x)$ might be nonlinear functions.

The basic idea of SQP is to form easier subproblems and solve them iteratively in order to converge to a solution of the global problem. Let

$$L(x, u, v) = f(x) + \lambda^T \cdot h(x) + \mu^T \cdot g(x)$$

be the lagrangian of the problem and let $H(x)$ be the hessian of $L(x, \lambda, \mu)$ as a function only of x at some fixed λ, μ. These λ, μ values are initialized as zero vectors and, at iteration $k \geq 2$, they are the optimal multipliers of the quadratic subproblem of the previous iteration.

At iteration k the quadratic subproblem is

$$\begin{aligned} &\min\ \frac{1}{2} \cdot d^T \cdot H(x_k) \cdot d + \Delta f(x_k) \cdot d(x) \\ &s.t.\ \Delta f(x_k) \cdot d + h(x_k) \leq 0 \\ &\quad\ \Delta g(x_k) \cdot d + g(x_k) = 0 \end{aligned}$$

This is a quadratic problem in the unknows d.

The solution d_k to the subproblem will give the direction to improve the iterate of the original problem solution.

$$X_{k+1} = X_k + d_k$$

To improve the convergence, a suitable α is calculated that minimizes a certain merit function and

$$X_{k+1} = X_k + \alpha \cdot d_k$$

The merit function $\Phi(\alpha)$ is designed to both improve the constraints violation threshold and the objective function value:

$$\Phi(\alpha) = \frac{|f(x_k + \alpha \cdot d_{k+1}) - f(x_k)|}{|f(x_k)|} + \omega \cdot \frac{|M(\alpha) - M(0)|}{|M(0)|}$$

where

$$\mathrm{M}(\alpha) = \max(\max g(x_k + \alpha \cdot d_{k+1}), \max(|h(x_k + \alpha \cdot d_{k+1})|))$$

is a weigthed sum of the relative improvement in the objective function and the relative improvement in the maximum constraint violation. The weight ω starts with value 1 and it is successively increased if the size of the step d_k is small enough and the constraints are still violated.

This merit function has given better performances in the specific optimization problem and in other test problems, when compared to other merit functions such as those described in [11].
To improve efficiency, the Hessian is not calculated at every iteration, but an approximation H^k is used. This approximation is updated according to the follwoing rule:

$$H^{k+1} = H^k + \frac{q_k \cdot q_k^T}{q_k^T \cdot s} - \frac{H^k \cdot s_k \cdot s_k^T \cdot H^k}{s_k^T \cdot H^k \cdot s_k}$$

with $s_k \coloneqq X_{k+1} - X_k = \alpha \cdot d_k$ and $q_k = \theta_k \cdot \eta_k + (1-\theta_k) \cdot H^k \cdot s_k$. Here η_k is the difference in gradients of the lagrangian function:

$$\eta_k = \Delta_x L(X_{k+1}, \lambda_{k+1}, \mu_{k+1}) - \Delta_x L(X_{k+1}, \lambda_k, \mu_k)$$

Finally θ_k is 1, if $s_k^T \cdot \eta_k \geq 0.2 \cdot s_k^T \cdot H^k \cdot s_k$ and

$$\theta_k = \frac{0.8 \cdot s_k^T \cdot H^k \cdot s_k}{s_k^T \cdot H^k \cdot s_k - s_k^T \cdot \eta\_k}$$

otherwise.
This update rule of the hessian function, besides saving computational time, is proven to provide a positive definite matrix at every iteration, when the starting hessian is positive definite. When this happens the quadratic subproblem is convex and thus solvable in polynomial time (it is solved optimally and fast). To have an initial positive definite hessian matrix, it is (roughly) approximated as a null matrix. That still guarantees a good approximation in the next iterations [11].
To solve the quadratic subproblem an active-set method is used, according to the approach proposed in [12].
It might be possible that the constraints of the quadratic subproblem become inconsistent during the iterations, although the original problem is feasible. To overcome this problem, if the subproblem is found to be infeasible, a new subproblem is formulated:

$$\begin{aligned} &min\ \frac{1}{2} \cdot d^T \cdot H(x_k) \cdot d + \Delta f(x_k) \cdot d(x) \\ &s.t.\ \Delta f(x_k) \cdot d + \delta \cdot h(x_k) \leq 0 \\ &\qquad \Delta g(x_k) \cdot d + \delta' \cdot g(x_k) = 0 \end{aligned}$$

where δ (δ') is a vector such that δ_i ($\delta_i{}'$) equals 1 if the $i-th$ inequality (equality) constraint is satisfied and δ_i ($\delta_i{}'$) equals a given positive value σ otherwise. The value σ starts from 1 and it is progressively halved until the subproblem is found to be feasible.
When the improvement in the objective function or the pace of the solution update (namely d_k) fall below given tresholds and all the constraints are satisfied, the algorithm stops and outputs the current iterate which is a good approximation of the soltions.
The computational time of this algorithm is relevant because the number of nonlinear constraints of the model increases considerably. Therefore, in order to reduce the computational time for very complex networks, a tailored version of branch and bound has also been developed.
The problem is treated as a MIQCQP (Mixed integer quadratically constrained quadratic problem), which is a subcategory of MINLP (Mixed integer non linear problems). The integrality constraints are used to model that the activation variables must be binary. The branch and bound method solves the original problem by solving a number of easier (relaxed) problems without the integrality constraints.
The process starts by solving the original problem without the integrality constraints: since the activation variables might get fractional values, this solution might be infeasible, but it provides a lower bound for the optimal solution. By forcing to 1 all positive activation variables (through linear constraints) another subproblem is generated and then solved: this provides an upper bound for the optimal solution. Thereafter, the space of all binary combination of the activation variables is explored: the lowest positive activation variable (say $y_{i_0 j_0}$) is considered and two branches are created (one by adding the constraint $y_{i_0 j_0} = 0$ and one by adding the constraint $y_{i_0 j_0} = 1$), a relaxed solution is seeked again for each branch. If a branch is infeasible (the constraints have no solution) or provides a solution whose value is less than the current upper bound, the branch is closed and not explored anymore, otherwise another binary branching is performed from that point, unless all the activation variables in the current solution are integer, in which case the upper bound is updated and the branch is closed. The process is repeated until all the produced branches are closed (note that the best solution might also be the initial approximated integer solution).
The number of subproblems to be solved is generally exponential in the number of activation variables, therefore, in order to avoid a computational explosion, the number of subproblems that can be solved is

limited. When this limit is reached, the best solution is selected among the integral approximations of the solutions obtained in the active branches.
For a general and more detailed discussion on branch and bound methods see [13].

4.5.3 Task 5.3 Multi-objective long term (set up) strategy planning optimisation considering demand and process uncertainty (multiple long term period) and Task 5.4 Scheduling for power generation optimisation

The main objectives of the two tasks are related to the optimization of the electric energy generation in a daily basis and the optimal distribution of the POG within the other users. The module takes into account the influence of the scheduling of each main process on the capability of the byproducts gases networks (such as BFG, BOFG and COG) to store the gas in the gasholder. In addition, it predicts possible issues related to their shortage and finally reacts accordingly, planning the optimal distribution of the use of BFG, BOFG and COG in the various processes, including the electrical power plants and the main consumers.
More in detail, the objectives can be summarized as follows:

- The optimization of the distribuition of byproduct gases;
- The maximization of the energy efficiency conversion in the powerplants;
- Minimization of the use of NG in each main consumer (powerplants, HSM, Steam boilers);
- Minimization of the byproduct gases flaring in torches and consequently the minimization of the environmental impact in the long term.

As a result of the optimization strategy, the module produces suitable references for the lower level optimization of each gas and steam network, starting from the predictions of production and consumption of each byproduct gases, through models designed with a lower time level detail, in which the only time dependencies are related to the dynamic of the gasholders and the steam stored in the accumulators. The steam network dynamics are considered istantaneus, as its mass flow and pressure dynamics fall within 15 seconds - 1-minute time ranges, that are sampling times not suitable for a daily/weekly optimization.
The optimization problem can be described starting from given data and assumptions:

1. Byproduct gases, suitable production units, boilers and other byproduct gas users, generation rate at a time and demand profiles in production units as forecasted by the models;
2. Dedicated gasholders, their minimum and maximum capacities, normal inventory levels, high and low inventory levels for safe operational regions;
3. Boilers, suitable fuels that can be fed, suitable steams that can be generated, maximum inlet flow rates of byproduct gases, thermal efficiency, minimum and maximum steam generation rates, and minimum heating values;
4. Burners, suitable byproduct gases, initial status and feed rates at a time;
5. Energy generation equipment (e.g. steam turbines, etc.), suitable steams that can be fed, suitable steams that can be generated, minimum and maximum feed rates, thermal efficiency, minimum and maximum generation rates, and minimum and maximum power generation rates;
6. Steam and electricity demand profiles with time, steam enthalpy, electricity energy content, maximum imported power from the grid, and maximum exported power to the grid;
7. Economic data: natural gas purchase cost, electricity sale price and purchase cost, penalty coefficients for by-product gas flaring and burner switching operations, penalty coefficients for deviations from normal inventory levels in gasholders and violations of low and high inventory levels of the safe operational region in a gasholder;
8. Planning horizon.

The solution of the optimization problem determines:

- The optimal distribution of byproduct gases among the users in a daily/weekly basis;
- The profiles of gasholders level in the time horizon;
- The future optimized objective function, related to Specific Economic Balance between costs and revenues:

$$Balance = CNG + CEl_{En} + Cpenalties_{emission} - SPEl_{En}$$

where:

- CNG is the cost of purchase of Natural Gas.
- CEl_{En} is the cost of electrical energy purchased from the grid.
- $Cpenalties_{emission}$ is the cost associated to flaring in torches.
- $SPEl_{En}$ is the revenues coming from selling the produced electrical energy or from the selling the off-gases.

The planning horizon is divided into period *T (t=1, 2, ..., T)*, the length of each period is denoted as τ_t. In each period the generation and the demand of off-gases, steam and electricity are considered piecewise constant. In the current implementation τ_t is equal to 15 minutes.

High Level Optimisation (HL)

From a mathematical point of view, the scheduling for Power Generation Optimization (PGO) is obtained starting from the minimization of a specific cost function:

$$J(u,N_p)=\sum_{k=t}^{t+N_p}\gamma^k\left(c_{NG}E_{NG}(k)+C_{EP}(k)E_{EP}(k)-C_{ES}(k)E_{ES}(k)+C_{T_{BOFG}}V_{T_{BOFG}}(k)+\ C_{T_{BFG}}V_{T_{BFG}}(k)+C_{CS}V_{S_{CS}}(k)+\boldsymbol{c}_s^T\boldsymbol{s}(k)\right)$$

where:

- c_{NG} is the cost of the NG consumption measured in [€/Mwh],
- E_{NG} is the total energy consumption related to the NG in [MWh],
- C_{EP} is the cost of the purchased electrical energy measured in [€/Mwh],
- E_{EP} is the purchased electrical energy in [MWh],
- C_{ES} is the cost of the sold electrical energy measured in [€/Mwh],
- C_{ES} is the sold electrical energy in [MWh],
- $C_{T_{BOFG}}$ is cost of wasting gas in the BOFG torches in [€/kNm^3],
- $V_{T_{BOFG}}$ is the volume of BOFG gas burned in the BOFG torches in [kNm^3],
- $C_{T_{BFG}}$ is cost of wasting gas in the torches in [€/kNm^3],
- $V_{T_{BFG}}$ is the volume of BOFG gas burned in the torches in [kNm^3],
- C_{CS} is the cost of wasting steam in the condenser in [€/t],
- $V_{S_{CS}}$ is the mass of steam condensed in the condenser in [t],
- $\boldsymbol{c}_s$ is the cost related to the slack variables in the problem,
- $\boldsymbol{s}=[s_1 \quad \cdots \quad s_{n_s}]$ are the slack variables.
- γ is a factor in the range $[0,\ 1]$ that takes into account the modelling errors, due the fact that the future is known with a decreasing accuracy
- N_p is the prediction horizon in samples.

The problem of optimum is then completed with a large set of constraints, related to the main consumers and producers, and the main dynamics and structural behavior of the gas, steam and electrical system. More in detail, to optimize the distribuition of offgases, the NG consumption, and the balance between purchased and internally produced electrical power, only the main consumers/producers are considered:

- Steam consumers and producers;
- Electrical networks and powerplants;
- Gasholders;
- Walking beam furnace;
- PCI plant

The other producers and consumers are considered in the mathematical formulation of the problem and are considered as a disturbance.

At this optimization level, the main **steam constraints** are:

- The steam mass flow balance at each considered period:

$$\alpha_s^k\sum_{h=1}^{N_{N_c}}\dot{m}_{c_h}(k)+\sum_{l=1}^{N_p}\dot{m}_{ncprod_l}(k)+\dot{m}_B(k)=0$$

  where:
  $\dot{m}_{c_h}$ is steam mass flow consumption of $h=1\dots N_c$ Number of consumers;
  $\dot{m}_{ncprod_l}$ is the non-controllable steam mass flow production of $l=1\dots N_c$ Number of non-controllable consumers (e.g. BOF steam mass flow production);
  $\dot{m}_B$ is the total steam mass flow production in the boilers;
  α_s^k is a factor that takes into account the issue related to the approximated modelling of the steam consumers and tries to demand more steam production to the optimization problem.
- The Energy Balance of boilers:

$$\sum_{m=1}^{M}P_{th,boiler,m}=\sum_{m=1}^{M}\eta_{boiler,m}\left(Q_{BFg,m}LVC_{BFg}+Q_{NG,m}\,LVC_{NG}\right)$$

  where:
  $P_{th,boiler,m}$ is the thermal power necessary for the production of the steam in the boiler;

m, $\eta_{boiler,m}$ is the efficiency of the boiler m,
$Q_{BFg,m}$ is the normal volume flow of the BFgas in the boiler m;
LVC_{BFg} is the Net Calorific Value of the BFG.

- The steam mass flow production in the auxiliary boilers:

$$\dot{m}_{B_i}(k) = k_{ABi} NCV_{gas}^{T}(k) Q_{gas}(k) + B_{AB_i}$$

Where:
$\dot{m}_{B_i}$ is the steam mass flow production in the i-th boiler
$NCV_{gas}^{T} = \left[NCV_{g_1}, NCV_{g_2}, \dots, NCV_{g_{n_G}}\right]$ is composed of the net calofic values of each gas burned in the boilers
$Q_{gas} = \left[Q_{gas_1}, Q_{gas_2}, \dots, Q_{gas_{n_G}}\right]$ is the normal volume flow of each gas burned in the boiler
k_{ABi} and B_{AB_i} are the parameters of the i-th auxiliary boiler

- Constraints on net calorific value and thermal power:

$$LVC_{BFg} \geq LVC_{BFg,min}$$
$$(P_{th,boiler,min,m})_{BFg} < Q_{BFg} LVC_{BFg} < (P_{th,boiler,max,m})_{BFg}$$
$$(P_{th,boiler,min,m})_{mix\ gas} < Q_{BFg,m}\, LVC_{BFg} + Q_{NG,m}\, LVC_{NG} < (P_{th,boiler,max,m})_{mix\ gas}$$

The set of contraints on the **electrical network** and **power plant** are described as follows:

- The balance of produced and consumed electrical energy:

$$\alpha_E^k \sum_{h=1}^{N_{N_c}} E_{c_h}(k) + \sum_{l=1}^{N_p} E_{ncprod_l}(k) + E_{pp}(k) + E_{\text{ext}}(k) = 0$$

where:
E_{c_h} is the electrical energy consumption of $h = 1 \dots N_c$ Number of consumers;
E_{ncprod_l} is the non-controllable electrical energy production of $l = 1 \dots N_c$ Number of non controllable consumers (e.g. electrical energy production in gas expansion turbines);
E_{pp} is the total electrical power production in the power plants;
E_{ext} is the electrical power flow to/from external grid, that allows to sell or purchase electrical power;
α_E^k is a factor that takes into account the issue related to the approximated modelling of the electrical power consumers, and tries to demand more electrical power production to the optimization problem.

- Energy Balance of Power Plant:

$$E_{pp} = \eta_{st}[\eta_{boiler}(Q_{mixed\ gas}\, LVC_{mixed\ gas} + Q_{NG}\, LVC_{NG})]$$

where:
E_{pp} is the electric power generated by the Power Plant;
η_{boiler} is the efficiency of the boiler;
η_{st} is the efficiency of the turbines;
$Q_{mixed\ gas}$ is the normal volume flow of the mixed gas;
$LVC_{mixed\ gas}$ is the Net Calorific Value of the mixed gas.

- Constraints on the net calorific value and thermal power:

$$LVC_{mixed\ gas,min} < LVC_{mixed\ gas} < LVC_{mixed\ gas,max}$$
$$P_{th,boiler,min} < P_{th,boiler} < P_{th,boiler,max}$$

The Dynamic and constraints of **Gasholders** are also considered in the set that defines the feasibility region of the problem, as the most important dynamic for short-long therm optimization, and have been mathematically described as follows:

- The dynamic of the level of gasholders:

$$L_{g,z,t}(k) = L_{g,z}(k-1) + Q_{g,t}\tau_k - \sum_{c=1}^{C} Q_{c,g,k}\tau_k - \sum_{f=1}^{F} Q_{g,f}$$

Where:
$Q_{g,t}$ is the generation rate of the type of off-gas g in period k;
$Q_{c,g,t}$ is the consumption rate of the type of off-gas g in the component c;
$Q_{g,f}$ is the amount of off-gas g emission during period k in the flare f.

- The gas holder must work in a safe operational range:

$$L_{g,z}^{l} - SL_{g,z}^{l} \leq L_{g,z} \leq L_{g,z}^{h} + SL_{g,z}^{h}$$

where:
$L_{g,z}$ is the level of the gas g in the gas holder z;
$L_{g,z}^{h}$is the high level of the gas g in the gas holder z in a safe operational zone;
$SL_{g,z}^{h}$is the slack variable defined as the violation of the high level of the gas holder z ($L_{g,z}^{h}$),
$L_{g,z}^{l}$ is the low level of the gas g in the holder z in a safe operational zone;
$SL_{g,z}^{l}$ is the slack variable defined as the violation of the low level of the gas holder z ($L_{g,z}^{l}$).
In general, the gasholder works in the nominal level ($L_{g,z}^{n}$), when it deviates from this values it is necessary to represent this deviation with other two slack variables ($SL_{g,z}^{d^+}$ and $SL_{g,z}^{d^-}$):

$$L_{g,z} - L_{g,z}^{n} = SL_{g,z}^{d^+} - SL_{g,z}^{d^-}$$

The **Walking beam furnaces** have been modeled as follows:

- Energy Balance of the WBF (Walking Beam Furnace):

$$\sum_{n=1}^{N} P_{th,WBF,n} = \sum_{n=1}^{N} \eta_{WBF,n} \left(Q_{BOFg,n}\, LVC_{BOFg} + Q_{NG,n}\, LVC_{NG}\right)$$

where $P_{th,WBF,n}$ is the thermal power necessary for the WBF n, $\eta_{WBF,n}$ is the efficiency of the WBF n, $Q_{BOFg,n}$ is the normal volume flow of the BOF gas in the WBF n, LVC_{BOFg} is the Net Calorific Value of the BOFG.
- Constraints on the LCV and volume flows:

$$LVC_{BOFg,min} < LVC_{BOFg} < LVC_{BOFg,max}$$
$$Q_{BOFg,n,\,min} < Q_{BOFg,n} < Q_{BOFg,n,max}$$

The **PCI plant** has been modeled as follows:

- Energy Balance of PCI Plant:

$$P_{th,coal} = \eta_{PCI} \left(Q_{mixed\ gas}\, LVC_{mixed\ gas} + Q_{NG}\, LVC_{NG}\right)$$

where.
$P_{th,PCI}$ is the thermal power necessary for drying the coal in the PCI;
η_{PCI} is the efficiency of the PCI Plant;
$Q_{mixed\ gas}$ is the normal volume flow of the mixed gas;
$LVC_{mixed\ gas}$ is the Net Calorific Value of the mixed gas.
- Constraints on the LCV and volume flows:

$$LVC_{mixed\ gas,min} < LVC_{mixed\ gas} < LVC_{mixed\ gas,max}$$
$$Q_{mixed\ gas,min} < Q_{mixed\ gas} < Q_{mixed\ gas,max}$$

As mentioned before, the other consumers and producers are considered as a disturbance in each balance of steam mass flows, electricity and gases. They have been modeled through simple linear correlations between the scheduled production of each important processes and the variables of interest (electricity, steam and gasses), where it was not possible to reuse the models developed and described in the previous annual reports in WP3.
The optimization strategy is formulated as a linear dynamic problem, initially solved through CPLEX algorithms. The final version of the software is based on Google OR-Tools library, an open source software suite for optimization, in particular integer, linear and constraint programming.

4.5.4 Task 5.5 Hybrid (Continuous and event triggered) online control

MPC 1: Mixed Integer Economic Model Predictive Controller (EMPC) of the BOF

This section describes the economic controller for the BOf gas network. First the model is introduced and then the controller is described

Model of the BOF net work:

In **Figure 30** the overall structure of the BOFG network is highlighted with an essential component.

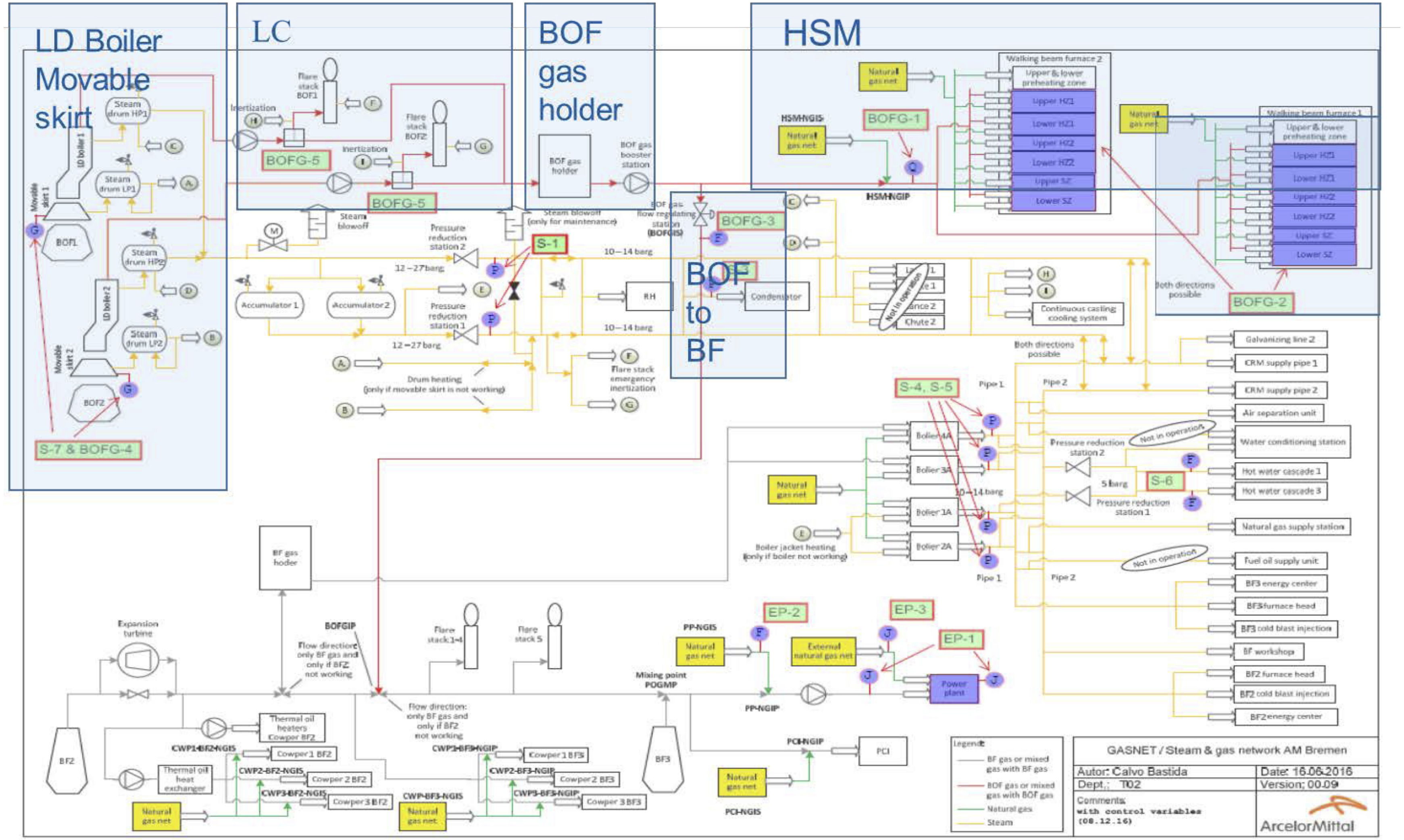


Figure 30: The BOFG network at ABG steelworks

The BOFG network consists of the following components:

- LD Boiler
- Flare stack
- BOFG holder
- Transfer pipeline to the BFG network - this describes the interconnection of the BFG network with BOFG network
- The Hot Strip Mill (HSM)

This results in the simplified structure of the control engineering model, which is shown in **Figure 31**.

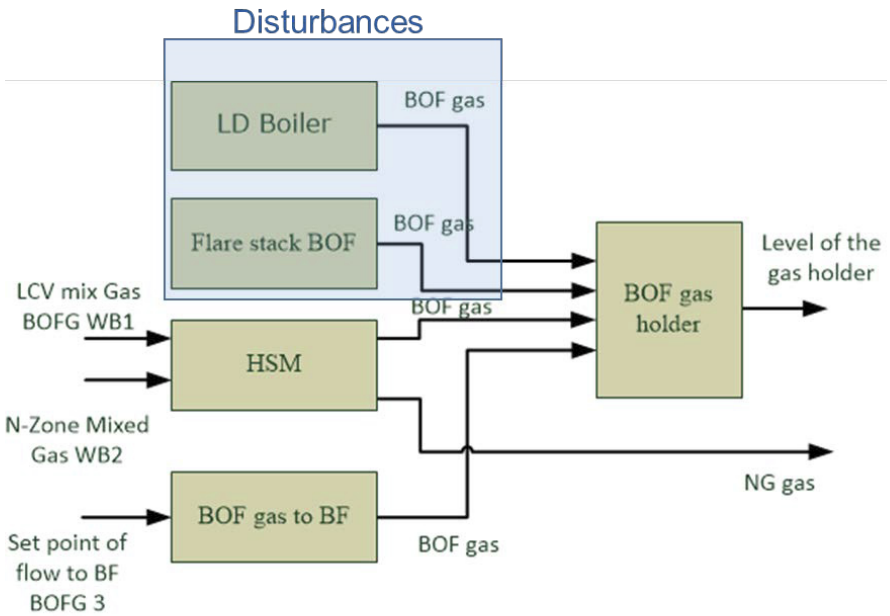


Figure 31: Structure of the control engineering model of the BOFG network.

The main output variable in this model is the fill level in the gasholder and natural gas consumption, since one of the control tasks is to keep the fill level high within a prescribed range and to minimies the cost of the natural gas.
Furthermore, the manipulated variables of the BOF network are entered with which one can actively influence the filling level in the gasholder:

- HSM:
  - LCV of the mixed gases for the reheating furnaces
  - Number of burners using natural gas or BOFG
- Transfer pipe to the BF network:
  - Set points of the volume flow in the transfer line from the BOFG network to the BFG network.

In the case of ILVA/AMI, as flaring is forbidden apart from emergencies, an additional control variable must be introduced so that the BOF gasholder does not overflow. Here, the scheduling in the BOF area is selected as an additional manipulated variable. This makes the control task solvable again i.e. feasible. In general, great care must be taken to ensure that the control task can still be solved by the introduction of state variables limitation.
In the following the most important models of the network are described, which appear later in the closed control loop of the BOF network:

- The Gas holder model can be described by a linear state model.

$$x(k+1) = Ax(k) + b_1\dot{V}_{BOF}(k) + b_2\dot{V}_{BOF,re}(k) + b_3\dot{V}_{BOF\ to\ BF}(k) + b_4 Q(\dot{k})$$

$$y_{LBOF}(k) = cx(k)$$

Whereas $\dot{V}_{BOF}(k)$ describes the BOF gas flow from the storage into the mixing station and $\dot{V}_{BOF,re}(k)$ represents the BOF gas the LD boiler is recovered. Finally, $\dot{V}_{BOF\ to\ BF}(k)$ defines volume flow of BOF gas into the BFG network and $Q(k)$ the flair. $y_{LBOF}(k)$ denotes the filling lovel of gas holder.

- The Mixing station: Mixing station mixes natural gas and BOF gas to provide a prescribed lower calorific value $LCV_{mix}(k)$ of the mixed gas used in furnaces of hot strip mill. The following static nonlinear model of the mixing station is obtained by means of an energy balance.

$$\dot{V}_{BOF}(k) = (1 - x_{LCV}(k))\dot{V}_{MIX}(k)$$
$$\dot{V}_{NG,M}(k) = x_{LCV}(k)\dot{V}_{MIX}(k)$$
$$x_{LCV}(k) = \frac{LCV_{mix}(k) - LCV_{BOF}(k)}{LCV_{NG}(k) - LCV_{BOF}(k)}$$

Whereby $\dot{V}_{MIX}(k)$ writes the total volume flow of mixed gas that is consumed in the furnace of the hot strip mill, which is composed of BOF $\dot{V}_{BOF}(k)$ and natural gas $\dot{V}_{NG,M}(k)$. The BOF gas has lower calorific value $LCV_{BOF}(k)$ and the Natural gas has lower calorific value $LCV_{NG}(k)$, both of which can change over time.

- HSM Model: The hot strip mill has two furnaces whose zones can be operated with either mixed gas or natural gas. The total volume flow of mixed gas into the furnaces then results in

$$\dot{V}_{mix}(k) = \sum_{i=1}^{NZone} \delta_{zone,i}(k)\, \dot{V}_{MIX,zone,i}(k)$$

and that of natural gas

$$\dot{V}_{NG,HSM}(k) = \sum_{i=1}^{NZone} \delta_{NG,i}(k)\, \dot{V}_{NG,zone,i}(k)$$

where $\delta_{NG,i}(k) \subseteq [0,1]$ describes that a zone is operated with natural gas and $\delta_{zone,i}(k) \subseteq [0,1]$

denoted that a zone is opeated with mixed gas. The condition

$$\delta_{zone,i}(k) + \delta_{NG,i}(k) = 1$$

ensures that a zone can only be operated with mixed gas or natural gas and not simultaneously with natural gas and mixed gas. The volume flows of mixed gas and natural gas can be calculated from the energy demand of the individual furnace zones.

$$\dot{V}_{MIX,zone,i}(k) = \frac{1}{LCV_{MIx}(k)} E_{zone,i}(k, \ldots..)$$

$$\dot{V}_{NG,zone,i}(\mathrm{k}) = \frac{1}{LCV_{NG}(k)} E_{zone,i}(k, \ldots \ldots)$$

This results in a nonlinear mixed logical dynamic model that can be simplified to a linear time variant mixed logical model, which is used for online optimization.

Controller of BOF net work:
The optimization criterion that explicitly considered the costs for the BOF network is as follows:

$$\text{minimize J} = \sum_{k=0}^{N} \gamma^{k}(l_{holder}(k) + l_{NG}(k) + l_{zone}(k) + l_{flare}(k) + l_{BOF\ to\ BF}(k))$$

The cost of consumed gas consists of the consumption in the mixing station and in the furnaces of the hot strip mill. The zones that can be operated with mixed gas or natural gas are considered. Since the costs can be influenced here:

$$l_{NG}(k) = c_{NG}(k)(\dot{V}_{NG,mix}(k) + \dot{V}_{NG,HSM}(k))$$

The profit contribution that can be generated by the transfer of BOF gas into BFG network is considered in the following manner:

$$l_{BOF\ to\ BF}(k) = C_{BOF_{to_{BF}}}(k)(\dot{V}_{BOF,demand}(k) - \dot{V}_{BOF\ to\ BF}(k))$$

$\dot{V}_{BOF,demand}(k)$ is the exchange volume flow between BOF and BFG network, which is assigned by the higher-level optimization. This ensures that the BOF-controller follows the allocated exchange flow rate in the middle. However, if it is economically necessary due to disturbances in the process or due to violation of the boundary conditions, it can deviate from the requirements. Furthermore, costs arise if BOF gas is not used and must be flared:

$$l_{\mathrm{flare}}(\mathrm{k}) = c_{\mathrm{emission}}(k)\dot{\mathrm{Q}}(\mathrm{k})$$

In addition, a cost term was added to ensure that the gas storage does not become too full or empty. This has the advantage that even in the event of unforeseen network disruptions, there is still enough space or volume in the gasholder facility to accommodate BOF gas in the holder or to supply the network even further.

$$l_{\mathrm{holder}}(\mathrm{k}) = \ \left(c_{\mathrm{holder+}}(\mathrm{k}) \max(0, y_{\mathrm{LBOF}}(\mathrm{k}) - \bar{y}_{\mathrm{LBOF}}\right) + c_{\mathrm{holder-}}(\mathrm{k}) \max\left(0, \underline{y}_{\mathrm{LBOF}} - y_{\mathrm{LBOF}}(\mathrm{k})\right)$$

To prevent the frequent switching of individual zones between operation with natural gas or BOF gas, the following cost function is added.

$$l_{\mathrm{zone}}(\mathrm{k}) = c_{\mathrm{changes}}(\mathrm{k})\left|(\delta_{\mathrm{zone,i}}(\mathrm{k}) - \delta_{\mathrm{zone,i}}(\mathrm{k}-1))\right|$$

Model uncertainties are first heuristically considered in this solution. For this purpose, the costs over the time horizon are weighted weaker by $\in [0, \ldots, 1]$. This has the effect that predictions that lie in the further future and are not so precisely known are weighted weaker and thus influence the optimization result lower.
Furthermore, it should be noted that in this control problem, in contrast to conventional MPC, no setpoint value is given. The target value results implicitly from the economic optimization and changes over time.

MPC 2: The BF network and electrical energy net and its control model structure.
Model of the BFG and electrical net work:
Figure 32 shows the sub-components of the BF network that are as follows:

- The BFG holder
- Two Blast furnaces
- The PCI
- The Cowpers
- Flare stack
- Power Plant
- Steam Boiler.

Similarly to the BOFG network, this results in a simplified control model structure, which is depicted in **Figure 33**, where, for the sake of the simplicity and durability of the BOF gasholder, only the level of the BF gasholder is shown as the output variable. However, additional parameters such as gas transfer to the power plant and natural gas consumption, for example in the boilers, must be taken into account when fulfilling the control task. These will be added in the following steps.

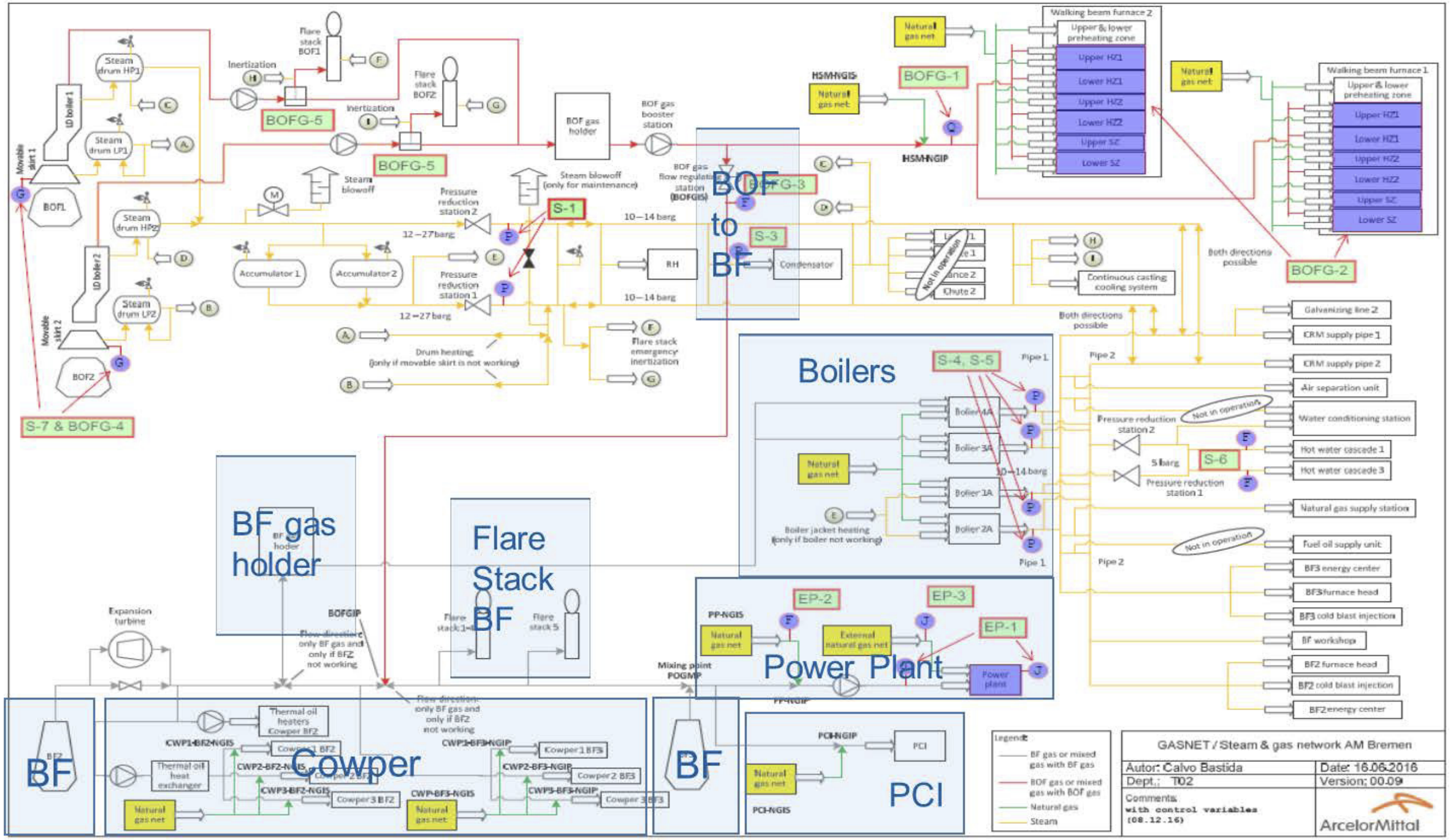


Figure 32: Components of the BFG network at ABG steelwork

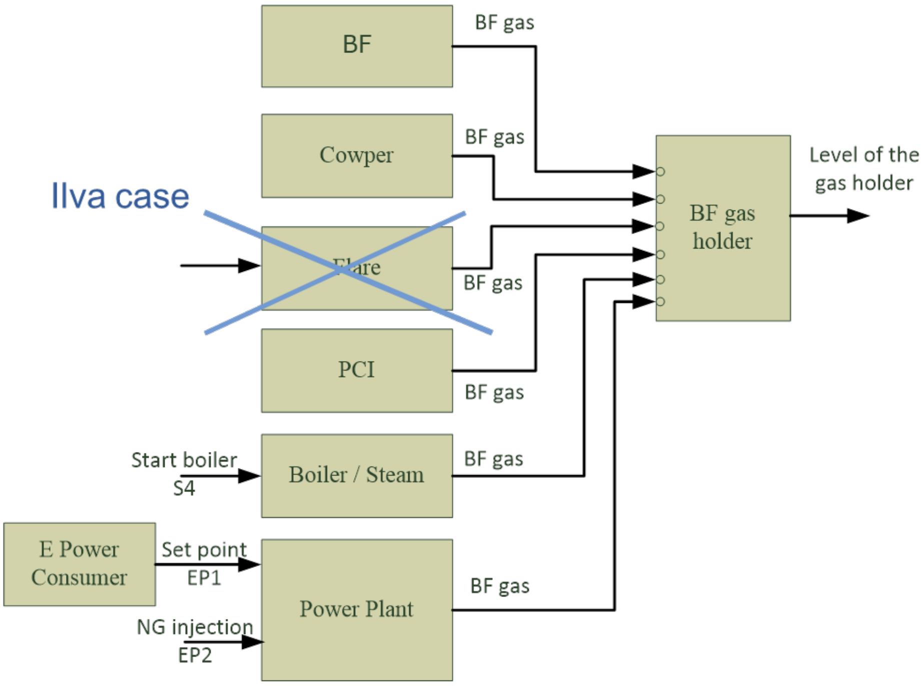


Figure 33: Control model structure of the BFG and electrical network

As shown in **Figure 33**, the filling level of the gasholder is affected only by the BOFG/BFG consumption of the power plant and in the steam boiler by the active burner with BF firing or natural gas supply.
In the following the most important models of the network are described, which appear later in the closed control loop of the economic model predictive controller of BFG and electrical network:

- The level BF $y_{LBF}(k)$ gas holder can be described by a linear state model

$$x(k+1) = Ax(k) + b_1\dot{V}_{BOF\ to\ BF}(k) + b_2\dot{V}_{BF\ to\ E}(k) + \sum_{i}^{n}\dot{V}_{BF,in,i} + \sum_{i}^{n}\dot{V}_{BF,out,i} + b_4\dot{Q}$$

$$y_{LBF}(k) = cx(k)$$

$\dot{V}_{BF,in,i}$ and $\dot{V}_{BF,out,i}$ respectively specify the volume flow in BF gas storage and from the gas holder. $\dot{V}_{BF\ to\ E}(k)$ is the volume flow from the BFG grid to power plant. Finally, $\dot{V}_{BOF\ to\ BF}(k)$ define volume flow of BOF gas into the BFG network and $Q(k)$ the flare.

- Mixing station: Mixing station mixes natural gas and BOF gas to provide a prescribed lower calorific value $LCV_{mix}(k)$ of the mixed gas transferred to BFG network. Here the same model is used as in the BOF network and is therefore not described again.

- Electrical network: The electrical network can be written using the following balance equation.

$$E_{Buy}(k) + E_{prod}(k) = E_{demand}(k) + E_{Sale}(k)$$

$E_{prod}(k)$ is the amount of electricity produced by the power plant in the steel mill and $E_{demand}(k)$ is the total electricity consumption in the steelworks that can be predicted by the model developed in WP3. $E_{Buy}(k)$ describes the amount of electricity that is bought from the energy supplier and $E_{Sale}(k)$ gives the amount that is sold to the energy supplier. Since the simultaneous sale and the purchase of energy should be avoided, the following constraints have been introduced

$$0 \leq E_{Buy}(k) \leq E_{Buy,max}(k)\delta_{Buy}(k)$$

$$0 \leq E_{Sale}(k) \leq E_{Sale,max}(k)\delta_{Sale}(k)$$

$$\delta_{Buy}(k) + \delta_{sale}(k) = 1$$

In this case, $\delta_{Buy}(k) \in [0,1]$ gives the energy the energy is bought and $\delta_{Sale}(k) \in [0,1]$ the energy is sold. Furthermore $E_{Buy,max}(k)$ and $E_{Sale,max}(k)$ specify the upper limit of the energy to be bought and sold respectively.

- Power station: can be described by a static non-linear model. Where $\eta(\ldots)$ is the efficiency and $\dot{V}_{Mix,BF}(k)$ is the amount of mixed gas burned in the power plant and $LCV_{Mix,BF}(k)$ is the lower calorific value of the mixed gas.

$$E_{prod}(k) = \eta\left(E_{prod}(k), \ldots\ldots\right)\dot{V}_{Mix,BF}(k)LCV_{Mix,BF}(k)$$

This results in a nonlinear mixed logical dynamic model that can be simplified to a linear time variant mixed logical model. Such model is used for online optimization.

BFG and electrical net Controller:
The optimization criterion that explicitly considers the costs for the BFG and electrical network is expressed as follows:

$$minimize \sum_{k=0}^{N} \gamma^k (l_{holder}(k) + l_{NG}(k) + l_E(k) + l_{flare}(k) + l_{demad}(k))$$

The cost of purchasing electrical energy from the energy provider or the profit that can be achieved by selling the electrical energy can be calculated as follows.

$$l_E(k) = c_{Buy}(k)E_{Buy}(k) + c_{Sale}(k)E(k)_{Sale}(k)$$

It is assumed that these costs can change over time.
The cost of consumed gas consists of the consumption in the mixing station as follwos:

$$l_{NG}(k) = c_{NG}\dot{V}_{NG}(k)$$

In addition, a cost term was added to ensure that the gas storage does not become too full or empty. This has the advantage that even in the event of unforeseen network disruptions, there is still sufficient space or volume in the gasholder facility to accommodate BFG gas in the holder or to supply the network even further:

$$l_{holder}(k) = \ c_{holder+}(k)\max(0, y_{LBF}(k) - \bar{y}_{LBF}) + c_{holder-}(k)\max\left(0, \underline{y}_{LBF} - y_{LBF}(k)\right)$$

Furthermore, costs arise if BFG gas is not used and must be flared

$$l_{flar}(k) = c_{emmission}\dot{Q}$$

Next a cost term

$$l_{demand}(k) = c_{demand}(E_{pp}(k) - E_{prod}(k))$$

is introduced at ensures that the BFG controller follows the allocated electrical energy production $E_{pp}(k)$ in the middle. However, if it is economically necessary due to disturbances in the process or due to violation of the boundary conditions, it can deviate from the requirements.

Model uncertainties are first heuristically considered in this solution. For this purpose, the costs over the time horizon are weighted weaker by $\gamma \in [0\ldots.1]$. This has the effect that predictions that lie in the further future and are not so precisely known are weighted weaker and thus influence the optimization result lower.

MPC3: The steam network and its economic model predictive controller
Figure 34 shows the components of the steam network within the overall network structure:

- LD Boiler
- Steam Accumulator
- Steam Network
- Steam Boiler
- Steam Consumer
- Condenser (flare)

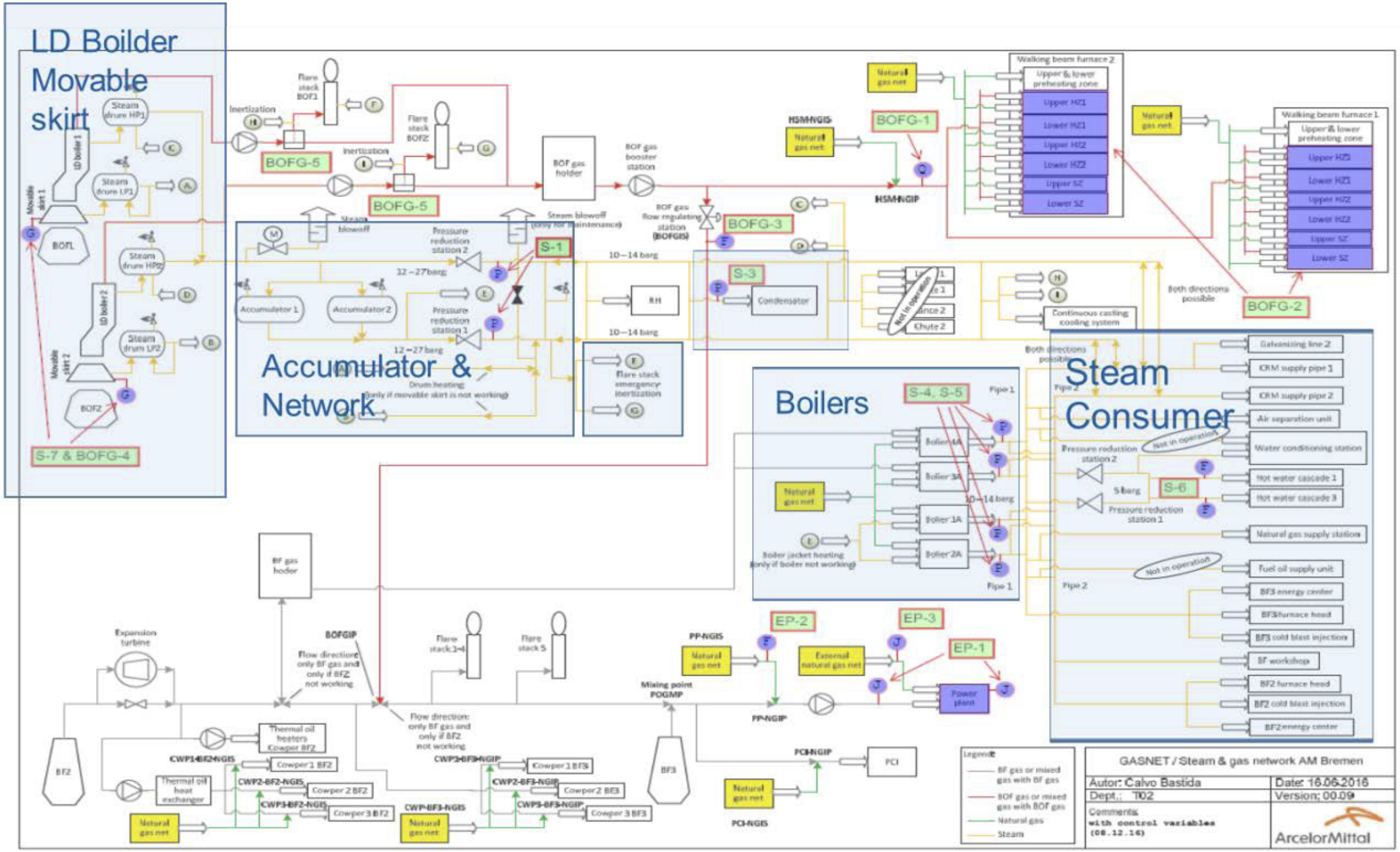


Figure 34: Components of the steam network at ABG steelworks

In contrast to the BFG and BOFG networks, this network holds two accumulators arranged one behind the other. The first accumulator is the main accumulator and the entire steam network can be considered as a secondary accumulator, since steam can be temporarily stored there by increasing the pressure.

Figure 35 depicts the Control model structure of the BFG steam network. For the sake of simplicity, only the pressure in the main accumulator is considered in subsequent analysis the pressure in the network will in the next step.

The pressure in the main accumulator can be actively influenced by the following manipulated variables:

- Skirt position of the Movable skirt in the LD boiler
- Set point of the pressure reduction station
- Set point of the condenser
- Start and stop of the steam boiler
- Set point of the hot water station

Such as already mentioned above, the relationship between control values and control quantities must firstly be described for the controller design.

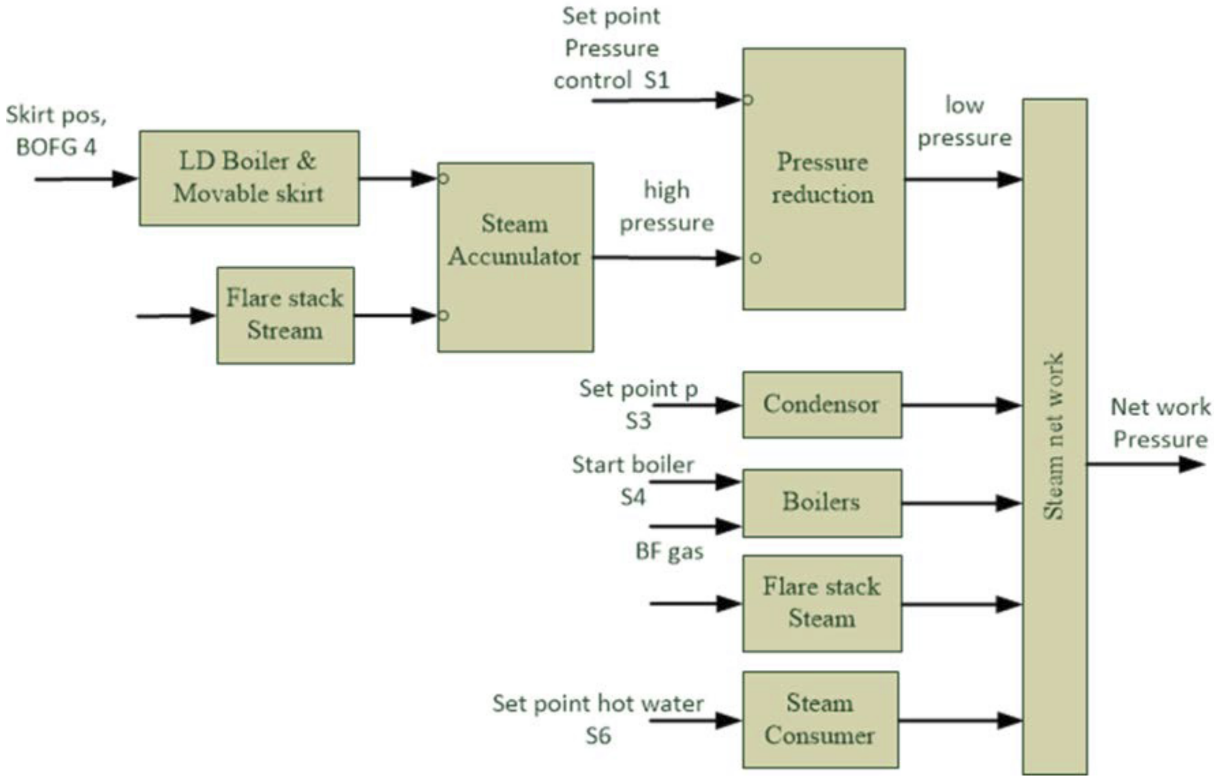


Figure 35: Control model structure of the BOFG steam network

The main objectives of the high-level steam network controller are:

- Control the Steam accumulators' pressure, ensuring that the steam pressure inside them is within an optimal range and constrained between a minimum and a maximum value;
- Control the steam pressure in the network within optimal range, constrained between a minimum and a maximum value;
- Optimize the distribution of steam between the various consumers while minimizing the use of natural gas in the auxiliary boilers through their optimal switching and a optimized scheduling of the use of byproduct gasses
- Minimize the condensed steam in the condenser

To achieve these goals the controller is designed to solve, in an MPC fashion, a problem of optimum that can be mathematically described as the minimization of a cost function J verifying a set of constraints (feasibility region). The cost function is described as follows:

$$\text{minimize} \sum_{k=0}^{N} \gamma^k \left(J_{\text{NG}}(k) + J_{P_{\text{acc}}}(k) + J_{\text{Bswitch}}(k) + J_{\text{cond}}(k) + J_{BFG \rightarrow AB}(k)\right)$$

where $J_{\text{NG}}(k)$, that is the cost related to a consumption of a volume flow of natural gas $\dot{m}_{NG}$, is computed as:

$$J_{\text{NG}}(k) = C_{NG}(k)\, \dot{m}_{NG}(k)$$

$J_{P_{\text{acc}}}(k)$ is a fictitious cost related to the accumulator pressure, which takes into account a soft constraint for the accumulator pressure P_{acc} in the range $\left[\underline{p}\,,\ \overline{p}\right]$, that allows to better ensure the hard constraint on the accumulator pressure (see **Figure 36**):

$$J_{P_{\text{acc}}}(k) = C_{P\,acc}(k)\max(0, P_{\text{acc}}(k) - \ \overline{p}\ ) + C_{P\,acc}(k)\max\left(0, \underline{p} - P_{\text{acc}}(k)\ \right)$$

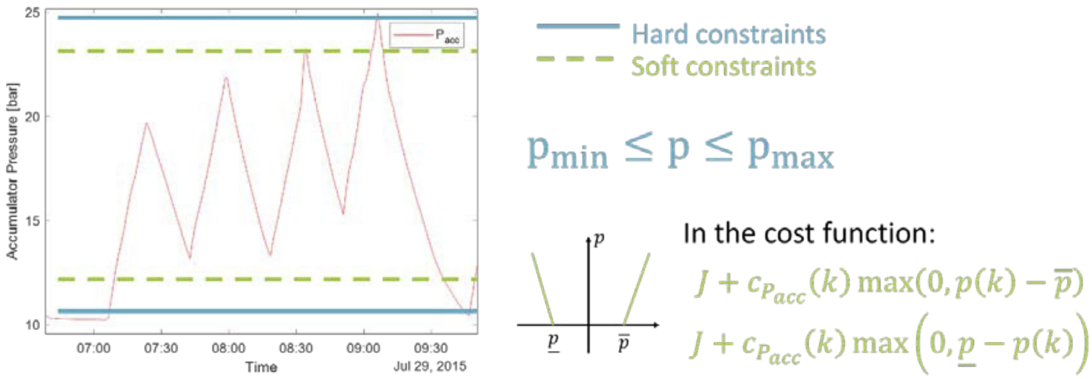


Figure 36: Hard and soft constraints on the steam accumulator pressure

$J_{\text{Bswitch}}(k)$ is the cost that allows to prevent the frequent switching of the steam boilers, and it is computed as:

$$J_{\text{Bswitch}}(k) = C_{switch}(k)\left|\delta_{B_i}(k) - \delta_{B_i}(k-1)\right|$$

where $\delta_{B_i}(k)$ is the boolean status (0 or 1) of the i-th steam boiler B_i at the time k.
The last term of the cost function $J_{\text{cond}}(k)$ is related to the cost of waste of steam in the condenser, which takes into account the energy loss due to the condensation of a steam mass flow $\dot{m}_{cond}(k)$:

$$J_{\text{cond}}(k) = C_{cond}(k)\ \dot{m}_{cond}(k)$$

Next cost term is indroduced ensure the connection to the high level optimizer

$$\mathrm{l}_{\mathrm{BFG}\rightarrow\mathrm{AB}}(\mathrm{k}) = \ \mathrm{C}_{\mathrm{BFG}\rightarrow\mathrm{AB}}(\mathrm{k})(\dot{\mathrm{V}}_{\mathrm{BFG}\rightarrow\mathrm{AB,demand}}(\mathrm{k}) - \dot{\mathrm{V}}_{\mathrm{BFG}\rightarrow\mathrm{AB}}(\mathrm{k}))$$

$\dot{\mathrm{V}}_{\mathrm{BFG}\rightarrow\mathrm{AB,demand}}(\mathrm{k})$is the exchange volume flow between BFG and Steam network, which is assigned by the higher-level optimization. This ensures that the Steam-controller follows the allocated exchange flow rate in the middle. However, if it is economically necessary due to disturbances in the process or due to violation of the boundary conditions, it can deviate from the requirements.

The optimum problem has to take into account a large set of constraints that have been designed to be as general as possible and applicable to each industrial partner. These constraints take into account:

- the dynamics of all the involved systems within the control loop (steam accumulator, network and boilers);
- the hard constraint on the steam accumulator pressure, minimum $\check{P}_{acc}$ and maximum pressure $\hat{P}_{acc}$;
- the minimum $\check{P}_{net}$ and maximum pressure $\hat{P}_{net}$ in the steam network;
- the minimum and maximum steam mass stored in the pipes of the network;
- the maximum steam mass flow produced by each steam boilers;
- the minimum and maximum thermal power of each burner of each boiler in each modality (only NG, only byproducts gases, mixed gas mode (MG));
- the balance of mass between steam consumption and production that flow in the steam network;
- the minimum time in which the boilers must remain on.

These constraints define a feasibility region of the problem that can be mathematically summarized as follows:

- Dynamics of the overall steam network and its constraints:

$$\begin{cases} x_{SN}(k+1) = A_{SN}x_{SN}(k) + B_{SN}u_{SN}(k) + B_D D(k) \\ y_{SN}(k) = \begin{bmatrix} P_{acc}(k) \\ \dot{m}_{\text{steam}\to\text{net}}(k) \\ P_{\text{net}}(k) \end{bmatrix} = C_{SN}x_{SN}(k) \end{cases}, u_{SN} = \begin{bmatrix} \dot{m}_{cond} \\ \dot{m}_{B_1} \\ \vdots \\ \dot{m}_{B_i} \\ \vdots \\ \dot{m}_{B_{N_B}} \end{bmatrix}, D = \begin{bmatrix} \dot{m}_{c_1} \\ \vdots \\ m_{c_{N_c}} \\ \dot{m}_{ncprod_1} \\ \vdots \\ \dot{m}_{ncprod_{N_p}} \end{bmatrix}$$

$$\check{P}_{acc} \le P_{acc}(k) \le \hat{P}_{acc}$$
$$\check{P}_{net} \le P_{net}(k) \le \hat{P}_{net}$$

where:
x_{SN} is the state of the steam network dynamics,
u_{SN} are the controllable variables in the steam network (the condensed steam mass flow $\dot{m}_{cond}$ and the produced steam mass flows $\dot{m}_{B_i}$ of each boiler B_i connected to the steam network),
D are the disturbances of the system that, in details, are the non-controllable steam mass flow consuptions $\dot{m}_{c_h}$ (with $h = 1 \dots N_c$ Number of non controllable consumers) and the non-controllable steam mass flow productions $\dot{m}_{ncprod_l}$ (with $l = 1 \dots N_c$ Number of non controllable consumers, e.g. BOF steam mass flow production),
$\dot{m}_{\text{steam}\to\text{net}}$ is the steam mass flow injected in the steam network,
P_{net} is the steam network pressure.

- Dynamic of the mass flow stored in the steam network pipes:

$$V_{SN_{acc}}(k+1) = V_{SN_{acc}}(k) - \dot{m}_{SN_{acc}}(k)\Delta t$$
$$0 \le M_{SN_{acc}}(k) \le \widehat{M}_{SN_{acc}}$$

where
$M_{SN_{acc}}$ is the total steam mass stored in the steam network pipes
$\dot{m}_{SN_{acc}}(k)$ is the fraction of steam mass flow consumed in the time k
$\widehat{M}_{SN_{acc}}$ is the maximum steam mass stored in the pipes;

- Dynamics of the i -th steam boiler and its constraints:

$$\begin{cases} x_{B_i}(k+1) = A_{B_i}x_{B_i}(k) + B_{B_i}u_{B_i}(k) \\ y_{B_i}(k) = \dot{m}_{B_i}(k) = C_{B_i}x_{B_i}(k) \end{cases}, u_{B_i} = \begin{bmatrix} \dot{m}_{\text{NG}_j} \\ \dot{m}_{\text{BFG}_j} \end{bmatrix}, i = 1 \dots N_B$$

where
x_{B_i} is the state of the i -th boiler B_i dynamics,
$\dot{m}_{NG_j}$ and $\dot{m}_{\text{BFG}_j}$ are, respectively, the NG and BFG consumption on each burner j,
$\dot{m}_{B_i}$ is the steam mass flow production.
Typical constraints are on the maximum and minimum produced steam mass flow:

$$0 \le y_{B_i}(k) \le \hat{\dot{m}}_{B_i}$$

on the minimum LCV of gas in input at boiler (in case of byproduct gases boilers):

$$\text{LCV}_{\text{gas}}(k) \ge \widehat{\text{LCV}}_{\text{gas}}$$

and on thermal power that depends on the type of the boiler and its modality:

1. NG Boiler:

$$\check{W}_{T_{\text{NG}_{\text{B}_i}}} \le \text{LCV}_{\text{NG}}(k)\, \dot{m}_{\text{NG}_j}(k) \le \widehat{W}_{T_{\text{NG}_{\text{B}_i}}}$$

Where there is a constraint on the minimum and maximum thermal power for each NG burner;

2. NG + BFG burners:
   a. Only NG burners switched on:

$$\check{W}_{T_{\text{NG}_{\text{B}_i}}} \le \text{LCV}_{\text{NG}}(k)\, \dot{m}_{\text{NG}_j}(k) \le \widehat{W}_{T_{\text{NG}_{\text{B}_i}}}$$

   where there is a constraint on the minimum and maximum thermal power for each burner j;

   b. Only BFG burners switched on:

$$\check{W}_{T_{\text{BFGonly}_{B_i}}} \le \text{LCV}_{\text{BFG}}(k)\, \dot{m}_{\text{BFG}_j}(k) \le \widehat{W}_{T_{\text{BFGonly}_{B_i}}}$$

c. Mixed mode (BFG burners + NG burners):

$$\breve{W}_{T_{\mathrm{NG}_{B_i}}} \leq \mathrm{LCV_{NG}}(k)\,\dot{m}_{\mathrm{NG}_j}(k) \leq \widehat{W}_{T_{\mathrm{NG}_{B_i}}}$$
$$\breve{W}_{T_{\mathrm{BFGonly}_{B_i}}} \leq \mathrm{LCV_{BFG}}(k)\,\dot{m}_{\mathrm{BFG}_j}(k) \leq \widehat{W}_{T_{\mathrm{BFGonly}_{B_i}}}$$
$$\breve{W}_{T_{B_i}} \leq \mathrm{LCV_{NG}}(k)\,\dot{m}_{\mathrm{NG}_j}(k) + \mathrm{LCV_{NG}}(k)\,\dot{m}_{\mathrm{NG}_j}(k) \leq \widehat{W}_{T_{B_i}}$$

Some boilers can have addictional constraints during mixed gas mode, as a constant NG flow consumption:

$$\dot{m}_{NG_j} = \dot{\overline{m}}_{NG_j}$$

- The mass flow balance:

$$\sum_{h=1}^{N_{N_c}} \dot{m}_{c_h}(k) + \sum_{l=1}^{N_p} \dot{m}_{ncprod_l}(k) + \sum_{i=1}^{N_{B_i}} \dot{m}_{B_i}(k) + \dot{m}_{SN_{acc}}(k) + \dot{m}_{cond}(k) = 0$$

The formulated problem is a Mixed Integer Linear Problem (MILP), as the continuos controllable variables are the condensed steam mass flow $\dot{m}_{cond}$ and the NG and BFG consumptions in each burner of each boiler B_i connected to the steam network and the discrete (Boolean) variables are the switching of the boilers. The optimum problem has been preliminary solved through GUROBI algorithms, but the final version of the software is based on Google OR-Tools library, an open source software suite for optimization, in particular integer and linear programming, and constraint programming. Due to the restrictions related to the use of license-free software for the implementation, the chosen solver is CBC (Coin-or branch and cut) an open-source mixed integer programming algorithm developed within the COIN-OR project, managed by the COIN-OR Foundation, Inc., a non-profit educational foundation.

4.6 WP 6: Industrial tests and validation

The objectives of WP6 are:

- To perform extensive tests of the developed advisory tool and evaluate the achieved results.
- To develop general guidelines for the analysis and optimization of gas networks inside the steelworks and for the application of the developed decision support tool
- To disseminate the project results in the scientific and industrial community

4.6.1 Task 6.1 Preliminary off-line tests exploiting the historical databases.

A substantial part of the offline test work was carried out in order to further validate the process models, which are part of the final library of the GASNET software. The models aim at predicting the most important quantities involved in the various optimization systems, therefore their accuracy is fundamental for the goodness of the overall optimization approach. The models forecast volumetric flow and energy contents of off-gasses, steam production and consumption of each main process, gasholder levels, dynamic behaviour of the steam network and electric power production and consumption within the steelworks.

In order to model the main charateristics of the processes, several techniques have been used during the modelling steps. The pursued approach can be summarized in the following principles:

- Each process that is directly involved in the control loop of the optimization strategy must possibly be modeled through linear techniques, in such a way as to fall within a linear framework, useful for defining realtime optimization strategies.
- When the accuracy of linear models within the control loop is not sufficient to describe in an effective way the dynamic of the process, the complexy of the following modelling approach has to be limited as possible, through use of well linearizable models, or through use of architectures that limit the nonlinearity and non-convexity of the system, so as to remain in a convex optimization framework, although non-linear.
- The processes that are outside the control loop (in general the non-controllable ones) can be modelled also through nonlinear techniques, as long as these techniques are not computationally heavy.

Following these rules, several techniques has been exploited such as: linear state space models, Hammerstein Viener, static (feedforward) and recurrent neural network approaches (e.g. ESN), Auto-Regressive Exogenous (ARX) models, and statistical modelling architectures based on Kernel methods.

The Main objectives of the model tests can be summarized as follows:

- Study and verify the effectiveness and reliability of modeling techniques and the architecture of the models used;
- Verify the accuracy of the models, trained or identified during the previous campaign of data acquisition;
- Study the best strategy for adapting the parameters of each model, develop specific auto-tuning strategies, re-identification and re-training periods of each model;
- Finalize the pre-processing and post-processing library useful to increase the final accuracy of each model in as many operating points as possible.

Here some interesting results, achieved during the test phase, are reported. In particular, some cases are shown, which allowed defining or refining the strategies to improve the reliability of the models.

- BFG production and HBS consumption of BFG and COG at Tata steelworks, example of a good and transferable modelling approach.
- RH Steam production models, example of well refined approach;
- LD High pressure steam production, example of model that can be adapted online without computational efforts;
- Expansion Gas turbine of BFG, example of model that can be improved online with specific addictional informations;

Moreover, some off-line tests of the strategy planning over data related to one day have been developed before the final implementation stage, which are here shown and discussed.

BFG and HBS models

A tailoring of BFG and HBS ESN-based forecasting models have been done for the case of Tata Steel, by considering their data, in order to show the goodness and transferability of the proposed modelling approach and some tests have been carried out. All the models allow making the prediction of desired output in a horizon of 2 hours with a forecasting frequency of 1 minute (for a total number of 120 forecasted samples).
An example of prediction 2 hours ahead of the BFG production from the two BFs of Tata Steel are shown in **Figure 37** and in **Figure 38**, where the real values are depicted in blue while forecasted values are shown in orange. For confidentiality constraints, the scale on the vertical axis is not shown.

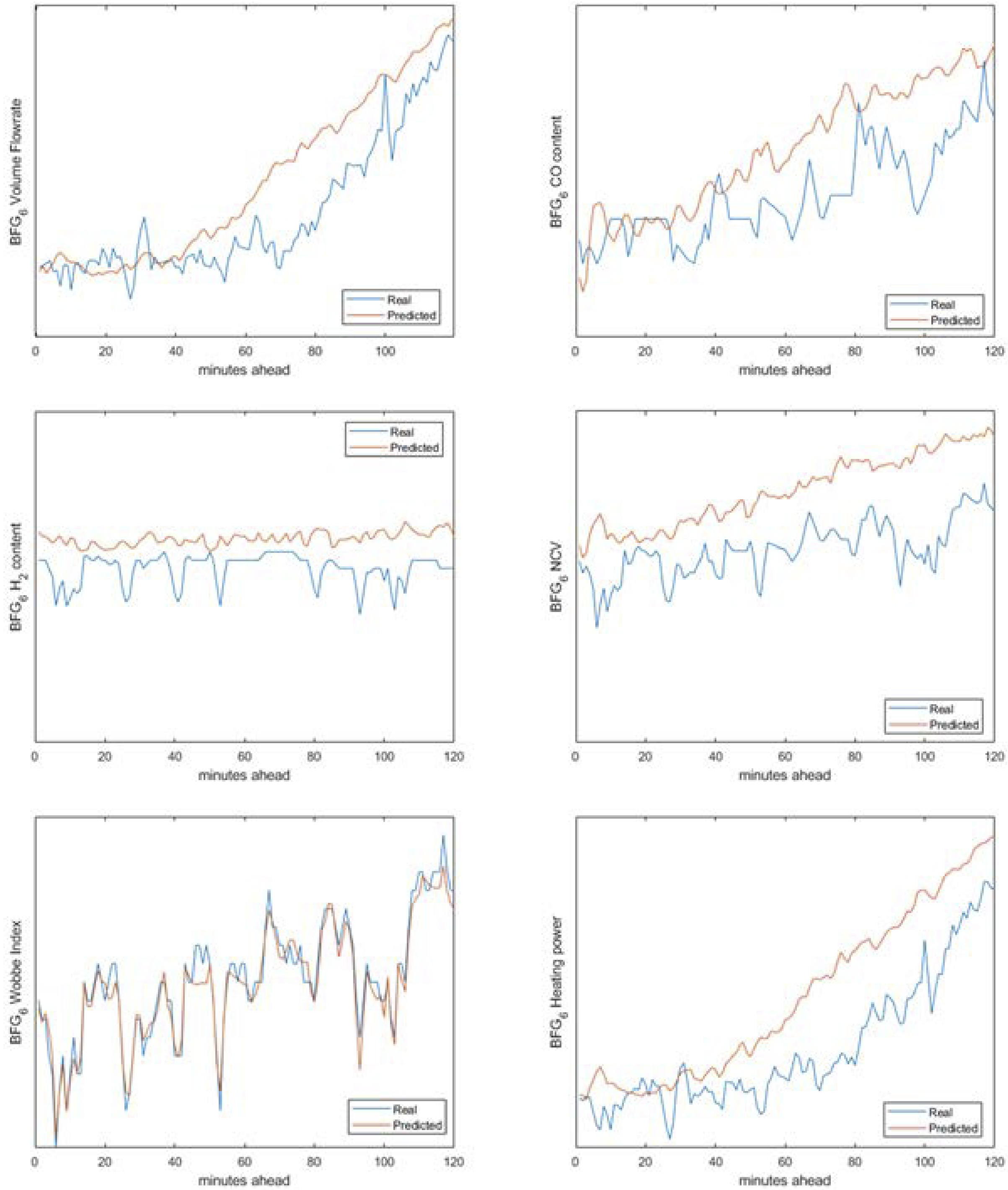


Figure 37: Comparison between real and forecasted values of BFG production for BF6 at Tata Steel steelworks

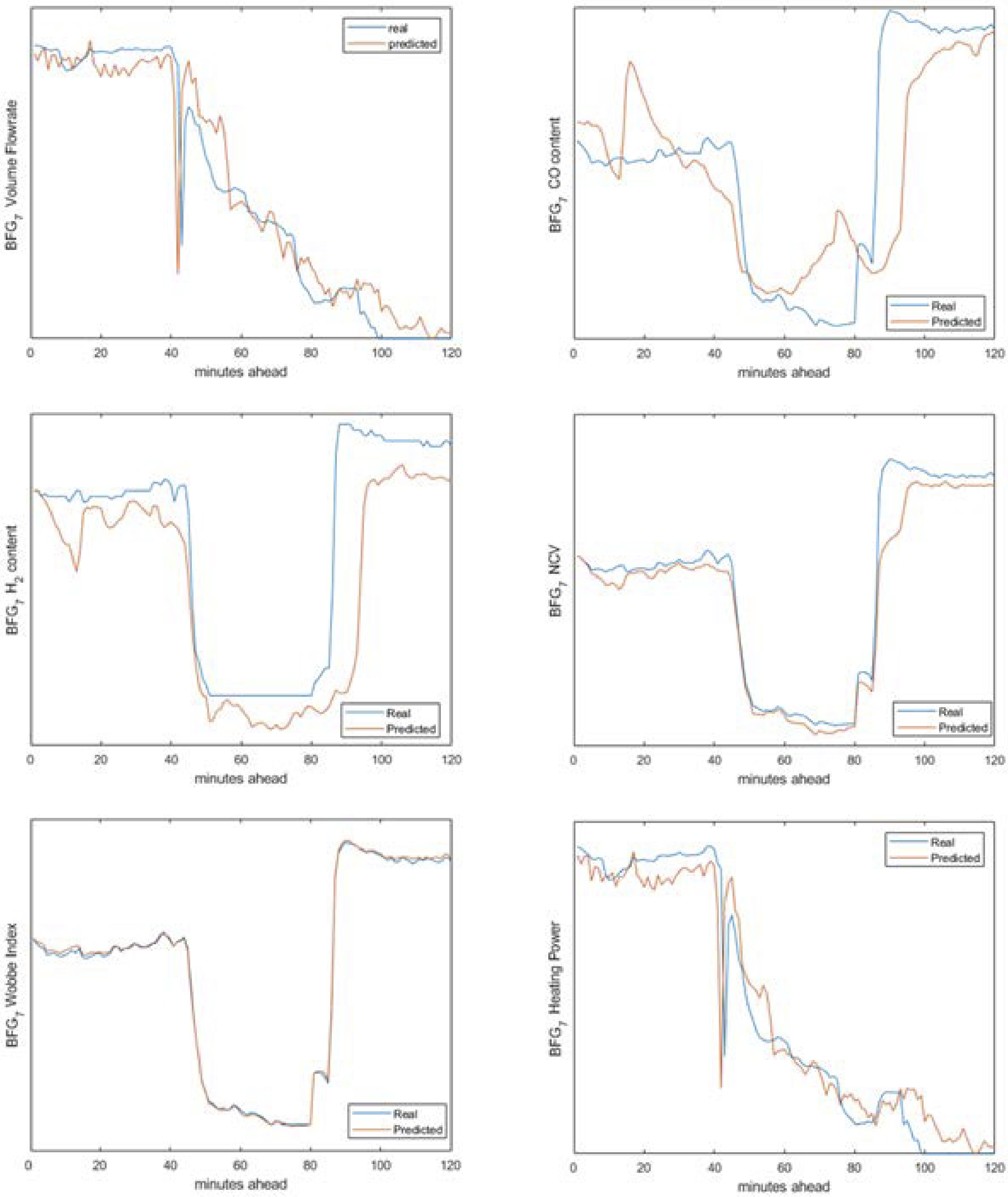


Figure 38: Comparison between real and forecasted values of BFG production for BF7 at Tata Steel steelworks

On the other hand, considering that in the Tata HBS, both BFG and COG are consumed, two examples of the forecasted consumption on a time horizon of 2 hours ahead are shown in **Figure 39** and **Figure 40**.

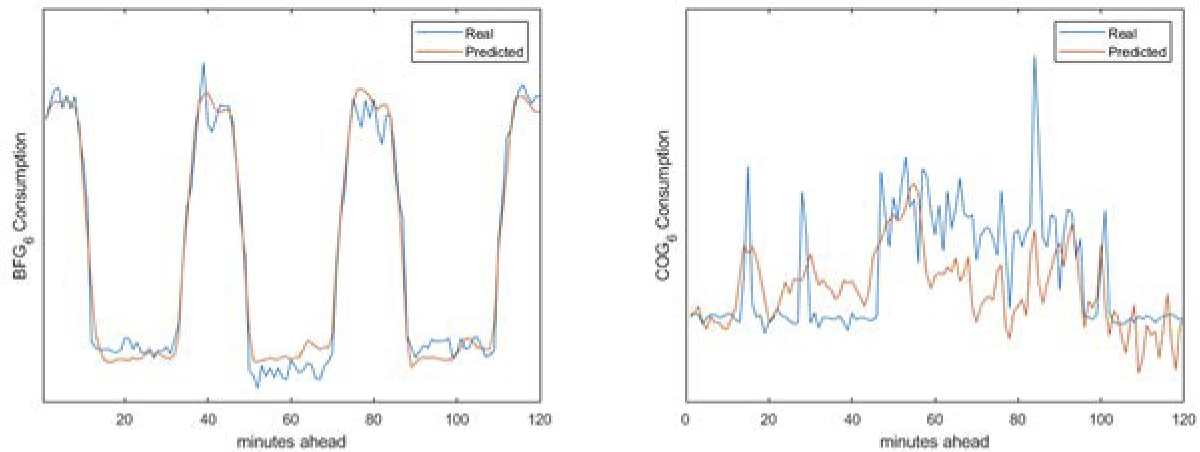


Figure 39: Comparison between real and forecasted values of BFG and COG consumption by HBS of BF6 at Tata steelworks

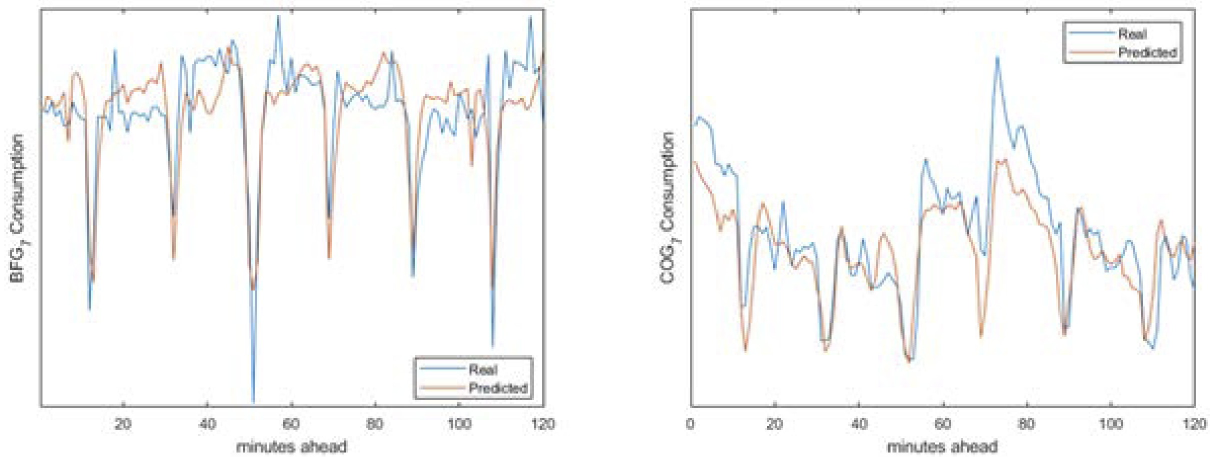


Figure 40: Comparison between real and forecasted values of BFG and COG consumption by HBS of BF7 at Tata steelworks

As expected, for all the models, the error is generally lower in the first samples of prediction and it tends to increase for the forecasting of a farer future, however the accuracy of the results is still acceptable. Some uncommon exceptions can be found and generally are related to some input data issues such as their significant deviation from the ones used during the training of the models. In case these deviations are not more unusual, but become frequent, for instance, due to change in operating procedures or conditions, a retraining of the model is recommended.

RH Steam production models.

The RH process uses steam in order to degass the steel, its steam consumption is modelled through ESN architecture trained starting from the future scheduling of the process and the current steam consumption. The model trained during the WP3 though AMB data for the year 2016, has been tested with AMB data acquired during the first quarter of 2019, in order to show the current accuracy of the models. The results are summarized in **Figures 41** and **42**, which show respectively an example of future prediction of steam consumption, starting from a time instant, and the Normalized Mean Absolute Error (NMAE) and Normalized Root Mean Square Error (NRMSE) for the dataset related to the first quarter 2019 in function of the distance of the future prediction. The model allows predicting the steam consumption in the RH process with the same accuracy achieved during the training session. In particular, with NRMSE error in the range 7.1-7.5%.

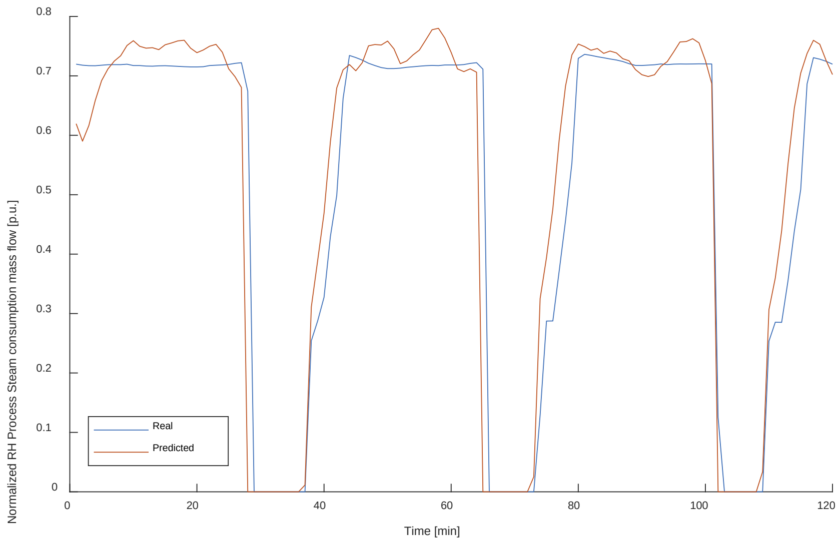


Figure 41. Example of prediction of the steam consumption in the RH degassing process

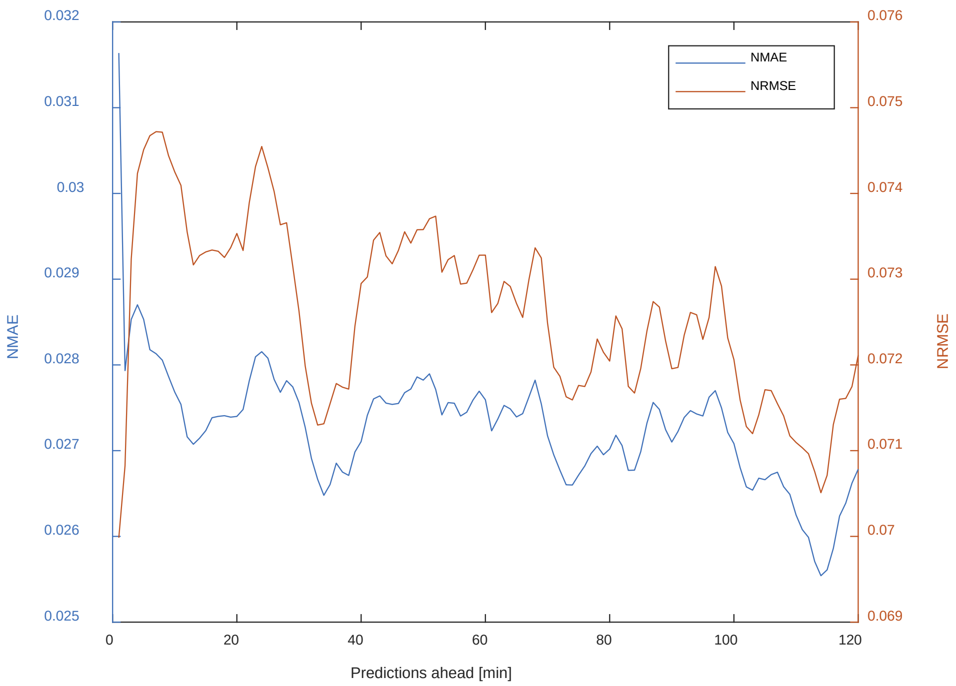


Figure 42. Normalized Mean Absolute Error (NMAE) and Normalized Root Mean Square Error (NRMSE) of RH Model during the test phase, in function of the temporal remoteness of the prediction.

The testing phase shows that this specific model can be not very sensitive to changes in the operating points of the process that may change over time.

LD High pressure steam production.

In the BOF a great amount of steam can be produced through termal exchange with BOFG recovered through the movable skirt and then subsequently treated before it can be stored in the gasholder. The BOFG has a sufficiently high heat that allows to produce quantities of steam with different pressure levels, through some boilers.
The following specific models, developed during WP3, shows that is possible to predict the future steam production starting from the future scheduling data, and some specific measurements of the current status of the process.
The steam production (in terms of t/h) is modelled through a deepESN architecture trained starting from the future scheduling of the process and the current status of the process. The model trained during the WP3 though AMB data for the years 2015/16, has been tested with AMB data acquired during the first quarter of 2019, in order to show the current accuracy of the models. The test results are summarized in **Figures 43** and **44,** which show, respectively, an example of future prediction of

steam production, starting from a time instant, and the Normalized Mean Absolute Error (NMAE) and Normalized Root Mean Square Error (NRMSE) for the dataset related to the first quarter 2019 in function of the distance of the future prediction.

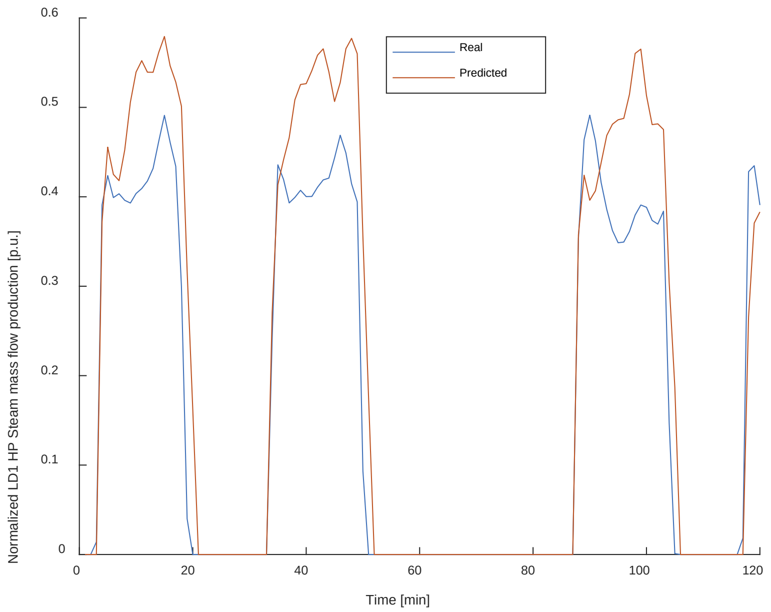


Figure 43. Example of prediction of the steam production in the HP steam system of the LD process

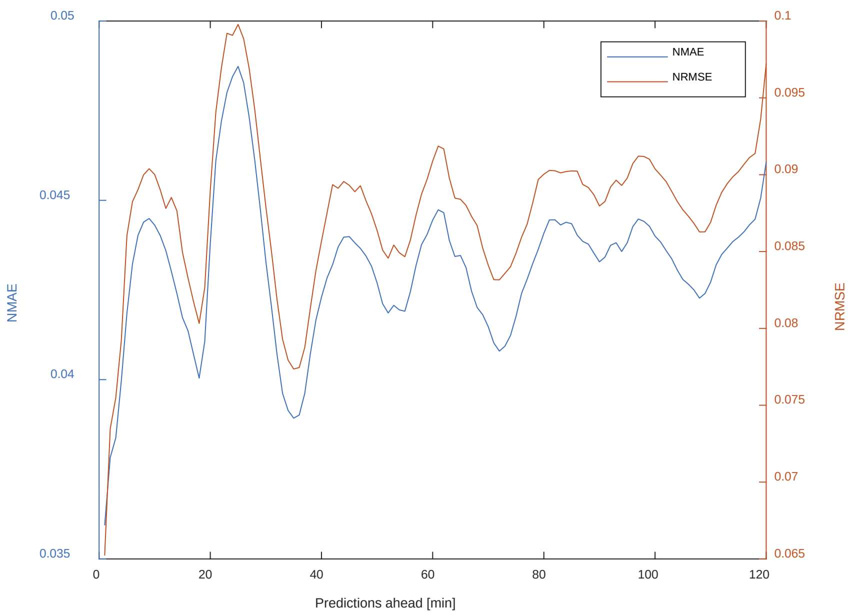


Figure 44. Normalized Mean Absolute Error (NMAE) and Normalized Root Mean Square Error (NRMSE) of LD High pressure steam production Model during the test phase, in function of the temporal remoteness of the prediction

The model allows predicting the steam production in the LD process with a decreased accuracy respect to the one achieved during the training session. In particular, with NRMSE error in the range 6.7-10%. An interesting analysis of the error is shown in **Figure 45**, which shows the trend of the ratio between the cumulative predictions and the cumulative target for each prediction in the future:

$$\text{Gain error}(k) = \frac{\sum_{i=0}^{k} \text{predicted mass flow}(i)}{\sum_{i=0}^{k} \text{target mass flow}(i)}$$

where k is the time of the dataset in samples. From a practical point of view, at the time k, it is the ratio between the total steam mass production predicted until the future time k and the total real mass flow production.

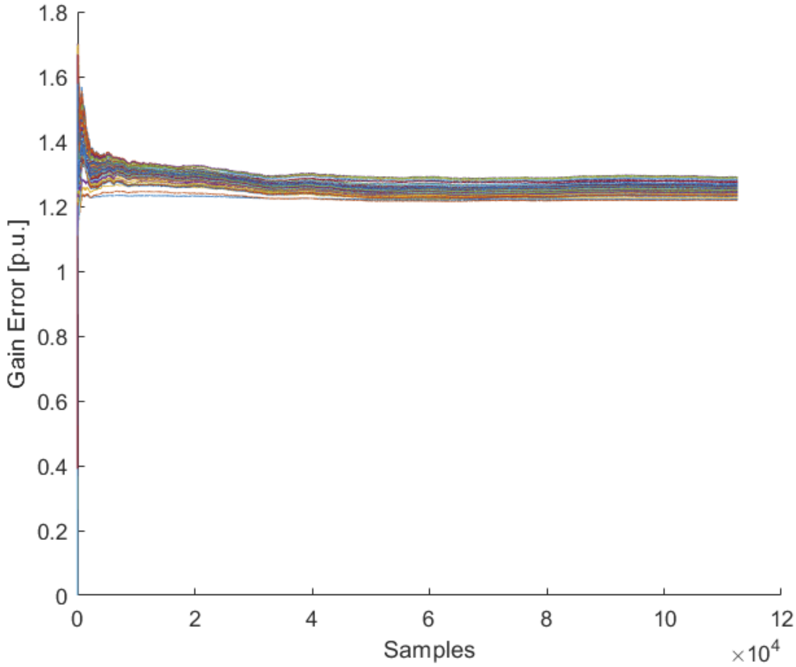


Figure 45. Example of gain error between the real data and the predicted values

This ratio, namely also ***gain error***, is relatively constant for all the dataset. More in details, this index gives an information about the difference of ratio between the static gain between the modelled system and the system itself. It is clear that the only difference between the predictions and the real system behaviour lies only in this characteristic. It suggests that it is possible to adapt the predictions through a post-processing of the output of the models as follows:

$$\text{correct predicted mass flow}(k) \cong \frac{1}{\text{Gain error}(k-1)}\text{predicted mass flow}(k)$$

where the prediction at the time k can be corrected through the gain error at the time $k-1$ $\text{Gain error}(\mathrm{k}-1)$.
Of course it is possible to correct the error in a good percentage through a re-training of the neural network itself whenever it is possible to schedule an offline update of the weights of the models, starting from the data in the Gasnet database archive.

Expansion Gas turbine of BFG.

The gas turbine allows to produce electrical power starting from the expansion of a certain amount of gas. In the steelworks very often it is possible to recover some energy through the expansion of the BFG produced in the Blast Furnace. In the case of AMB plant, for example it is possible to expand the BFG produced in the BF2. This model describes the behaviour of the produced electrical power in function of the expanded volume flow of the BFG. The system has been modelled through the use of a static feed-forward neural network (FFNN) that allow to obtain good prediction results.
The following model, developed during WP3, shows that is possible to predict the future electrical power production starting from the future predictions of the BFG production.
In particular, in the case of AMB it is possible to control the BFG flow through the gas turbine by means of a valve, which information (% opening). In general, the valve is fully opened, but in some operative points it is possible to bypass the turbine, in order to increase the pressure in the BFG network system, leading to the production of zero electrical power.
The model trained during WP3 though AMB data for the years 2015/16, has been tested with AMB data acquired during the first quarter of 2019, in order to show the current accuracy of the models. The test results are summarized in **Figure 46 and 47**. **Figure 46** shows an example of future prediction of electrical power, starting from a time instant. **Figure 47** offers a detail of the difference between the measured electrical power, the prediction of the power when the status of the valve is known, and its prediction when the status of the valve is unknown.

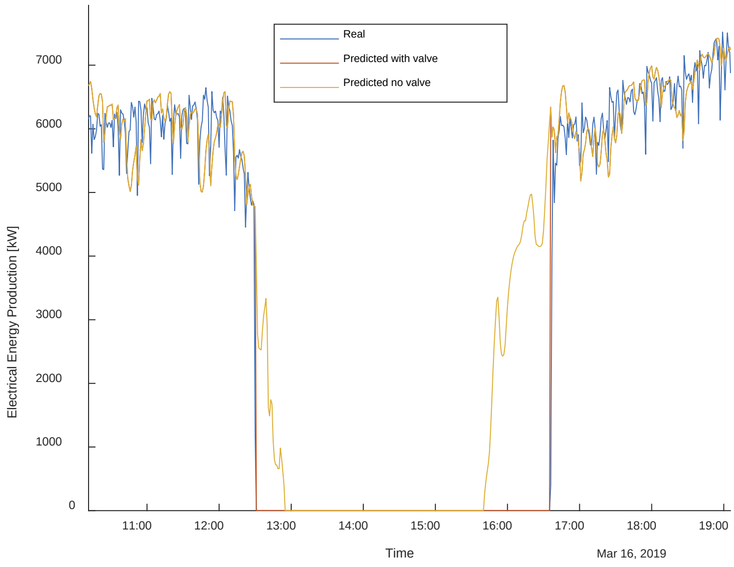


Figure 46. Example of prediction of the electrical power production in the BFG turbine

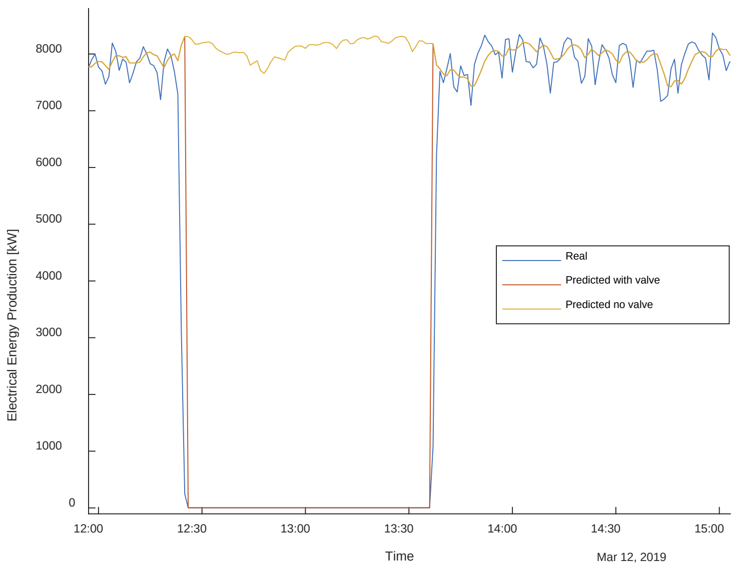


Figure 47. Example of prediction of the electrical power production in the BFG turbine: measured electrical power production (blue), predicted electrical power with a known information about the opening of the bypass valve (orange), predicted electrical power without information about the opening of the bypass valve (yellow).

If it is possible to measure or predict the future status of the bypass valve, the NRMSE is in the range of 3-3.2%, slightly increased respect to the errors achieved during the training session. In this case, it is obviously possible to improve the accuracy of the model through a simple retraining of the neural network. In the case the status of the bypass valve is unknown (due to data communication errors), the lack of information about the bypass and the inlet valves of the gas turbine can be partially overcome by taking into account the past information of the generated electrical power. If in the near past the electric power produced is zero it means that the bypass valve is kept fully open and the inlet valve of the gas turbine if fully closed. This type of correction means that when the valve is closed or opened, we cannot instantly correct the value of future predictions but there will be a time delay equal to the sampling time of the electrical power (15 minutes).

Test on the HL and hybrid online control strategies

in order to test the effectiveness of the control strategy presented in task 5.3/5.4 and 5.5, numerous simulations were carried out to identify the weak points and strengths of the approach followed.

HL optimizer

The effectiveness of the control action of the HL optimizer has been preliminary tested over a time horizon chosen related to one day of productive scheduling forward. The approach has been simulated for a dataset of real data, relating to the ABG in some days characterized by a rather constant and stable production.

The control results relating to a couple of exemplar days is presented here, in terms of distribution of Process Off-Gases (POG) and NG, production of electricity in the power plant, purchase and sale of electricity, the control of the specific process variables of the steam network and the use of POG torches. The results on the optimization strategy of POG distribution is compared to the actual distribution.
For each the graphs are shown, which refer to:

- the dynamics of the BFG and BOFG gasholder level; the trends of internal production, sale and purchase of electricity,
- The distribution of consumption in the BOFG network, in particular with respect to the use of NG and BOFG in WBFs, the use of torches and the transfer of BOFG to the BFG network;
- The operation of the steam network, in particular the use of the auxiliary boilers and the condenser;
- The distribution of consumption in the BFG network, the use of torches and finally the trends in the use of NG in controllable plants.

Day 1 – Test results

The results regarding the first day are shown in **Figures 48, 49, 50 and 51.** In particular, in **Figure 48** the top diagram shows the energy stored in the BFG gasholder and compares the trend achieved through the application of the proposed strategy (blue line) and the actual trend (red line). The diagram figure shows the BOFG gasholder level and compares the trend achieved through the application of the proposed strategy (blue line) and the actual non optimized trend (red line). Finally, the bottom diagram shows the electrical power generated in the power plant, the purchased and the sold electrical power: here the trends obtained through the application of the purposes control strategy are depicted in continuous lines, while the non-optimized ones are depicted in dash-dotted lines.
In **Figure 49**, the top diagram shows the BOFG used in the WBFs, and compares the trend achieved through the application of the proposed strategy (blue line) and the actual trend (red line). The central diagram shows the BOFG consumption in the BOFG torches: the red and yellow lines refer to the BOFG transferred to the BFG network, respectively, when the proposed control strategy is applied and in the standard situation. Finally, the bottom diagram shows the NG consumption in the WBFs when applying the proposed strategy (in blue line) and in the non-optimized situation (in red line).
Figure 50 refers to the BFG network. In particular, the top diagram refers to the BFG consumption in the torches and the blue line refers to the control strategy, while the red one to the non-optimized situation. The central diagram shows the BFG production (blue line), the MG burned in the power plant (red, the control strategy), the BFG burned in the auxiliary boilers (yellow line), the cowpers (purple line) and PCI plant (green line). The bottom diagram shows, respectively, the total controlled NG consumption in the integrated steelworks, which is achieved through the application of the proposed control strategy, and the NG consumption in the not-optimized scenario.
Figure 51 refers to the steam network and is articulated as follows: the top diagram depicts the not controllable steam production (blue line) and consumption (red line). The central diagram shows the control actions in terms of steam mass flows produced in the AB and condensed in the condenser, in the case of an optimized control action (blue and red line) and in the not optimized scenario (yellow and purple lines). The bottom diagram shows the total BFG and NG consumption in the ABs when the proposed strategy is applied (blue and red line) and in the not optimized scenario (yellow and purple lines).

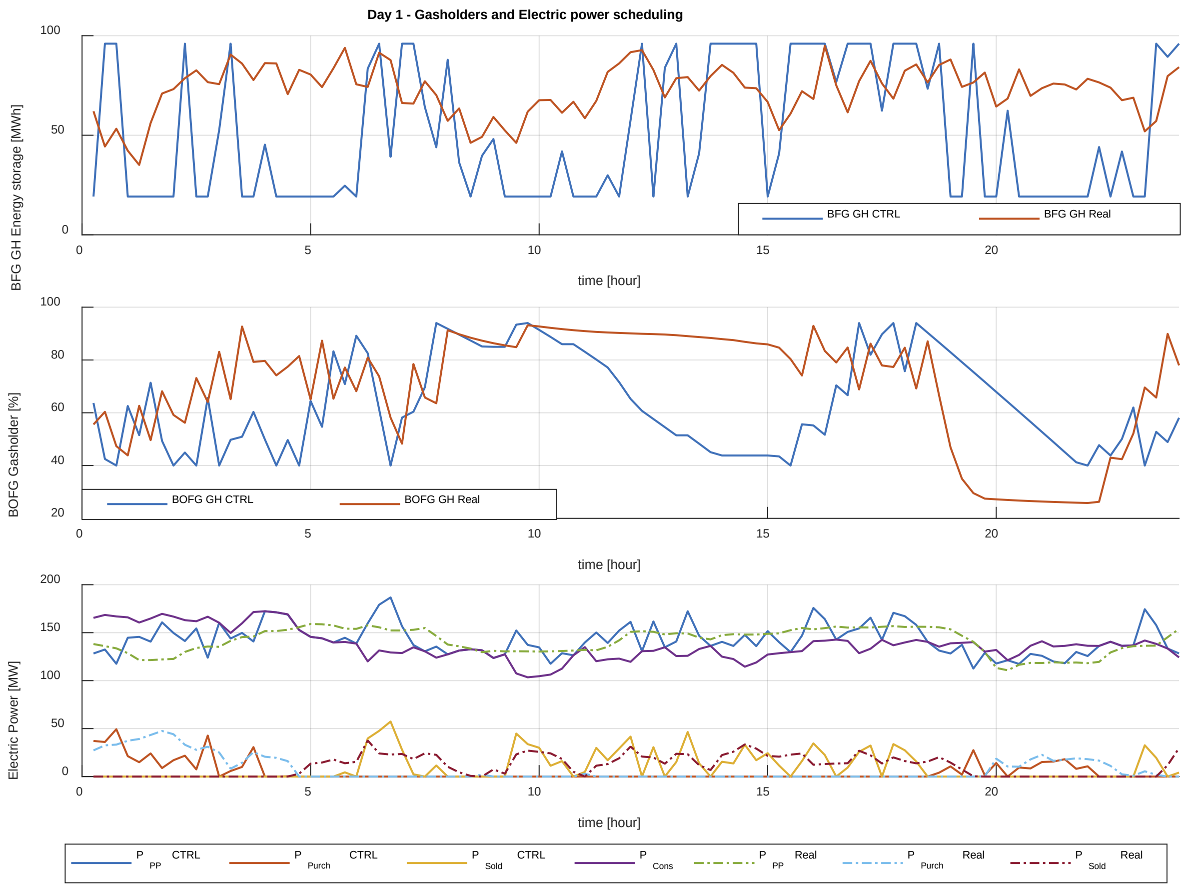


Figure 48: Day 1: Gasholders and Electric power trends

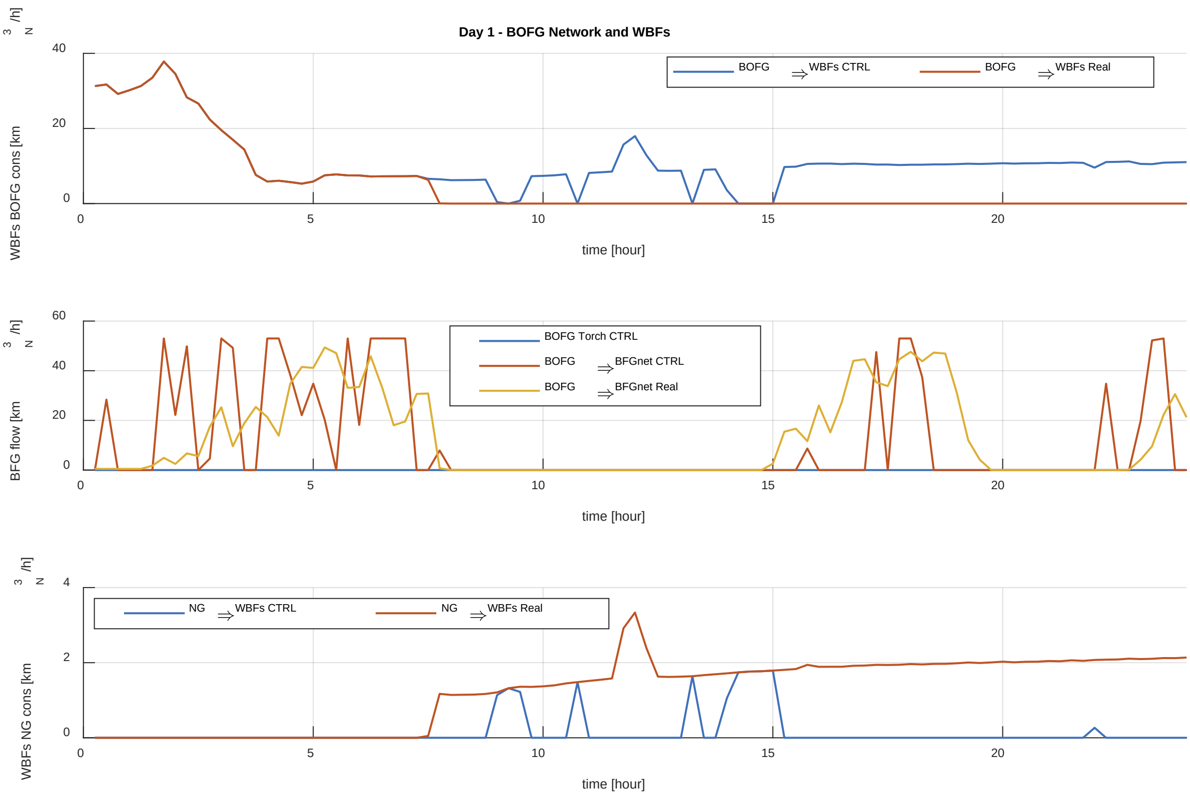


Figure 49: Day 1: BOFG Network control, WBFs NG and BFG consumptions

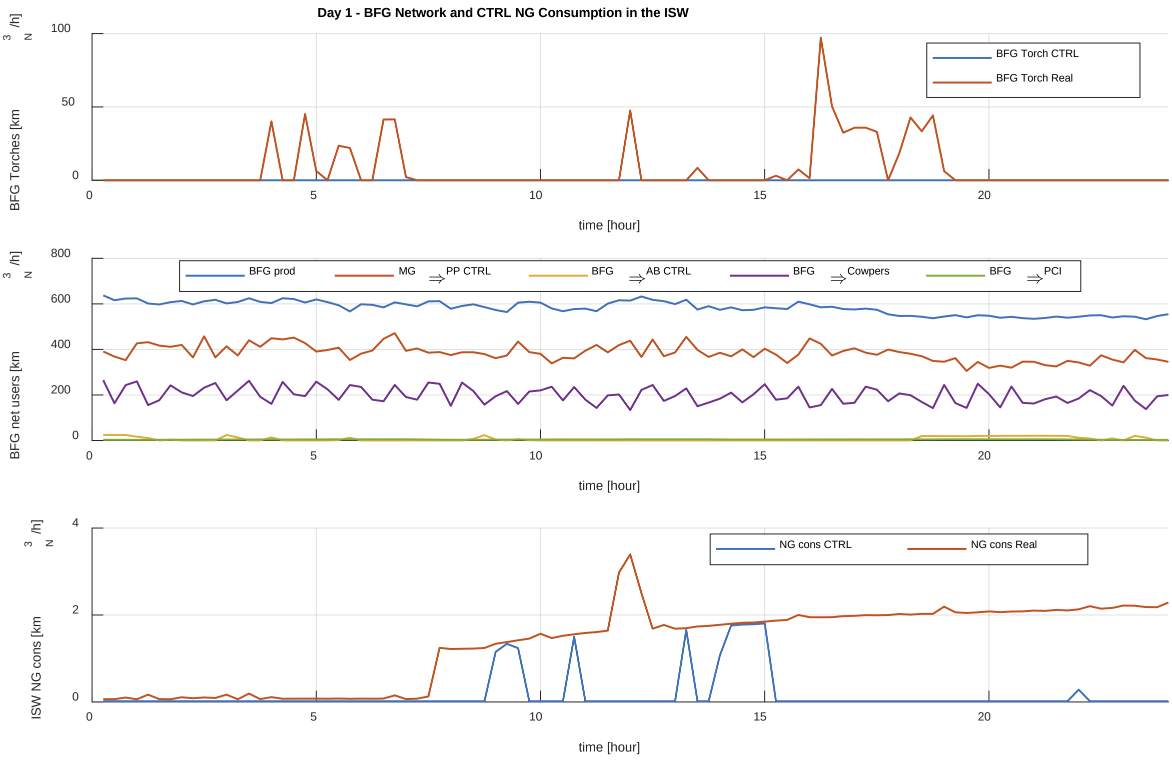


Figure 50. Day 1: BFG network control, BFG net users and total Controlled NG in the integrated steelwork plant

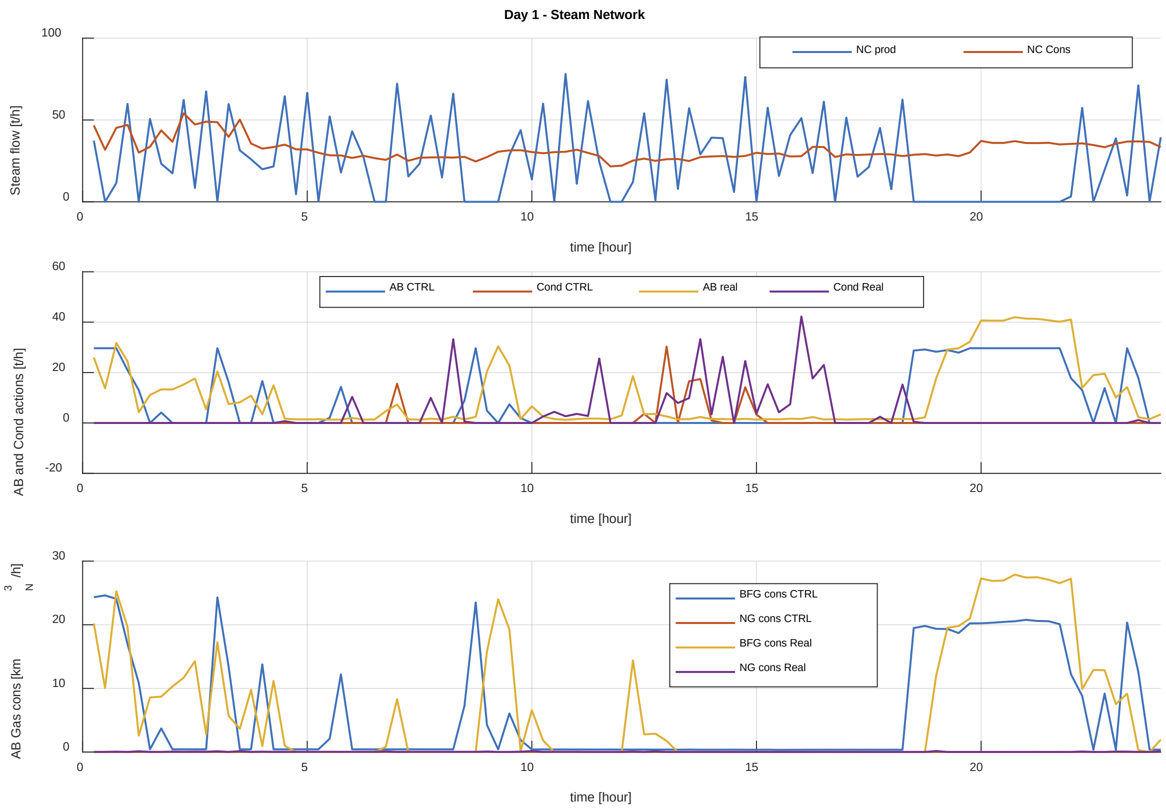


Figure 51. Day 1: Steam network control, Auxiliary boilers and condenser control actions, consumption of BFG and NG in the auxiliary boilers

Day 2 – Test results

The results regarding a second day are shown in **Figures 52, 53, 54 and 55**.

In particular, in **Figure 52** the top diagram shows the energy stored in the BFG gasholder and compares the trend achieved through the application of the proposed strategy (blue line) and the actual trend (red line). The diagram figure shows the BOFG gasholder level and compares the trend achieved through the application of the proposed strategy (blue line) and the actual non optimized trend (red line). Finally, the bottom diagram shows the electrical power generated in the power plant, the purchased and the sold electrical power: here the trends obtained through the application of the purposes control strategy are depicted in continuous lines, while the non-optimized ones are depicted in dash-dotted lines.

In **Figure 53**, the top diagram shows the BOFG used in the WBFs, and compares the trend achieved through the application of the proposed strategy (blue line) and the actual trend (red line). The central diagram shows the BOFG consumption in the BOFG torches: the red and yellow lines refer to the BOFG transferred to the BFG network, respectively, when the proposed control strategy is applied and in the standard situation. Finally, the bottom diagram shows the NG consumption in the WBFs when applying the proposed strategy (in blue line) and in the non-optimized situation (in red line).

Figure 54 refers to the BFG network. In particular, the top diagram refers to the BFG consumption in the torches and the blue line refers to the control strategy, while the red one to the non-optimized situation. The central diagram shows the BFG production (blue line), the MG burned in the power plant (red, the control strategy), the BFG burned in the auxiliary boilers (yellow line), the cowpers (purple line) and PCI plant (green line). The bottom diagram shows, respectively, the total controlled NG consumption in the integrated steelworks, which is achieved through the application of the proposed control strategy, and the NG consumption in the not-optimized scenario.

Figure 55 refers to the steam network and is articulated as follows: the top diagram depicts the not controllable steam production (blue line) and consumption (red line). The central diagram shows the control actions in terms of steam mass flows produced in the AB and condensed in the condenser, in the case of an optimized control action (blue and red line) and in the not optimized scenario (yellow and purple lines). The bottom diagram shows the total BFG and NG consumption in the ABs when the proposed strategy is applied (blue and red line) and in the not optimized scenario (yellow and purple lines).

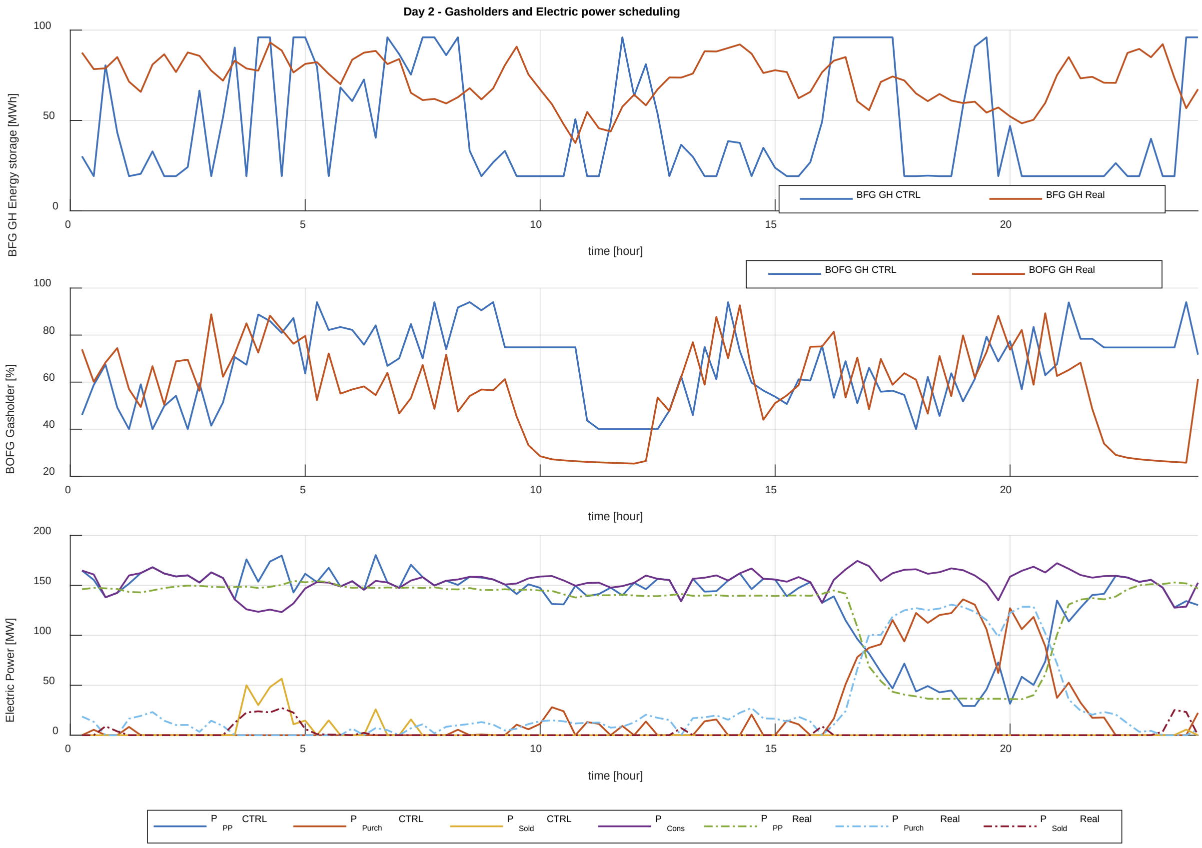


Figure 52: Day 2: gasholders and electric power trends

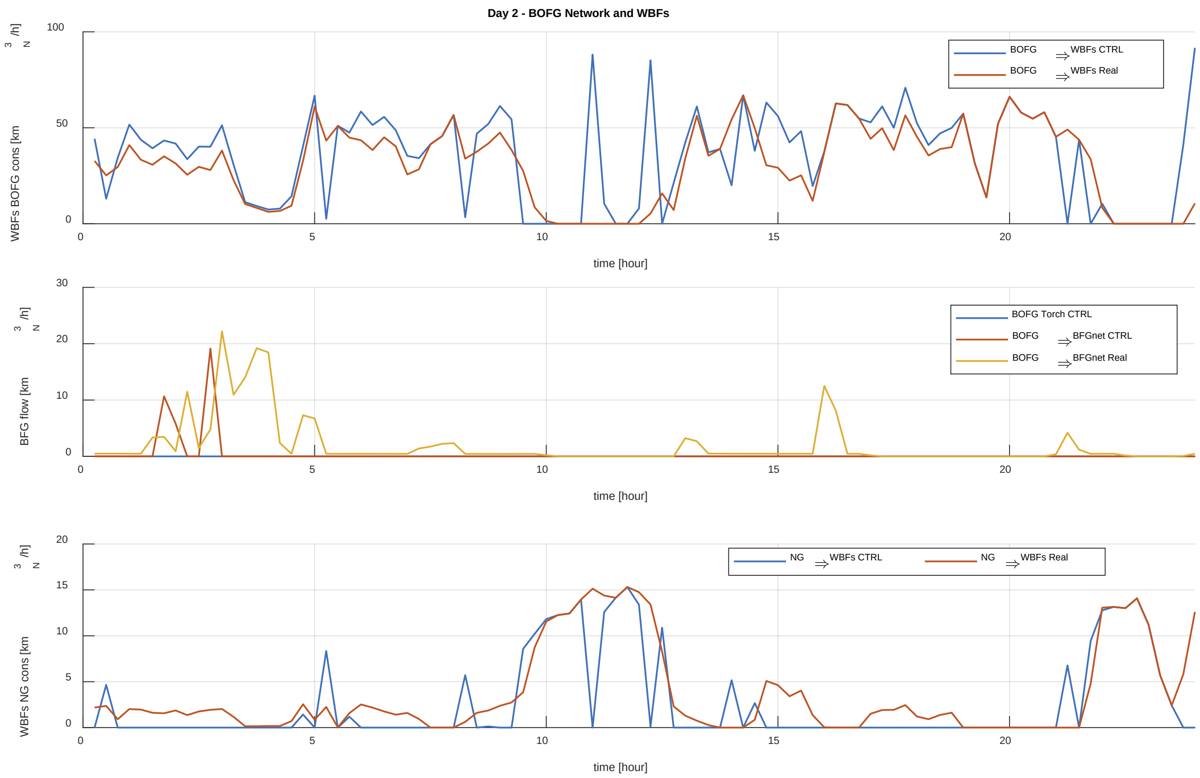


Figure 53: Day 2: BOFG network control, WBFs NG and BFG consumptions

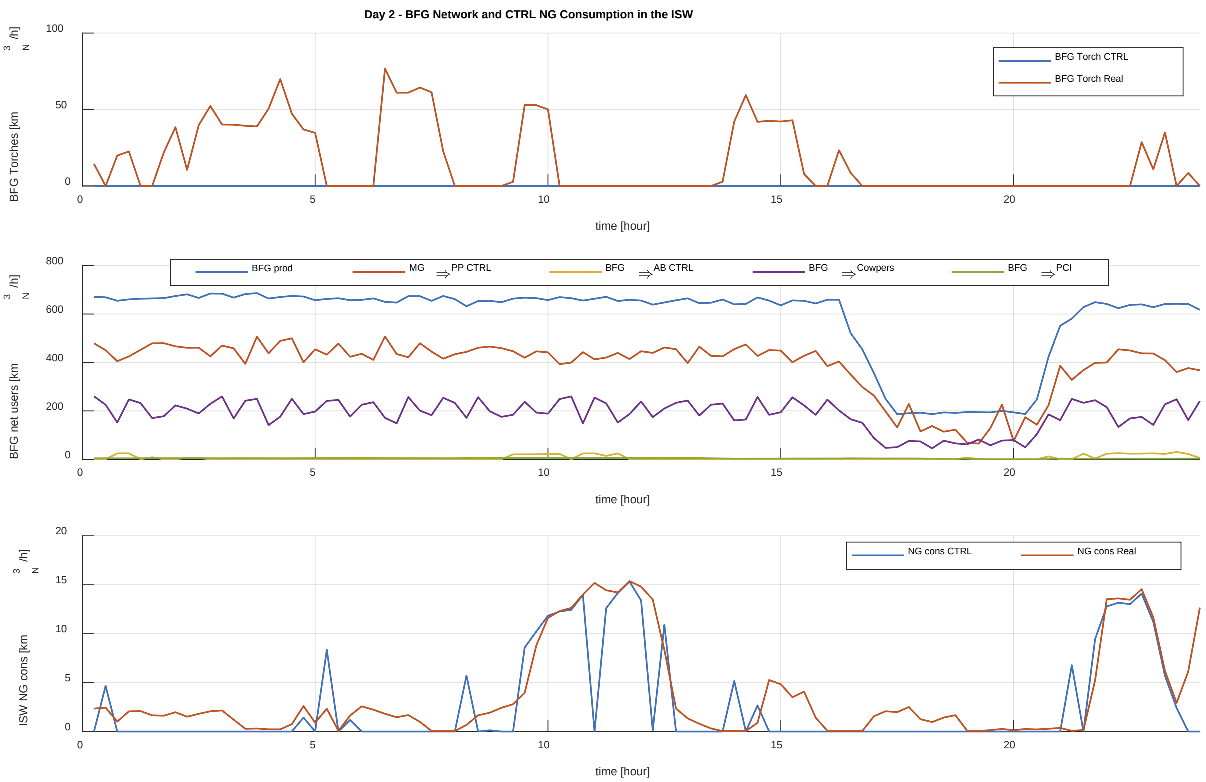


Figure 54: Day 2: BFG network control, BFG net users and total controlled NG in the integrated steelwork plant

Figure 55: Day 2: steam network control, auxiliary boilers and condenser control actions, consumption of BFG and NG in the auxiliary boilers

Steam Network controller

In this section are reported the test results of EHMPC related to the steam network. In particular, **Figure 56** shows the mission description, the BFG and BOFG productions are depicted in the top diagram, while the noncontrollable total steam production and consumptions are depicted in the bottom diagram.

Figure 57, 58 and 59 show, in the top diagrams, the accumulator pressure in the case of an optimized control action (red line) and the real one (yellow line). The central diagrams show the field data related to the noncontrolled steam production and consumption and the actual condenser control strategy. The bottom diagrams show a comparison between the optimized control strategy and the real one, in terms of steam mass flow production in the auxiliary boilers and condensed steam in the condenser.

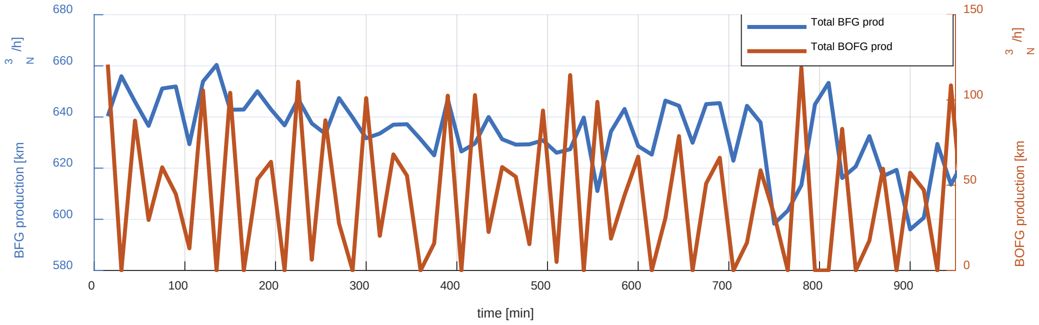


Figure 56: Mission definition: BFG and BOFG productions (top diagram); non-controlled steam production and consumption (bottom diagram)

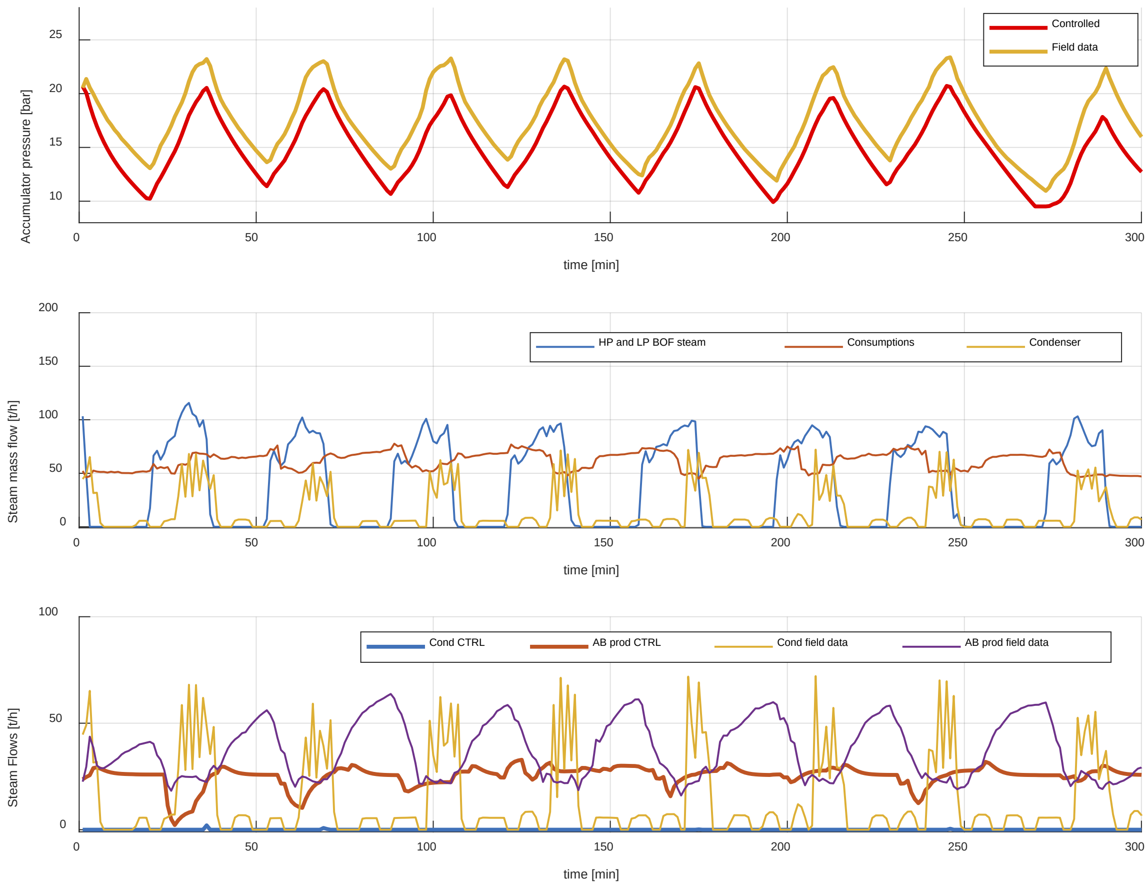


Figure 57: Steam Network Control, example 1: accumulator pressure (top diagram); field data (central diagram); comparison between optimized control actions and field data (bottom diagram)

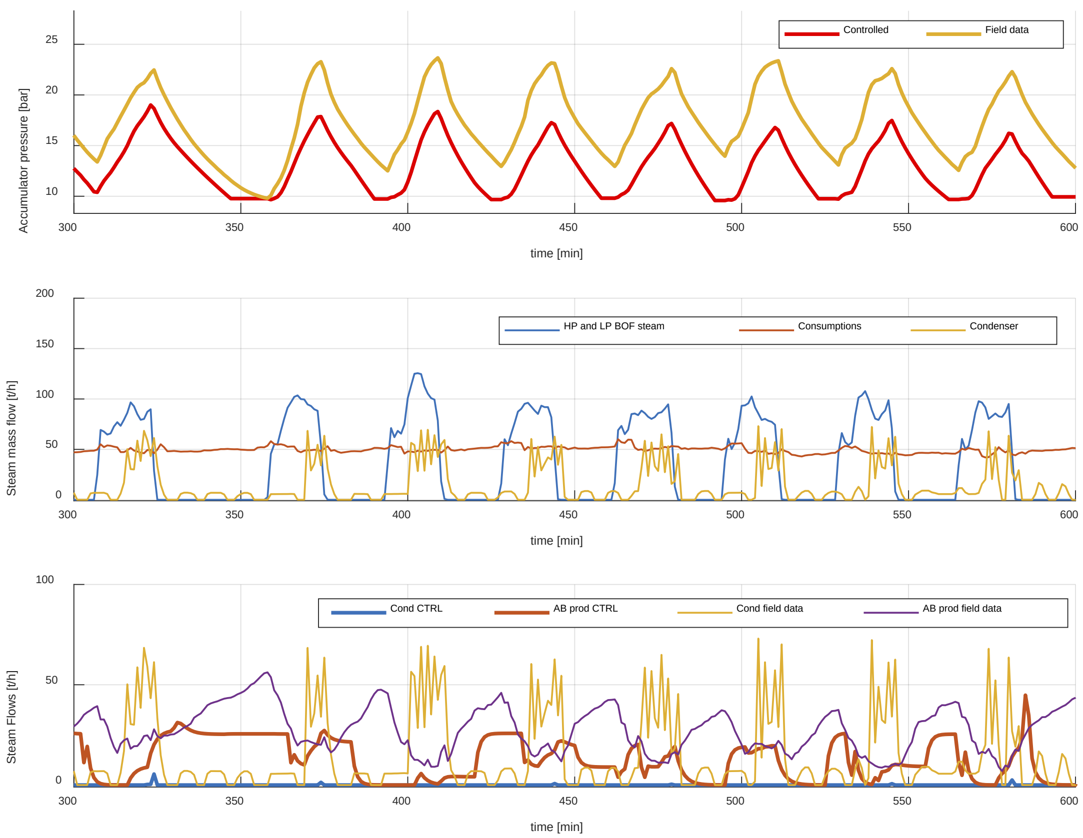


Figure 58: Steam Network Control, example 2: accumulator pressure (top diagram); field data (central diagram); comparison between optimized control actions and field data (bottom diagram)

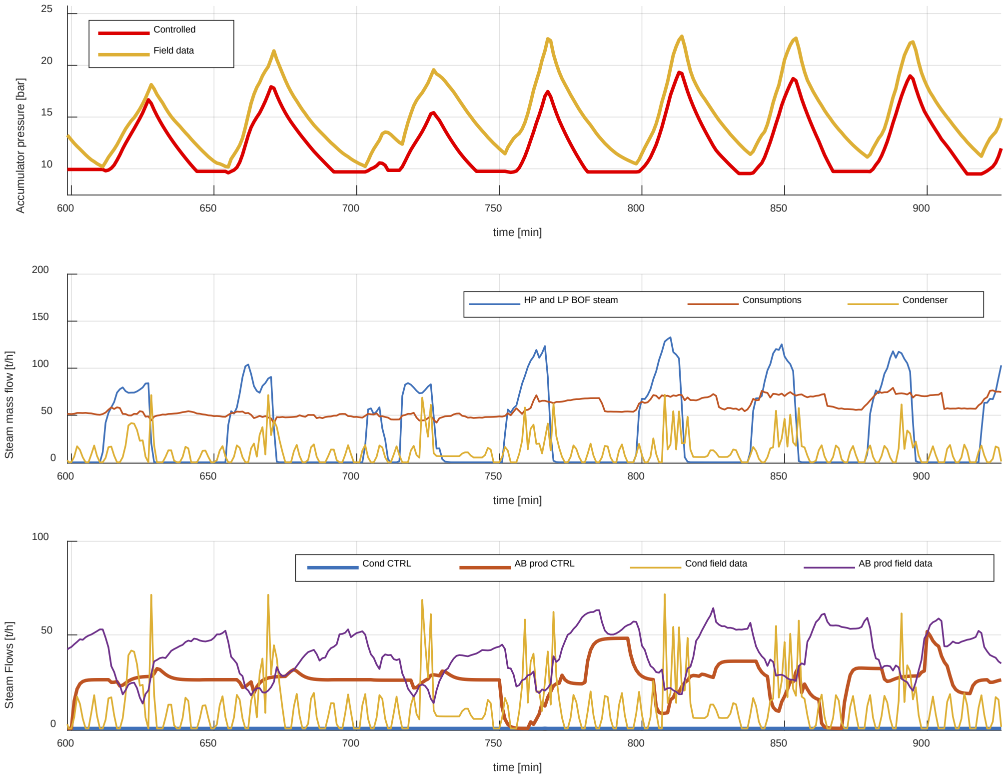


Figure 59. Steam Network Control, example 3: accumulator pressure (top diagram); field data (central diagram); comparison between optimized control actions and field data (bottom diagram)

Figure 60, 61 and 62 show, in the top diagram, a comparison between the optimized control strategy and the real one, in terms of NG consumption in the boilers. The central diagram show a comparison in terms of BFG consumption in the auxiliary boilers. The bottom diagram shows a comparison in terms of total BFG consumption and the reference tracking ability of the controller.

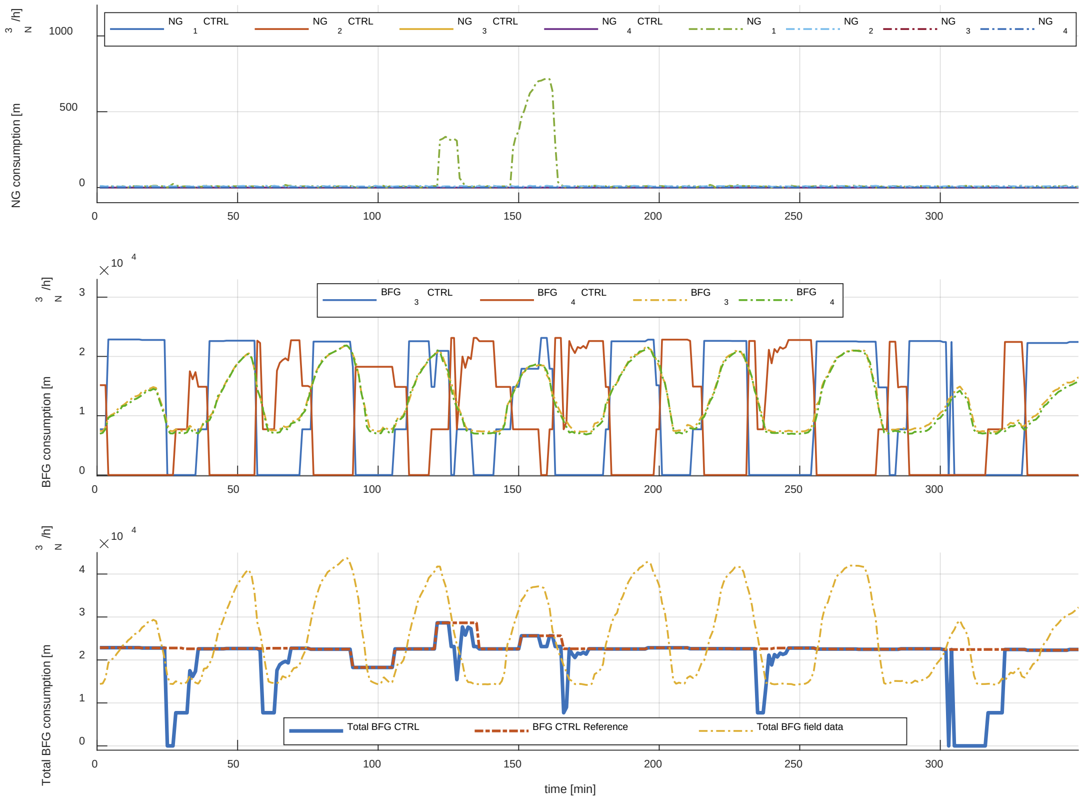


Figure 60: Steam Network Control, example 1: controlled NG consumption (top diagram); Controlled BFG consumption (central diagram); BFG consumption reference and total BFG controlled consumption (bottom diagram)

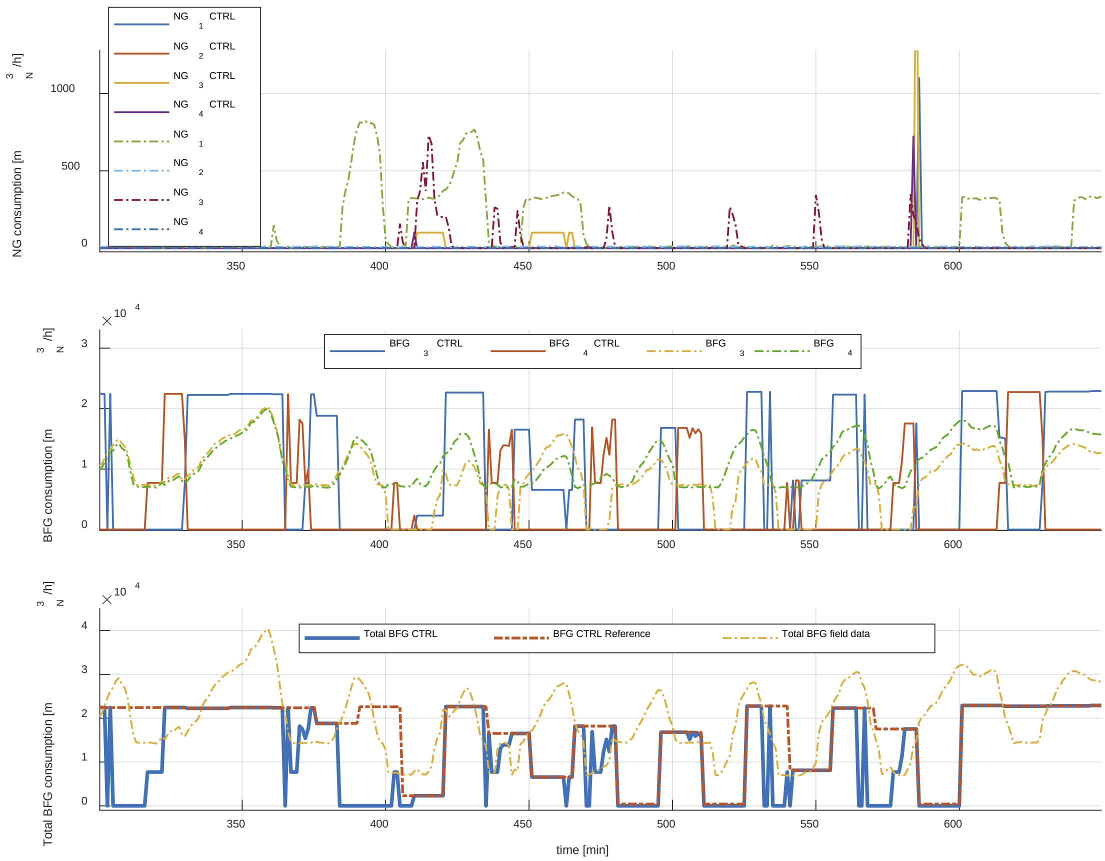


Figure 61: Steam Network Control, example 2: controlled NG consumption (top diagram); Controlled BFG consumption (central diagram); BFG reference and total controlled consumption (bottom diagram)

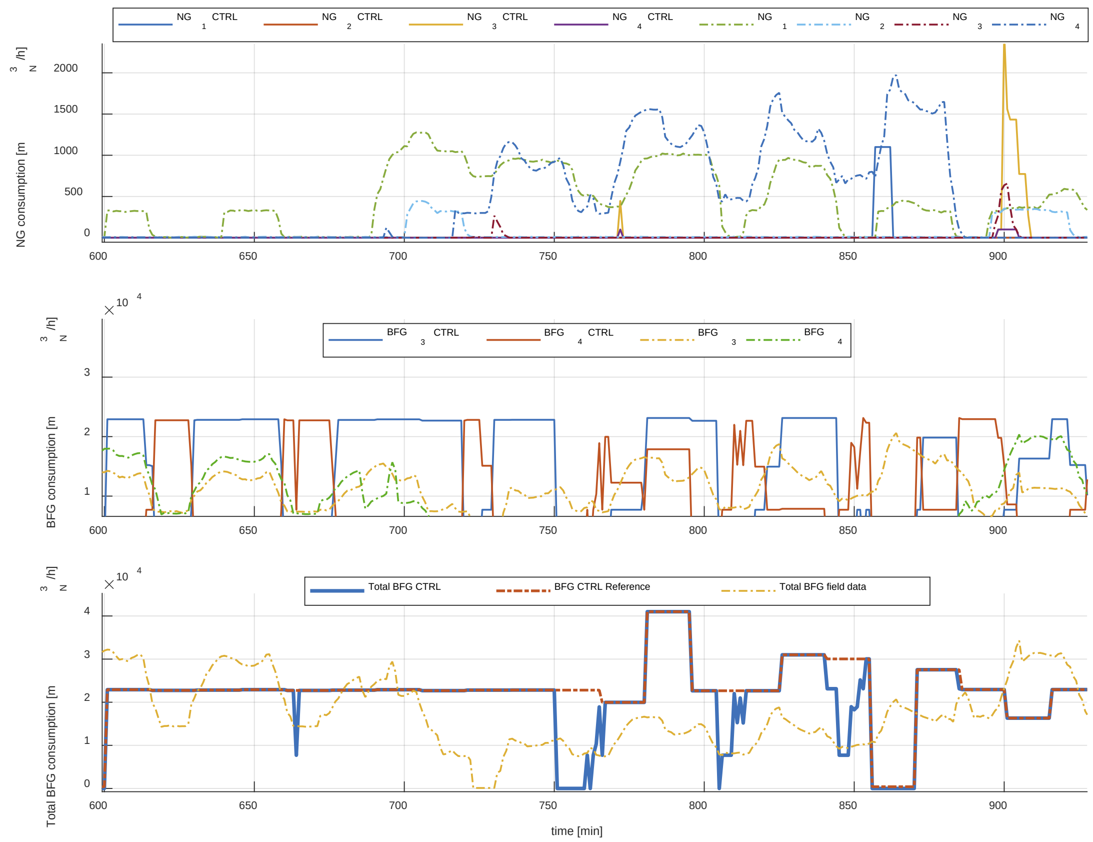


Figure 62: Steam Network Control, example 3: controlled NG consumption (top diagram); Controlled BFG consumption (central diagram); BFG reference and total controlled consumption (bottom diagram)

The analysis of the results shows, also in this case study, a marked improvement in the conditions of the steam network as a function of the new control strategy. In particular, the controller is able to stabilize the operation of the accumulator in a safe range, and allows to reduce the use of the condenser for a total of steam saved equal to 210 tons, which consequently allows to effectively reduce also the production of steam in the auxiliary boilers by 213 tons. In addition, the tracking capabilities of the controller with respect to reference received from the high-level controller allow on the one hand to significantly decrease the use of BFG in the network by 31.7 $[km_N^3]$, on the other hand to use a little more NG gas equal to 0.68 $[km_N^3]$. The total gas savings in energy terms of 22.65 MWh.

BOFG and BFG network controllers

In the following simulations the effect of the changed economic benefit of the transfer of BOF gas into the BF gas network have been investigated.

Figures 63-66 show simulations over 2.5 hours (150 minutes) in which the economic benefit of transferring BOF gas to the BF gas network increases gradually. For these simulations, the maximum volume flow that can be transferred between the BOF and BF networks is set equal to the maximum volume flow in the transport pipe.

In the first graph of **Figures 63-66** the filling level of the gasometer is shown. The second graph shows the course of the recovered BOF gas of the LD converter. The third graph shows which zones of the two reheating furnaces are fired with BOF gas (highlighted in yellow). Next, the fourth graph shows which zones of the reheating furnaces (highlighted in yellow) are supplied with natural gas. Finally, the fifth graph shows the time course of the BOF gas fed into the BFG network.

Figure 63 shows the case where only a very low profit is achievable in relation to the cost of natural gas consumption. Here one can clearly see that the BOF gas is mainly used in the reheating furnaces and only occasionally BOF gas is transferred into the BF network. In this case the controller can keep the BOF gas tank level in the middle range.

In **Figure 64**, the gain that can be achieved by transfer from BOF was increased. As can be seen, whenever BOF gas of the LD is recovered, a portion of the BOF is transferred to the BF network. For this purpose, some zones of the reheating furnace are operated with natural gas for a certain period of time. In the process, an attempt is made to operate the individual zones with one type of gas for as long as possible. Furthermore, the LCV value is temporarily increased.

If the profit for the transfer of BOF values is further increased, more and more zones are operated with natural gas, as can be seen in **Figure 65**. in addition, the LCV value is almost always kept at its maximum value.

In **Figure 66** the profile is further increased, and one sees that the time span in which BOF gas is transported into the BF network is increased. For this purpose, almost all zones of the reheating furnace are fired with natural gas for some time. Due to the bilinear behavior of the mixing station and the reheating furnaces, the controllability of the processes is lost by the LCV values, so that strong oscillations occur in the LCV values. One way to counter this would be to add an additional constraint that would keep the LCV value constant when all zones of the reheating furnaces are natural gas powered. Furthermore, the BOF gas level drops to a very low level. It should be considered if the soft constraint of the BOF should be increased for the filling level.

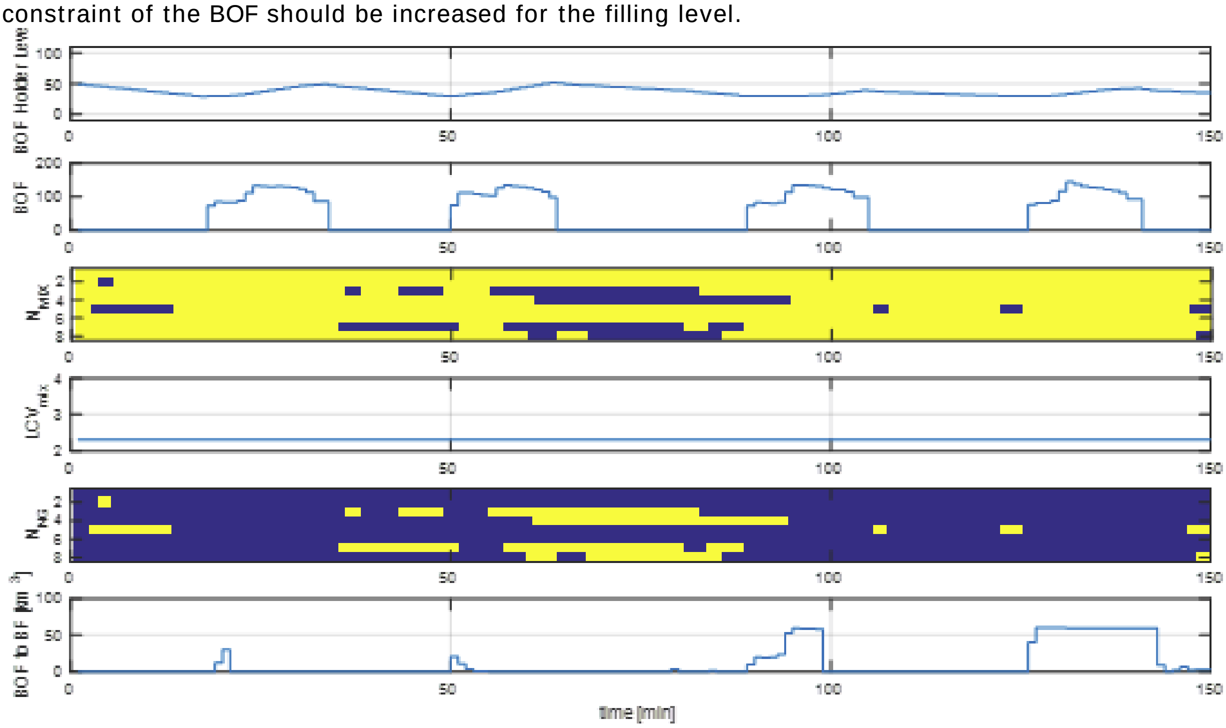


Figure 63: Simulation of the BOF network's economic MPC's

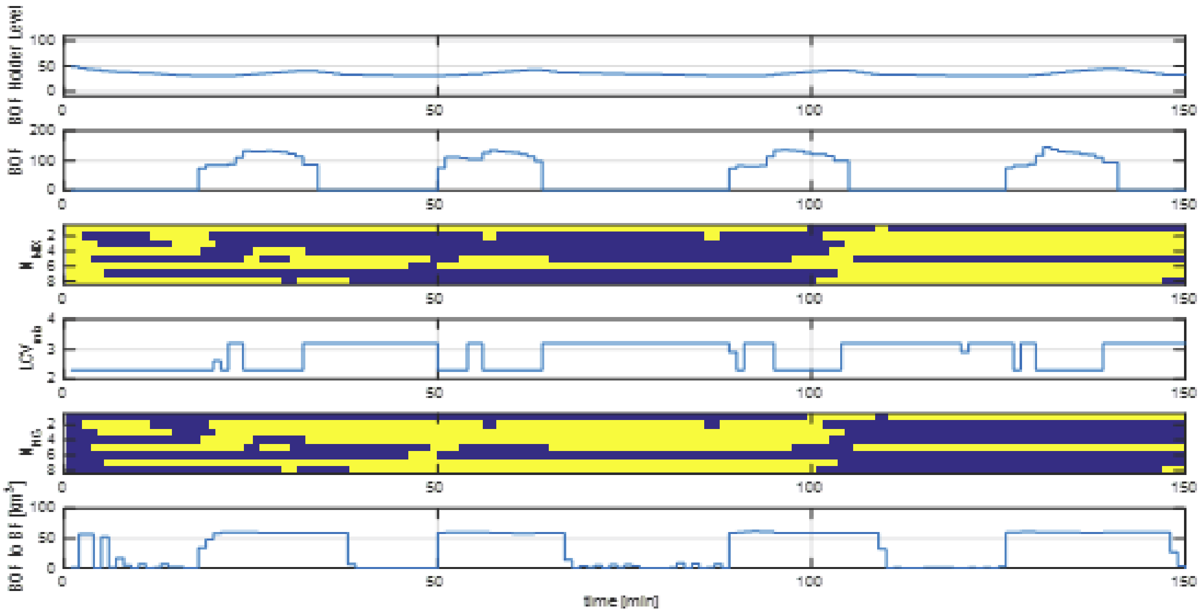


Figure 64: Simulation of the BOF network's economic MPCs

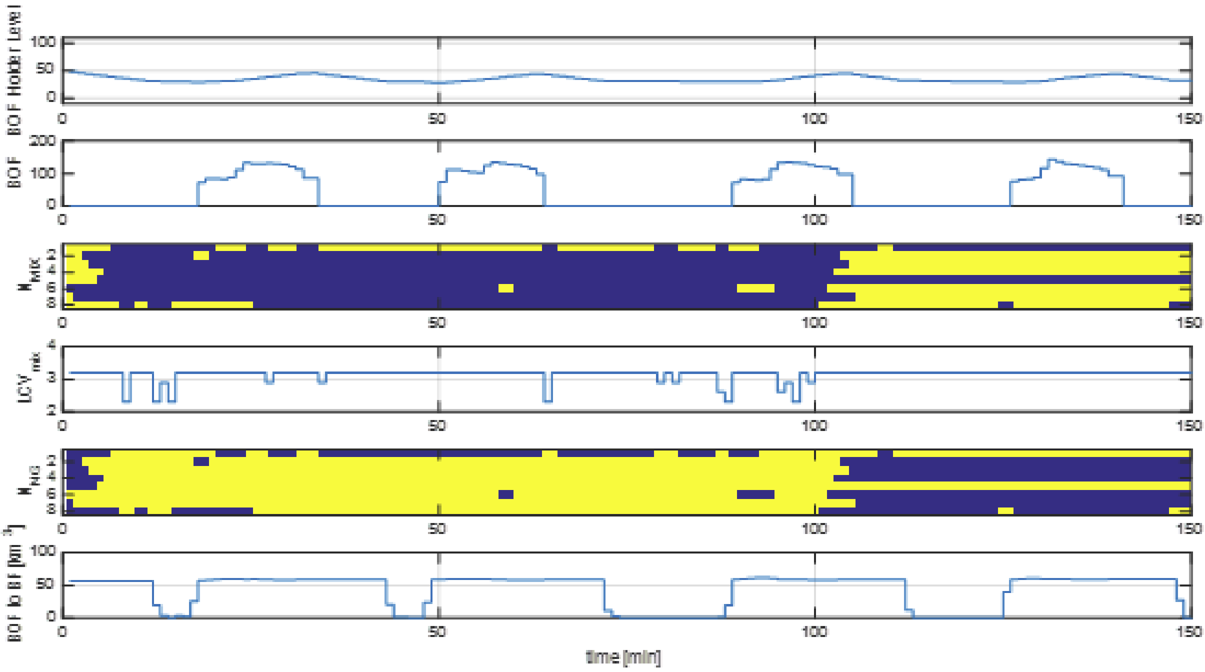


Figure 65: Simulation of the BOF network economical MPCs

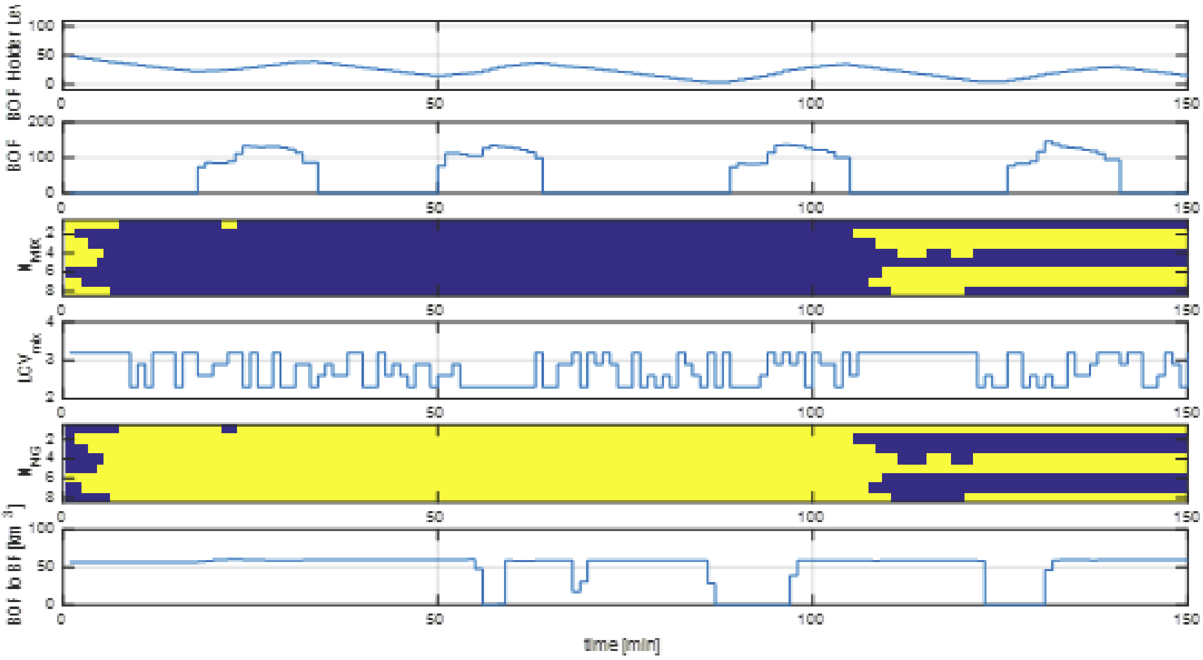


Figure 66: Simulation of the BOF network economic MPCs

Figure 67 shows a long-term simulation over 20 hours (1200 minutes) of the BOF network. It is assumed that no BOF gas is transported into the BFG network. The first curve shows the filling level of the gas storage tank. In the second graphic the course of the recovered BOF gas of the LD converter is displayed. The third graphic shows which zones of the two reheating furnaces are fired with BOF gas and the fifth graphic shows which zone is fired with natural gas. Finally, the fourth figure shows the course of the LCV values over time.

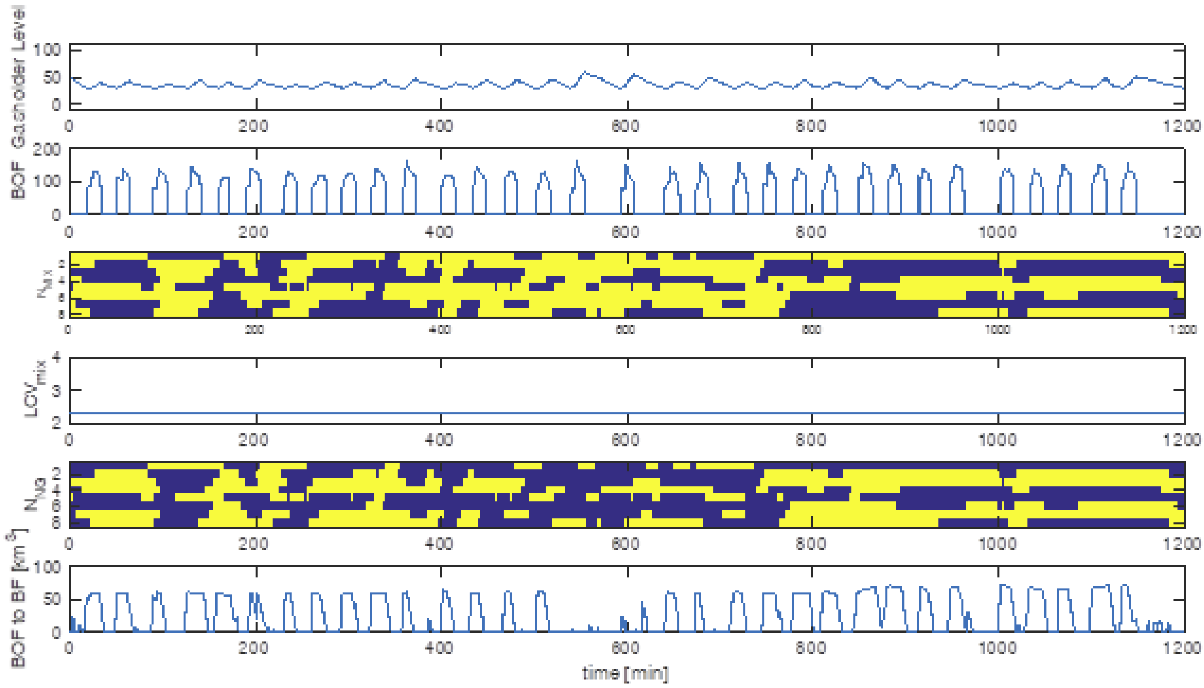


Figure 67: Long-term simulation of the BOF network economical MPCs

As can be seen from the simulations, the filling level of the gasholder is kept approximately at a medium level. Depending on the economic benefit, the EMPC decides whether to use more BOF gas in the reheating furnace or to transfer BOF gas to the BOF gas network. Accordingly, some zones are switched from reheating furnaces to natural gas if the pauses between the recovered BOF gas flows become too long. Mostly during the period when BOF is recovered, BOF gas is transferred to the BF network. The LCV value is kept at a low level. In the simulation, a forecast horizon of 2 hours was defined for the prediction model. In order to reduce the necessary computing time, a blocking strategy was used. Here, individual manipulated variables are kept constant over a certain period of time. As the simulations show, this seems to be sufficient.

Figure 68 shows a long-term simulation of the BOF and electrical network controllers over 20 hours. The prediction horizon of the prediction model is 2 hours. Since the Model BFG network has a sampling time of 1 minute and the electrical network has a sampling time of 15 minutes, this is a multirate system. The controller is updated every minute, which means that the optimization must be completed within one minute. In order to meet this requirement, a block strategy has been used as with EMPC of the BOF network. The first graph shows the filling level of the BFG holder This is kept in the middle range as far as possible. The second graph shows the course of sold and bought electrical energy. As can be seen in the graph, in the first part of the graph, electricity is bought and in the second part, energy can be sold. The third graph shows the course of energy produced by the power plant and turbine and the amount of energy consumed by the company. Finally, the course of the mixed gas transferred to the power plant is shown

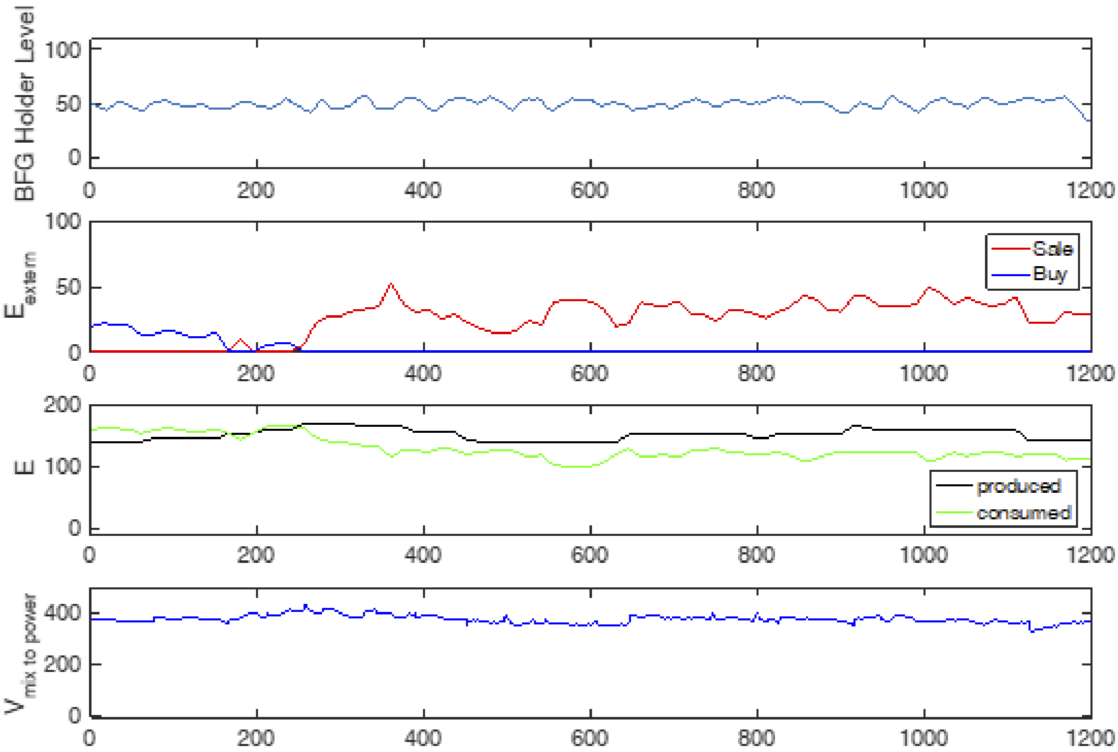


Figure 68*:* Long-term simulation of the BF and electrical network's economical MPC

4.6.2 Task 6.2 Industrial tests of the decision support tool on the different plants.

The tests on the off-line optimization tool have been performed by considering the neworks of all the three involved industrial steelworks to the aim of verifying its main functionalities.

The simulation of the ABG network is displayed in **Figure A.10** in **Appendix A** and has been already performed as a benchmark in the tool development stages. The optimization algorithm proved its capability to find a realistic solution in a reasonable time by respecting all the constraints.

The overall network of ILVA/AMI has been simulated, although with some simplifications due to its huge complexity. In order to simplify the network, some multi-modular units have been considered as a single block (i.e. vertex of the digraph). For instance, the coke oven batteries are contracted into a single vertex (COP) and the same holds for the two power plants (PP). The NG network is considered as a single producer vertex. Moreover, the piping lines are significantly simplified. **Figure 69** shows the network digraph as drawn in the interface:

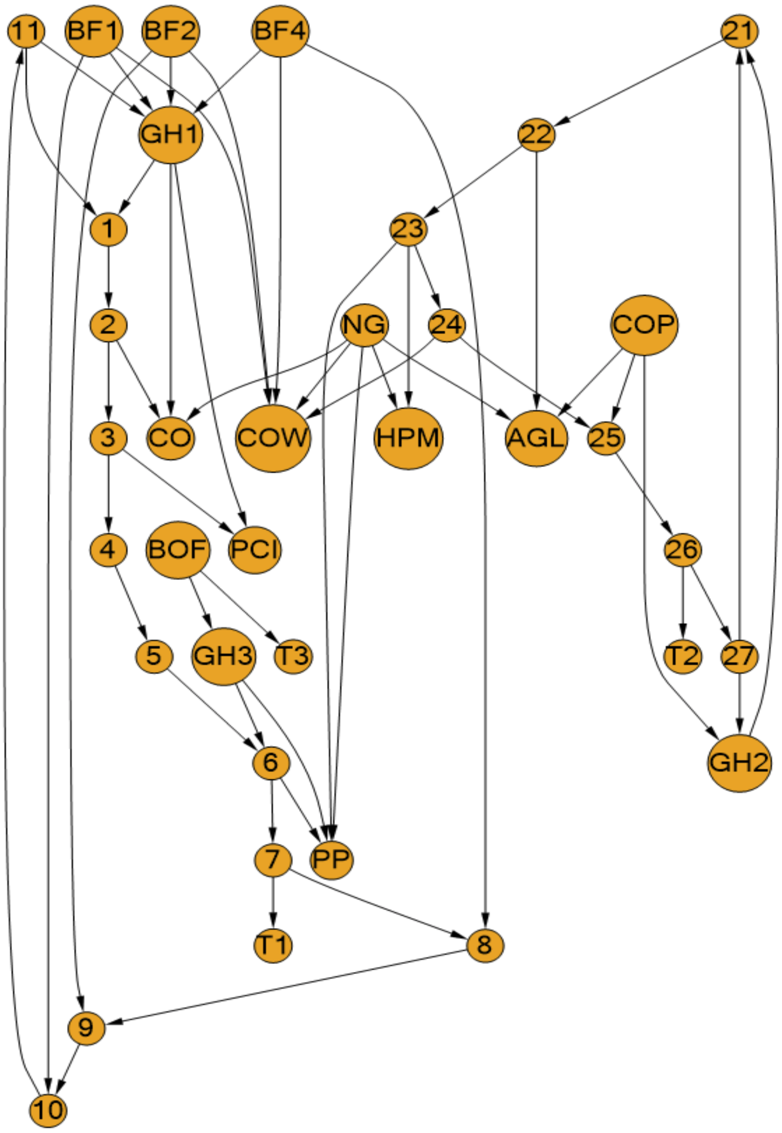


Figure 69: Simplified representation of the ILVA/AMI gas network

The network contains five gas producers: 3 BFs, BF1, BF2, BF4, 4 Coke Ovens assumed as a single unit (COP) and a blast oxygen furnace BOF. The production flow rates are summarized in **Table 4.**

Gas Producer	Gas Type	Flow Rate [Nm^3/s]
BF1	BFG	55,6
BF2	BFG	55,6
BF4	BFG	66,7
COP	COG	18,9
BOF	BOFG	55,6

Table 4: Assumptions for gas production in the simulation of the AMI/ILVA network

The network contains 6 consumers: two power plants considered as a single unit (PP), 4 coke ovens considered as a single unit (CO), the pulverized coal injection (PCI), the cowpers unit (COW), the Agglomeration plant (AGL) and the hot plate mills unit (HPM). Their energetic consumption is summarized in **Table 5**.
The gasholders related to each gas type are assumed as single units corresponding to the total available storage volume that can both supply and receive gas. The volume ranges for each gasholders are reported in **Table 6**.

Gas Consumer	Energy Demand [MJ/s]

PP	1042,56
CO	274,8
PCI	3,3
COW	159,7
AGL	19
HPM	645

Table 5: Assumptions for gas consumption in the simulation of the ILVA/AMI network

Gasholders	Gas Type	Volume range [Nm^3]
GH1	BFG	10000-58000
GH2	COG	24000-147000
GH3	BOF	36000-130000

Table 6: Assumptions for the gasholders involved in the ILVA/AMI network

The objective function for the optimization accounts for the gain of gas recycling by selling the electricity produced by power plants (15 €/MWh), the cost of buying NG (41 €/MWh) for the consumers supply and the cost of flaring (36 k€/MWh), which is assumed to be the highest one. All these cost values are fictitious and do not correspond to actual data from the Italian scenario, they have been adopted only for the simulation purposes. In effects, flaring is not allowed and, therefore, the cost of flaring is assumed to be three orders of magnitude higher than the other ones.
The algorithm manages the flows, optimizing the cost function according to the feasibility constraints. Furthermore, it allows investigating the possibility of pipes building or dismantling based on the respective costs. For instance, the suggestion is provided to investigate the possibility to connect GH1 to the all BFs and GH2 to COP, while the the connection to the torch T2 is analysed for possible dismantling (in order to save maintenance costs), which implies that flaring into torches is avoided. Obviously the torches have also a safety function and cannot be dismantled, but the outcome of the simulation represents the fact that no flaring of useful gases is performed. This investigation has been performed using fictitious costs for building, demolition and maintenance of the selected piping.
Finally, a slightly simplified version of the Tata Steel network has been constructed and simulated to test the functionality of the off-line simulation tool. In total, there are 7 producers: 2 BFs, 3 BOFs and 2 coke plants. There are 3 gasholders, one of them storing a mix of BFG and BOFG, another storing pure BOFG and the last one storing COG. Each gas holder is connected to a torch. There are 8 consumers: 2 BF hot stoves, a sinter plant, a pellet plant, coke plant batteries, 2 boilers and a HSM. Moreover, 3 power plants are present. Additionally, there are various mixing points between the producers and the consumers, a NG supplier and a nitrogen supplier.Representative production and consumption rates as well as assumed gas holder capacities are summarized in **Table 7**.

Producers	**Production rate [Nm^3/s]**
Blast furnaces – BFG (total)	100
Basic oxygen furnace – BOFG (total)	75
Coke plant – COG (total)	33
Consumers	**Consumption rate [MJ/s]**
Hot stoves (total)	150
Sinter plant	50
Pellet plant	50
Coke plant batteries	30
Boilers (total)	60
Hot strip mill	250
Gas holders	**Level constraints [Nm^3]**
Enriched BFG	10000 – 140000
BOFG	10000 – 60000
COG	5000 – 50000

Table 7: Representative production and consumption rates and assumed gasholder capacities for the gas network of Tata Steel Ijmuiden site

The simplified representation of the gas network of Tata Steel Ijmuiden site is shown in **Figure 70**. Costs are associated to flaring produced gases and NG purchasing. Unit-wise, the cost of flaring COG is highest and the cost of flaring enriched BFG is lowest. Purchasing NG is more expensive than flaring any other gas. Moreover, revenue is associated to the production from power plants. Consequently, the algorithm found a realistic solution to the optimization problem by respecting the constraints.

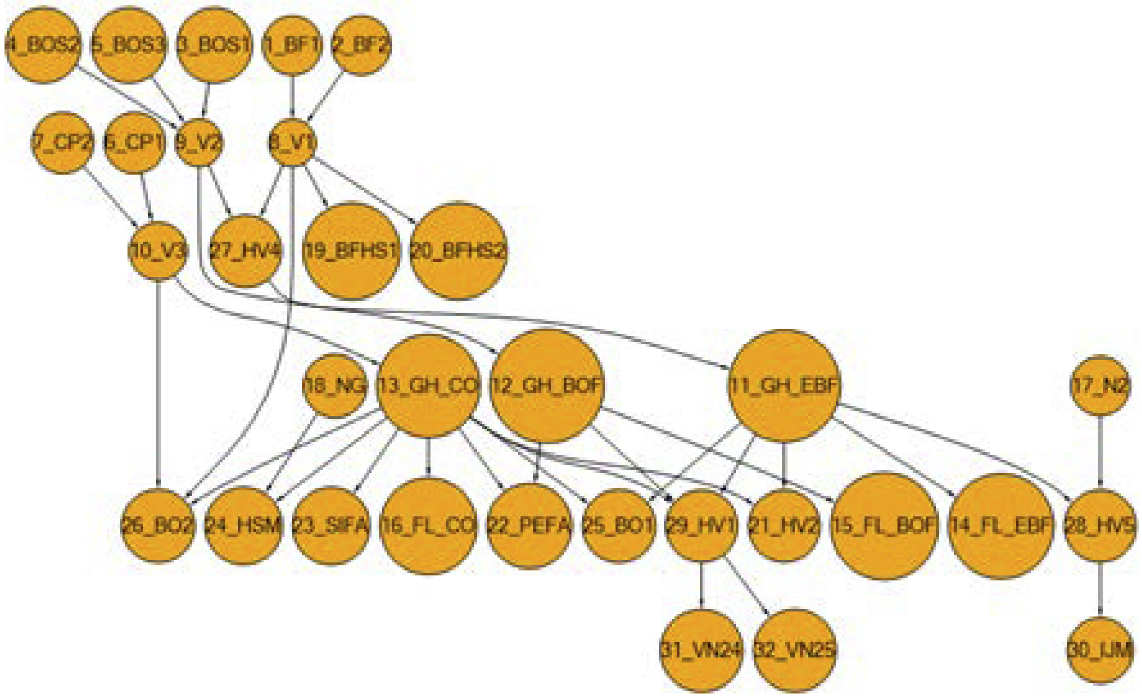


Figure 70: Simplified representation of the gas network of Tata Steel Ijmuiden site

The functionalities of the on-line monitoring and decision support tool have been tested only by ABG, while ILVA, the subcontractor of SSSA, could not develop the onsite test due to its particular internal situation. The amount of the subcontract have been further reduced as a consequence of this fact.
Some exemplar screenshots of the monitored variables are shown in **Figure 71**.
Figure 72 proposes a comparison among real data and values, which are forecasted by the models. In particular the the figure on the upper left corner refers to a model implemented via an ESN, which shows acceptable results.
In the screenshot reported in **Figure 72** some of the models (which are not treated beforehand due to their simplicity) have been implemented by means of constant values deriving from an average of the previously measured data. This approach has been selected in the project for those variables, which are considered less relevant with respect to the optimization problem (e.g. due to a minor contribution to consumptions or production of the considered gas or of the steam). This approach is also advisable in the case of missing punctual field data, i.e. an initial rough estimate based on domain knowledge can be included if no data are (initially) available which allows designing or tuning of a parametric model of any nature. This represents an element of flexibility for the developed software, as the user can start using it by collecting the data, which are fundamental for designing and tuning of complex (also AI-based) models related to the most important processes (e.g. BFs, BOFs, HSMs, etc.), while roughly estimating the behaviour of other processes by means of constant values. Through this procedure, some meaningful indications can be obtained at an early stage, while the system can be refined and improved afterward, by increasing the level of complexity of the models (e.g. testing an ESN-based model in place of an ARX-based one when sufficent data are available or changing the internal paramenters of the ESN), as well as by adding new models for the processes, which have been initially neglected and modelled through constant values.

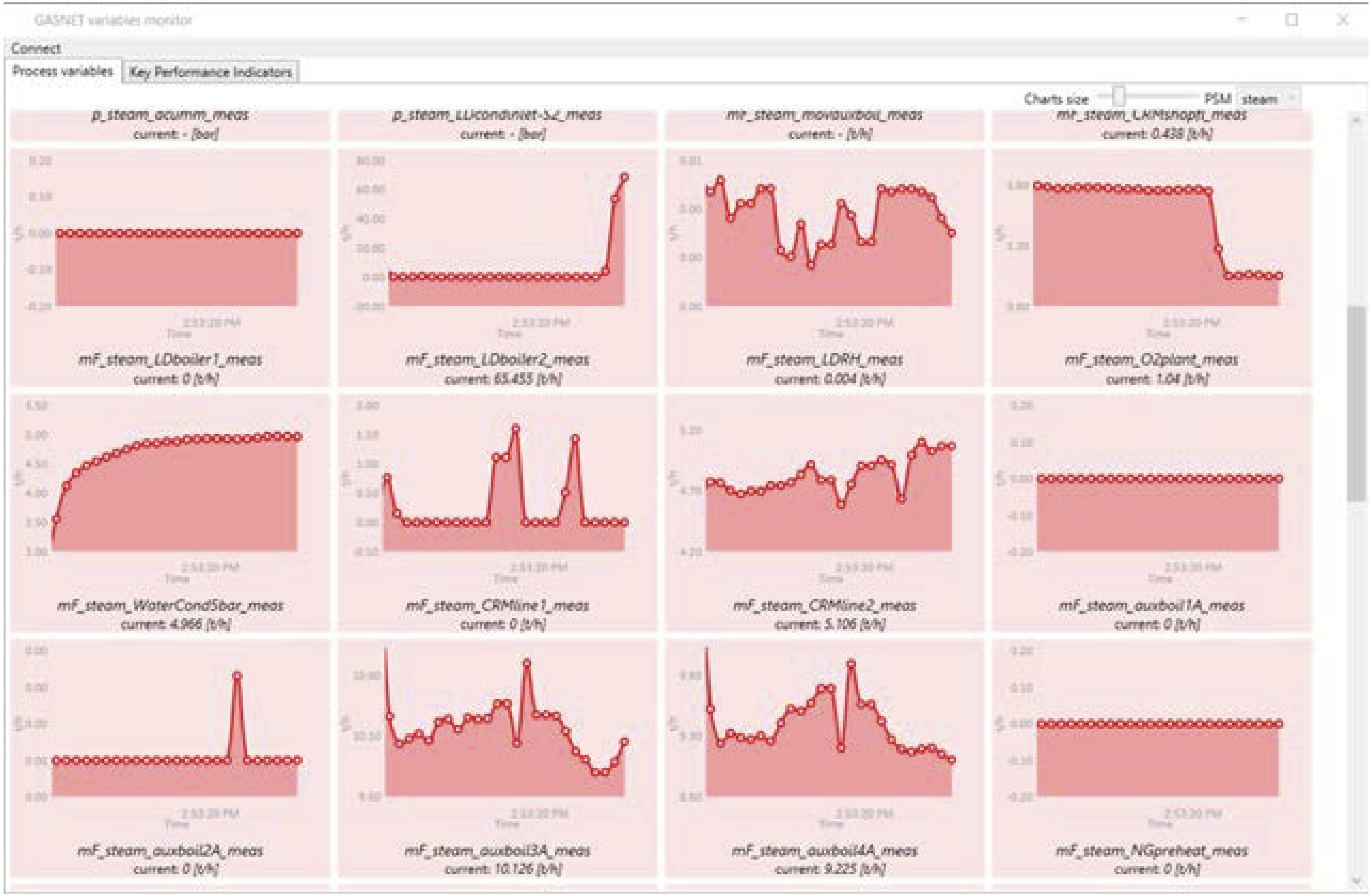


Figure 71: Exemplar charts depicting measured variables related to the steam network

Figure 72: Exemplar comparison of measured and predicted variables referring to BGF management

The visualization of all the variables is possible on different time horizon, by thus allowing analyses focused on different production periods. By pointing on each represented point, the indication of the corresponding exact value and time is shown.
Figure 73 provides an exemplar trend of one of the selected KPIs, which is computed on a monthly basis.

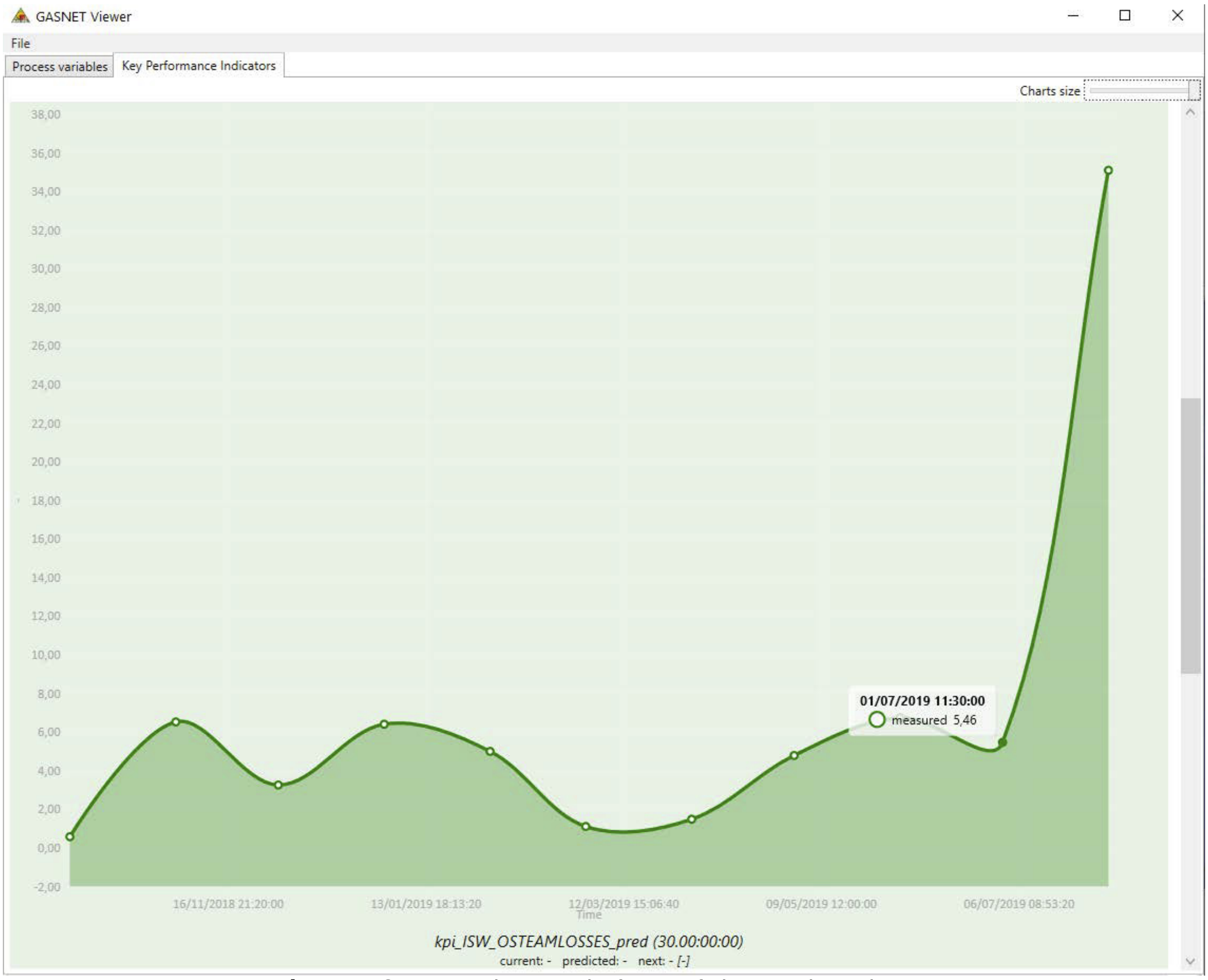


Figure 73: Exemplar trend of one of the monitored KPIs

The effectiveness of the HL optimizers has been tested by exploiting information and data coming from ABG. The test of such functionality has been possible only in an off-line way, through a comparison of the actual outcome of the management of the gas network and what could be achieved if the HL optimization had been exploited.
Here the results are depicted related to two so-called “missions”, namely periods with a duration of several days.
Mission 1 is characterized by a duration of 10 days and a standard trend of the production, with all the gasholders in operation.

Figure 74 shows the field data of mission 1 relating to the production BFG and BOFG, the internal electric energy consumption, the production of steam in the uncontrolled processes of BOF boilers (HP and LP steam systems) and the internal uncontrollable consumption of steam.

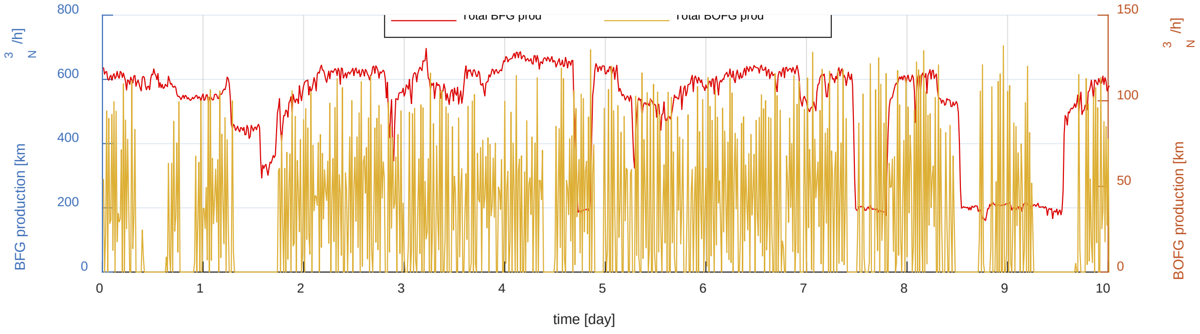
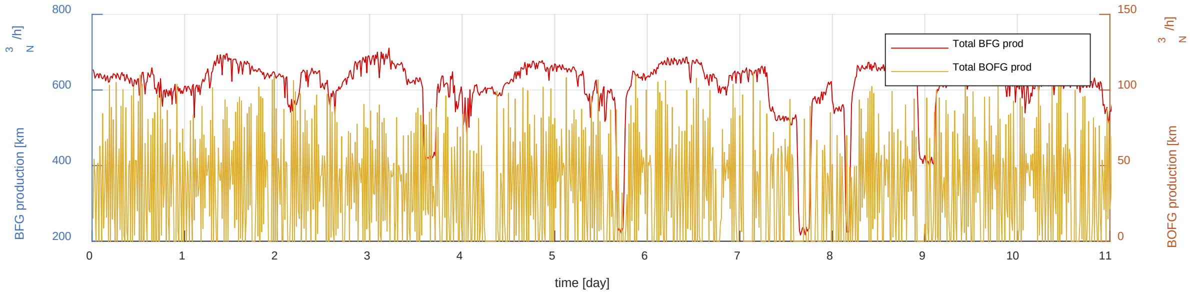


Figure 74: Test mission 1 definition, duration 10 days: POG production (top diagram), Internal Electric power consumption (central diagram), non-controllable steam production and consumption (bottom diagram)

On the other hand, Mission 2 refers to a period of 22 days and is is particular interesting, as it refers to a situation in which the BFG are constantly used with a large waste of energy. Within the mission, a fairly constant period of pig-iron and steel production is observed and the WBFs are not scheduled until day 6, when the ovens begin to be pre-heated and after a day and a half start-up, the slabs processing are started. Therefore, in the first 6 days there is an excess of BOFG, which must be disposed of through its use in the power plant or the possible use of torches.
Figure 75 shows the same data for the first 11 days of mission 2 (for improving the readability of the figure only half of the period is shown)



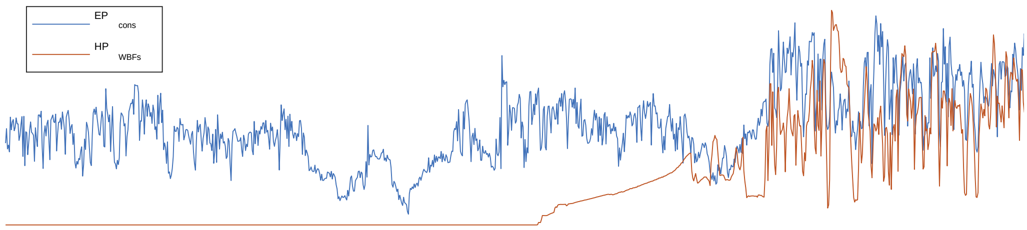


Figure 75: Test mission 2 (first 11 days over a total duration of 22 days). POG production (top diagram), Internal Electric power consumption (central diagram), non-controllable steam production and consumption (bottom diagram)

The specific costs related to the purchase of NG c_{NG} and electricity C_{EP} and the selling of electricy C_{ES} for both missions are reported in **Table 8**.

c_{NG} [€/MWh]	C_{EP} [€/MWh]	C_{ES} [€/MWh]
41	30	15

Table 8: Costs defined in the objective function of the HL controller for the optimal scheduling of power generation

In order to evaluate the performance of the hierarchical control system, some Key Performance Indicators (KPIs) are calculated. In particular, the first indicator refers to the economic savings that can be obtained through the application of the references calculated by the high-level control system in comparison to the real case, in both absolute value $KPI_{€}$ and percentage $KPI_{€\%}$. The second KPI quantifies the increase of electric energy production that can be achieved through an optimized consumption scheduling of the POG in the internal power plant, in both absolute value KPI_{EPPint} and percentage $KPI_{EPPint\%}$. The third KPI quantifies the decrement of energy waste in the torches with respect to the real case, in both absolute value $KPI_{Torches}$ and percentage $KPI_{torches\%}$. The fourth KPI refers to the decrease in the use of NG in the controllable systems, both in absolute value KPI_{NG} and in percentage $KPI_{NG\%}$. The KPIs are computed through the following equations:

$$KPI_{€} = C_R - C_{CTRL}$$

$$KPI_{€\%} = 100\frac{C_R - C_{CTRL}}{C_R}$$

$$KPI_{EPPint} = E_{PPint_{CTRL}} - E_{PPint_R}$$

$$KPI_{EPPint\%} = 100\frac{E_{PPint_{CTRL}} - E_{PPint_R}}{E_{PPint_R}}$$

$$KPI_{Torches} = E_{Torches_R} - E_{Torches_{CTRL}}$$

$$KPI_{torches\%} = 100\frac{E_{Torches_R} - E_{Torches_{CTRL}}}{E_{Torches_R}}$$

$$KPI_{NG} = E_{NG_R} - E_{NG_{CTRL}}$$

$$KPI_{NG\%} = 100\frac{E_{NG_R} - E_{NG_{CTRL}}}{E_{NG_R}}$$

An important aspect to clarify is that the economic and energy analysis of the management of gas distribution refers only to the portion of the gases that can be controlled in the considered processes. In this analysis NG flows are not taken into consideration in some sections of WBFs, a large heat consumer, which are controlled only through NG and on which therefore it is not possible to obtain any energy optimization through optimal POG management. In this analysis, therefore, as regards the NG, we refer only to the portion of the processes which are actually controlled and not to the overall consumption within the integrated steelworks.

The analysis of the results is completed with a general overview of the main quality indices to evaluate the control action aimed at optimizing the distribution of POG and NG among the main consumers of the integrated steelwork plant. The results achieved by applying the proposed strategy are identified by the string ***CTRL***, while the actual values are indicated as ***Real***.

<u>*Results of Mission 1*</u>

Firstly, the economic balance linked to the purchase and sale of electricity and the purchase of NG is shown in **Figure 76**. In particular, the top diagram shows the total costs on a daily basis, while the bottom diagram compares the overall costs for the whole test mission (overall duration of 10 days); the costs related to the application of the optimization strategy are shown in green, the costs in the absence of an optimized control strategy are shown in red. The proposed strategy allows an average daily saving of 17’510 € and an overall saving of 27.49 % with respect to the current approach. However, as far as the NG is concerned, it is important to underline that the relative costs only concern the consumed amount that can actually be controlled within the plant.

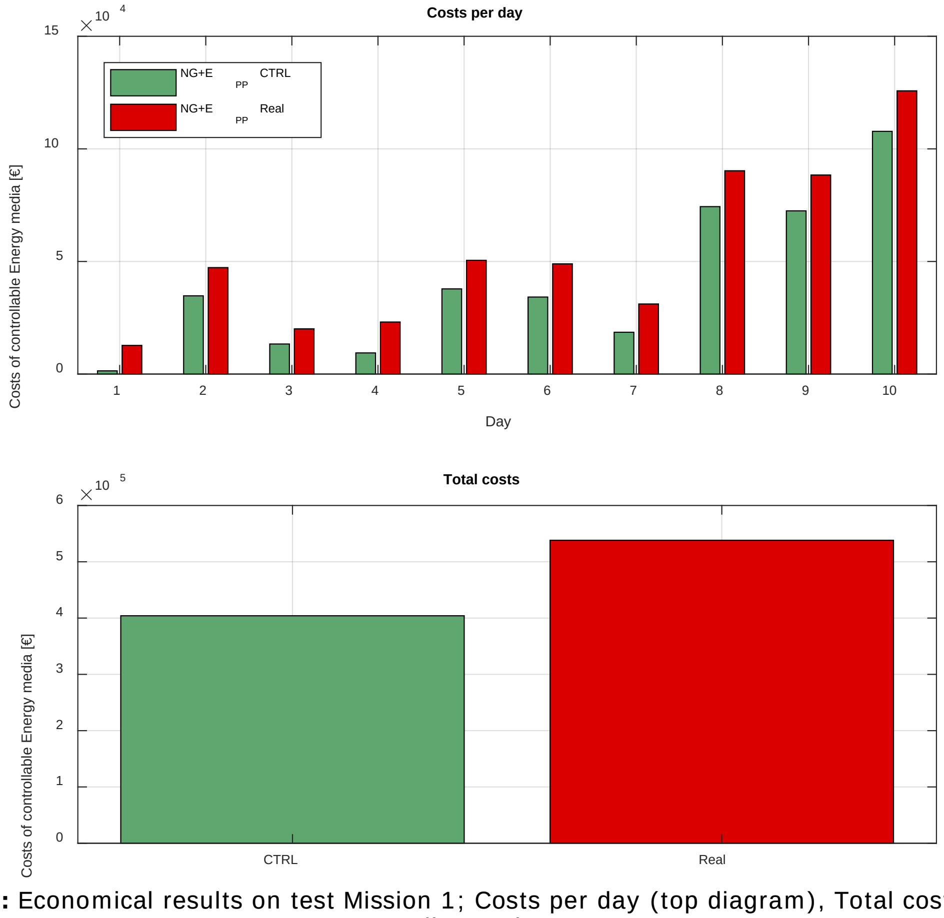


Figure 76: Economical results on test Mission 1; Costs per day (top diagram), Total costs (bottom diagram)

Figure 77 depicts the specific costs of each energy media. In particular, in the top figure the costs are depicted on a daily basis, while in the bottom diagram figure the total costs for the whole test mission are compared.

The proposed strategy allows an average daily saving of NG and Epp of 15’260 € and 2’346 €, respectively, and an overall saving of 41.56% and 6.12% with respect to the current approach. The optimized control approach allows to efficiently distribute POGs, such as to produce more electricity and consume less NG, with significant savings in economic terms.

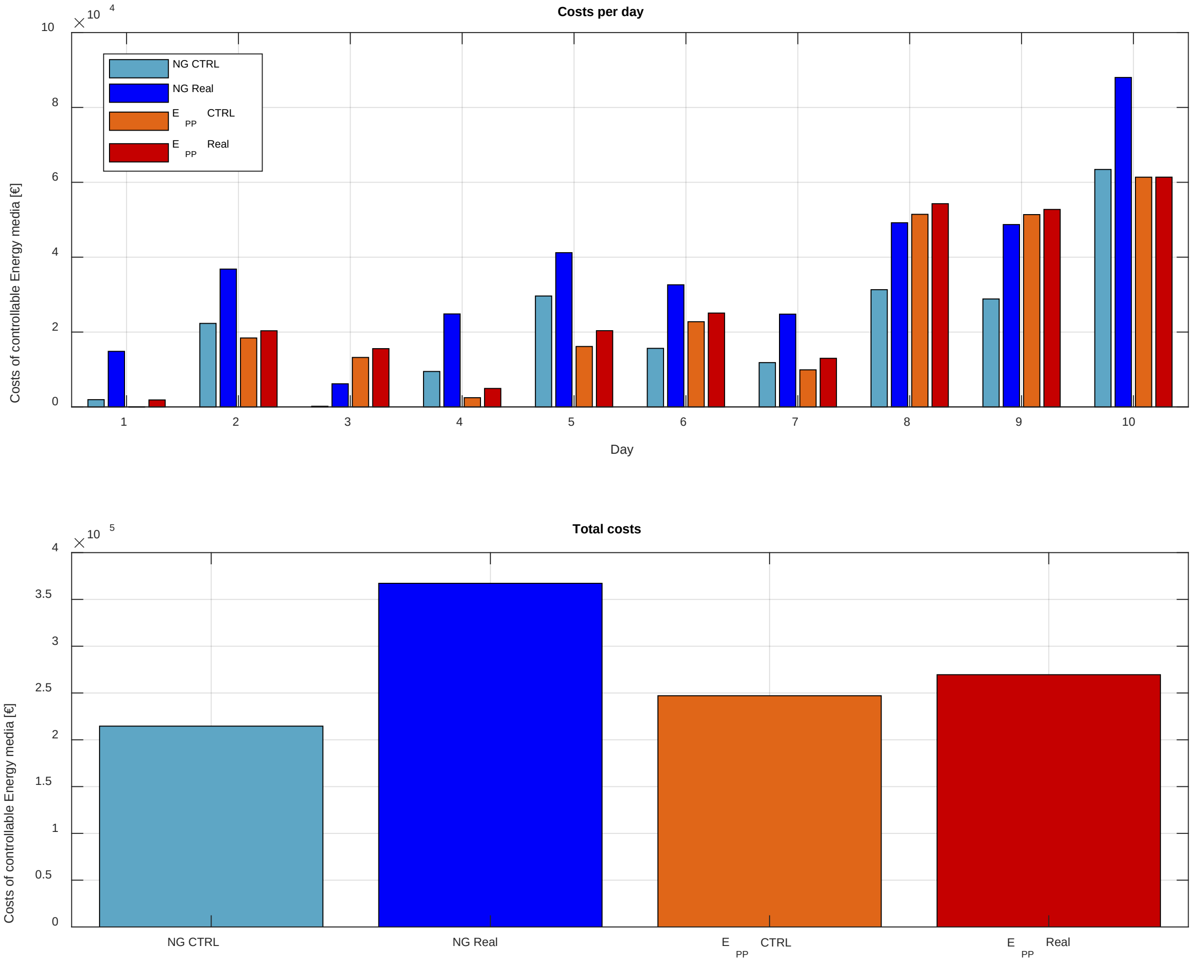


Figure 77: Economical results on the test mission, costs of each energy media: costs per day (top diagram), total costs (bottom diagram)

Figure 78 shows the electric energy production in the internal power plant, the purchased and sold electric energy. In particular, the top diagram depicts the electric energy on a daily basis, while in the bottom diagram refers to the total electric energy production over the whole duration (10 days) of test mission.

The proposed strategy allows an average daily variation of electricity production, electricity purchased and electricity sold of 69 MWh, -79 MWh and -5.87 MWh, and an overall variation of 2.46% -8.06% and -8.85% with respect to the current approach. An optimal distribution of POGs allows to produce internally more energy and consequently to buy less from the external network. Furthermore, in this case the electricity sold to the external grid is lowered. The control action, due to the prices of the NG and the sale of electricity, gives higher priority to the lower consumption of NG compared to the use of POGs for the sale of electricity.

Figure 79 shows the total controlled consumption of NG on a daily basis (top diagram) and the total costs for the whole mission duration, i.e. over all the considered 10 days (bottom diagram).

The proposed strategy allows an average daily saving of NG of 32.9 $[km_N^3]$ and an overall saving of 41.55 % with respect to the current approach. The control action, due to the prices of the NG and electricity, where is possible, gives higher priority to the lower consumption of NG compared to the use of POGs for the electricity.

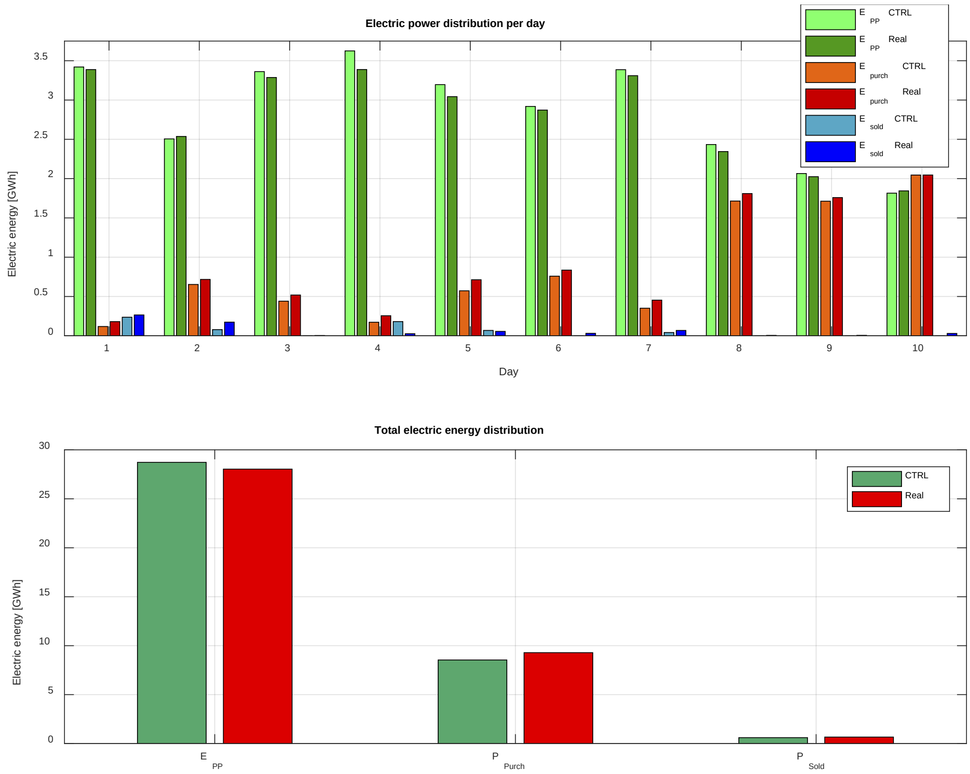


Figure 78: Mission 1, electric energy distribution between generated, purchased and sold: per day (top diagram), total (bottom diagram)

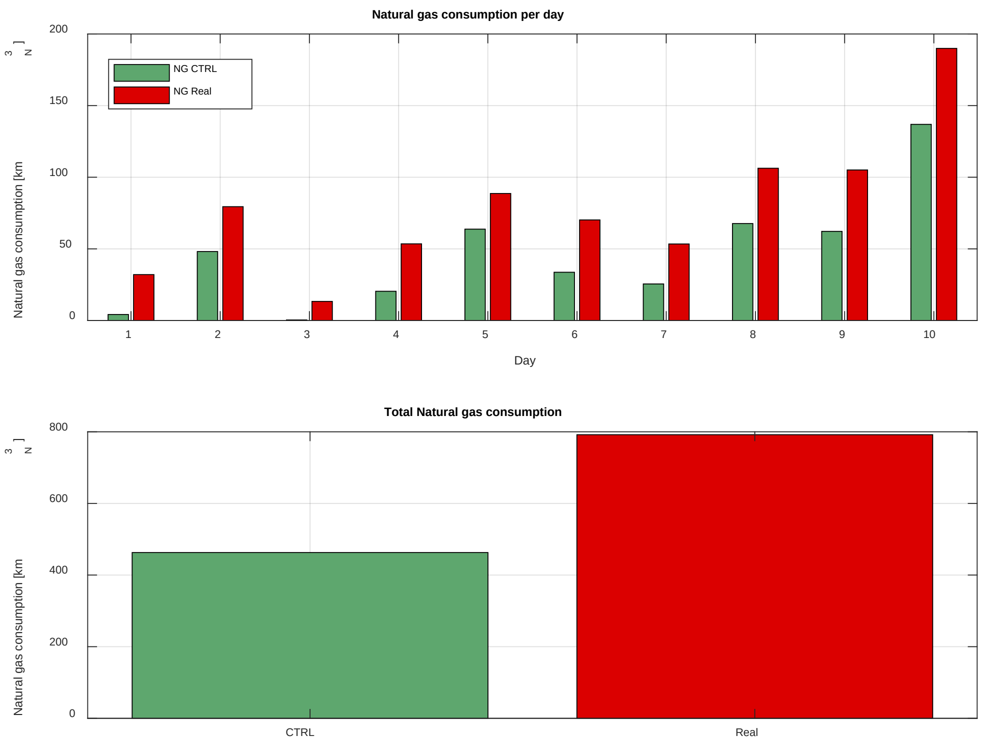


Figure 79: Mission 1, NG consumption in the controlled processes: consumption per day (top diagram), total consumption (bottom diagram)

Figure 80 reports the amount of BFG burned in the torches on a daily basis (top diagram) and the total of ten days (bottom diagram). Noticeably the proposed control strategy allows almost avoiding the usage of torches, apart from day 4, with a decrease of 97.1 % with respect to the current approach. The optimized approach allows to distribute the BFG excess to the power plant, in order to produce more electricity respect to the current approach, with a greater economic advantage and a huge decrease of the environmental impact.

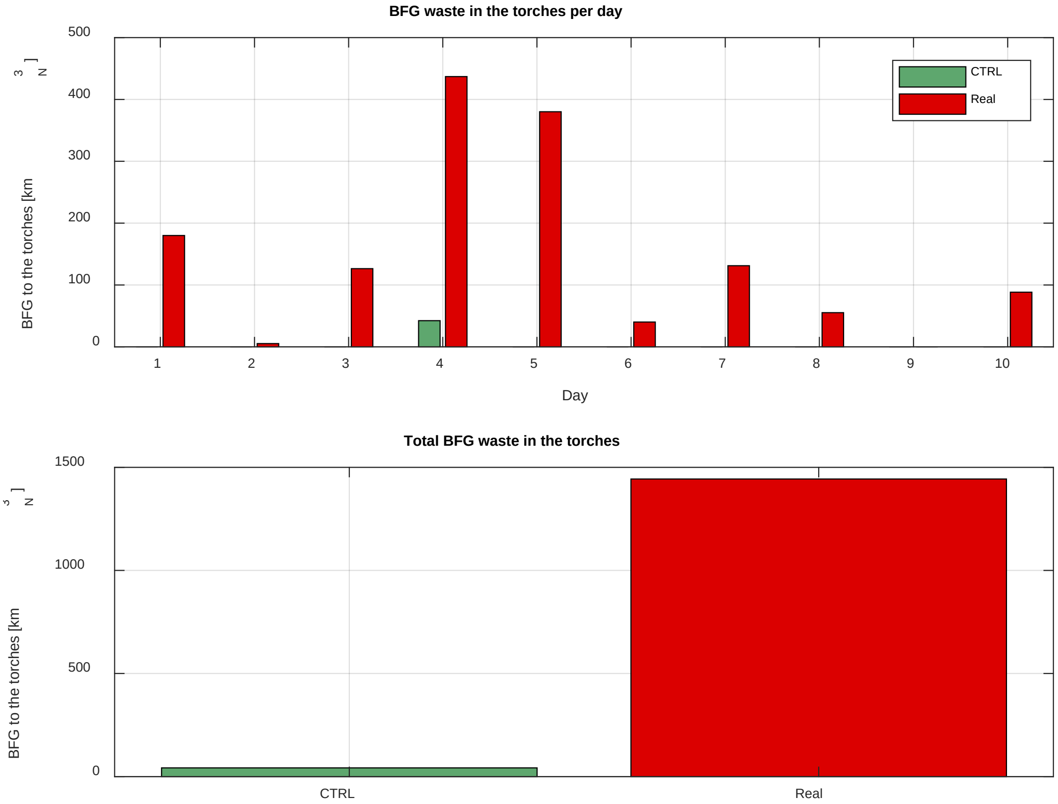
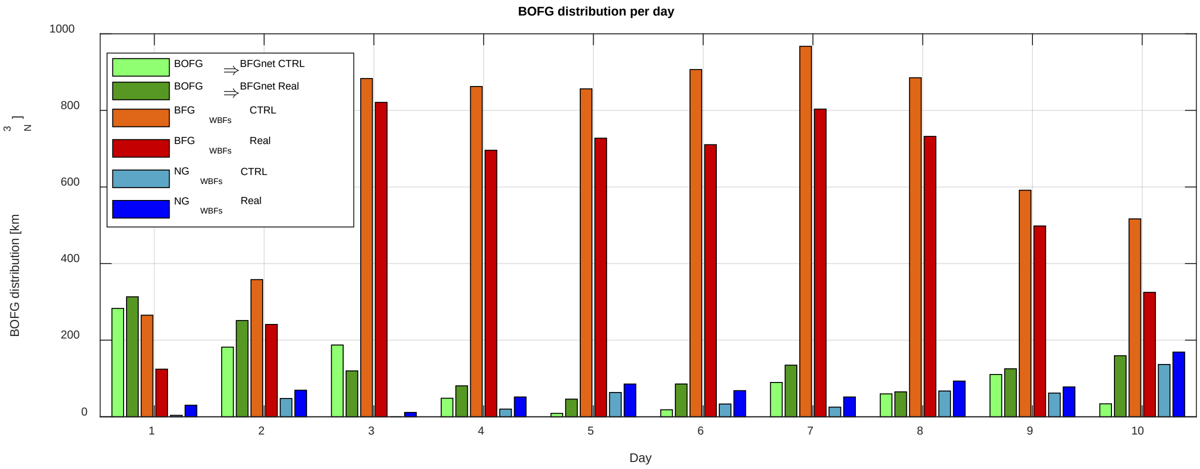


Figure 80: Mission 1, BFG waste in the torches: per day (top diagram), total (bottom diagram)

Figure 81 shows the BOFG distribution among the users for each day (top diagram) and the total distribution for the whole mission duration (bottom diagram).
The proposed strategy optimizes the BOFG used in the WBFs to decrease the NG use. In particular, it allows an average daily saving of NG of 24.9 $[km_N^3]$ and an overall saving of 35.17%% with respect to the current non-optimized approach. The optimized control approach allows to efficiently distribute BOFG to the WBFs, with an increment of 24.9 % with respect to the current approach.
The transfer of BOFG to the BFG network is lower respect to the current non-optimized control, maybe due to a wrong set-point on the mixing station at the input of the WBFs.
The BOFG torch in this mission was never used, for this reason, the respective values are not reported.



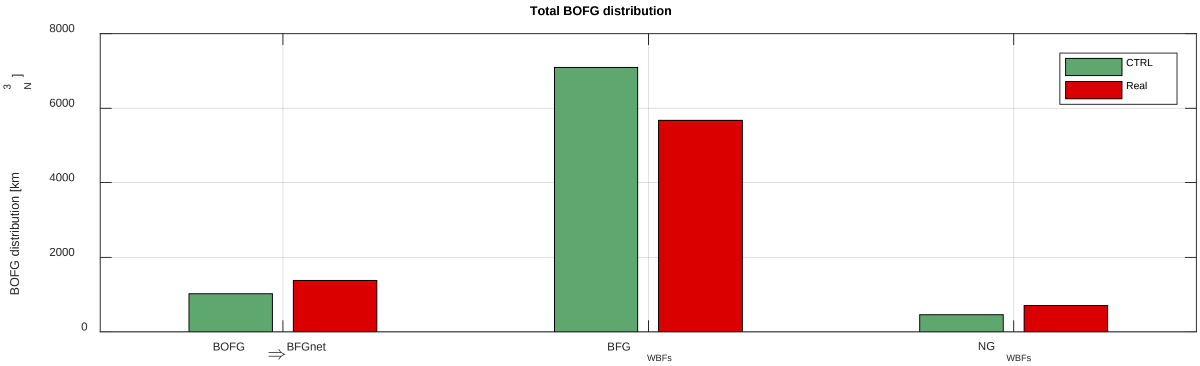


Figure 81: Mission 1 BOFG distribution: per day (top diagram), total (bottom diagram)

Figure 82, 83 and 84 depict the results related to the steam network. In particular, Figure 55 shows the condensed steam for each day (top diagram) and the total condensed steam for the whole mission duration (bottom diagram). Figure 56 show the total gas consumption on the auxiliary boilers for each day (top diagram) and the whole mission duration (bottom diagram). Figure 57 shows the steam network balance in terms of steam mass flows in the case of the proposed approach (left diagram) and the current one (right diagram).

The proposed strategy allows to manage the steam network with a great saving in terms of condensed steam, with an average daily saving of 47.13 tons, and an overall saving of 48.31%. An optimized use of the condenser and a different timing of steam production also allows to decrease the production of steam in the boiler auxiliaries by 35.56 % in total.

The achieved balance in the steam network allows to obtain an overall decrease of BFG in the auxiliary boilers of 0.6 %.

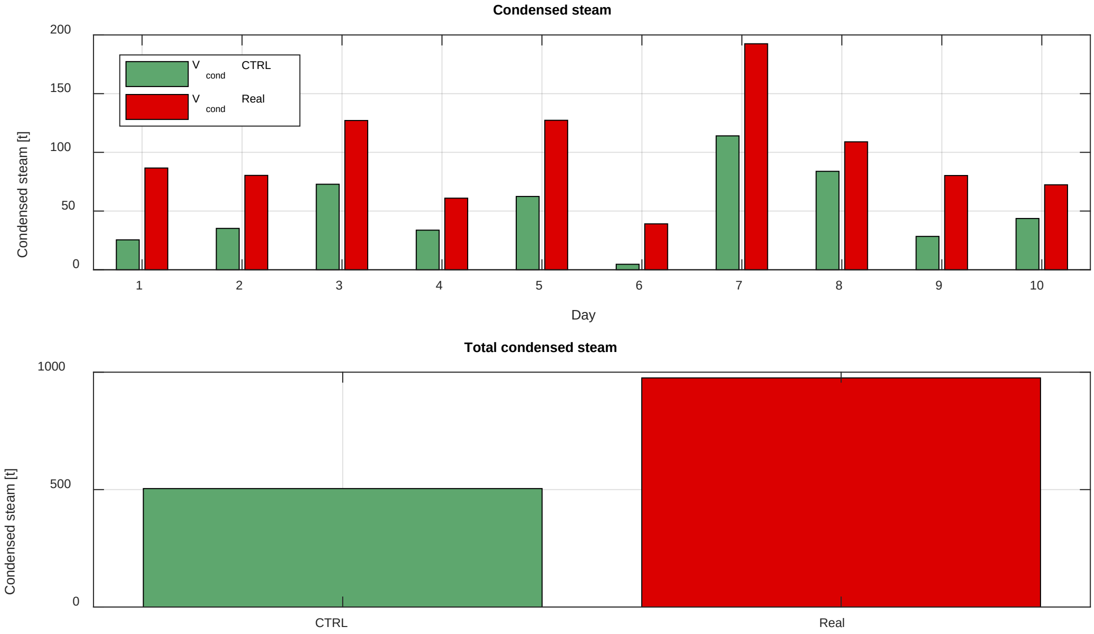


Figure 82: Mission 1, Condensed steam: controlled case (top diagram), real case (bottom diagram)

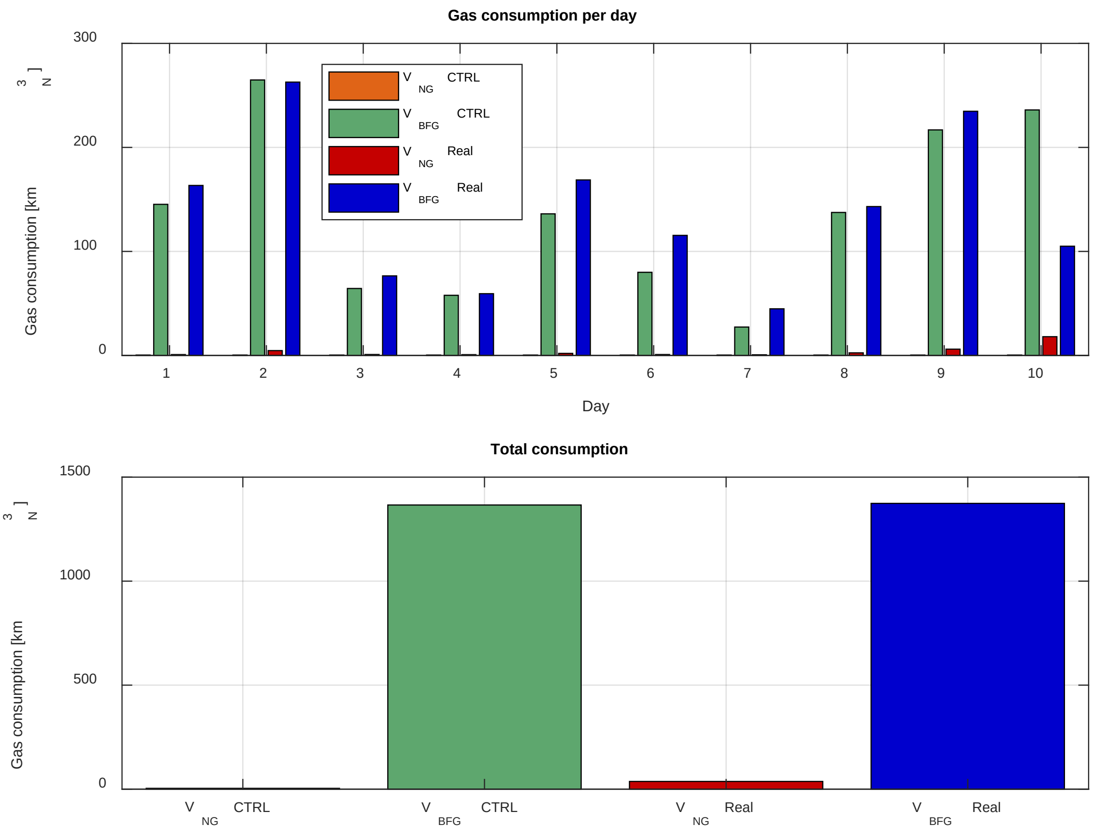


Figure 83. Mission 1, gas consumption: gas consumption per day (top diagram), total gas consumption (bottom diagram)

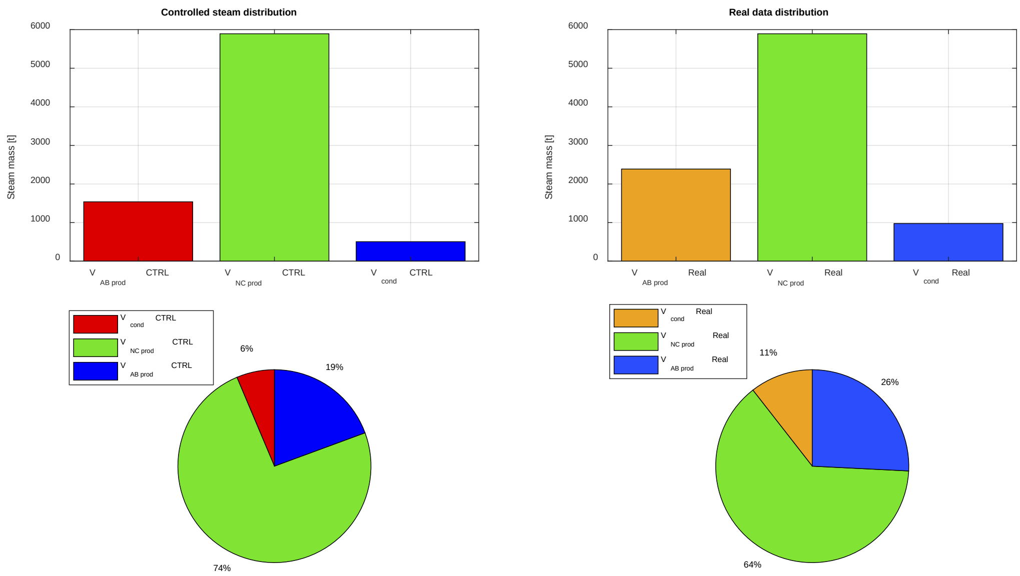


Figure 84: Mission 1, steam network, steam distribution: controlled case (left diagrams), real case (right diagrams)

Results of Mission 2

The analysis begins with the evaluation of the economic balance linked to the purchase and sale of electricity and the purchase of NG, shown in the **Figure 85**. In particular, the top figure shows the total costs for each day, while the bottom figure shows the overall costs for the 22 days of mission 2; the costs related to the application of the optimization strategy are shown in green, the costs in the absence of an optimized control strategy in red.

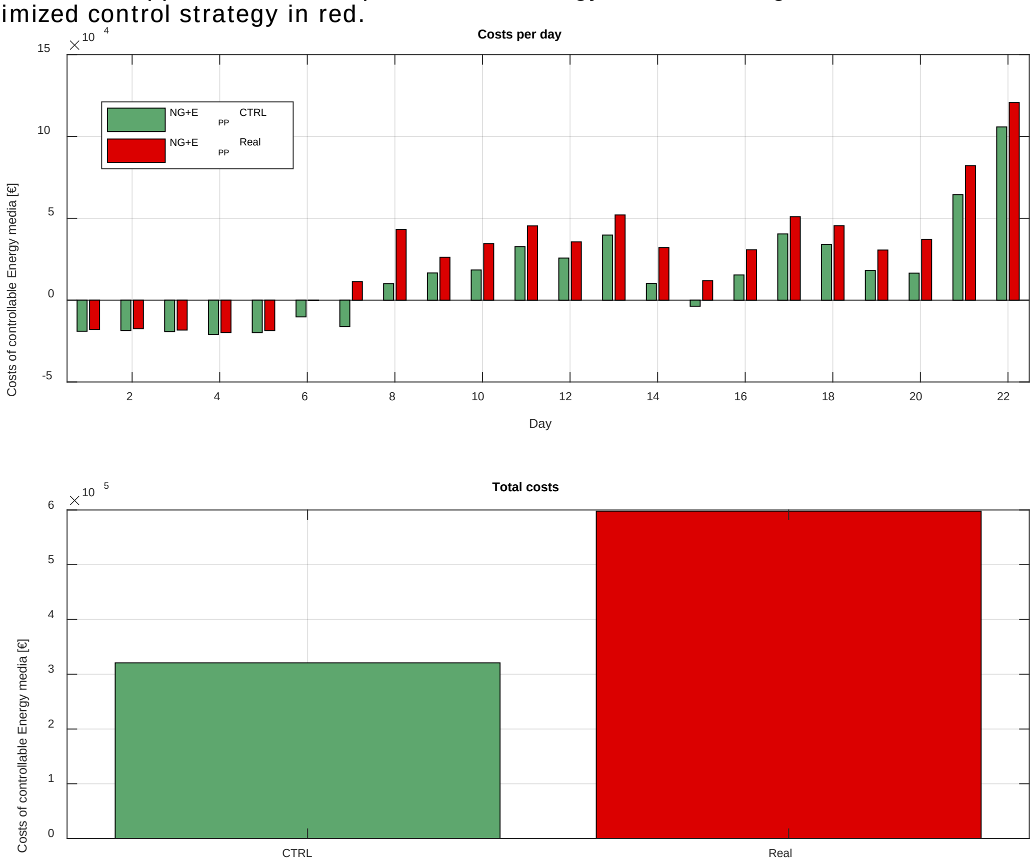
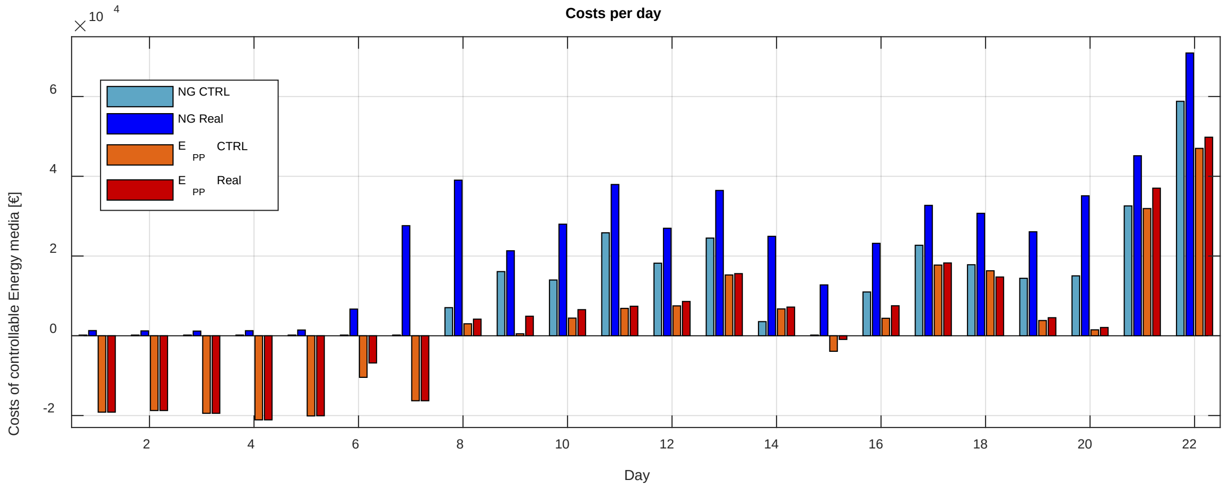


Figure 85: Mission 2: Costs analysis in the case of optimal distribution of POG and NG and in the Real case per day (top diagram), total (bottom diagram)

The proposed strategy allows an average daily saving of 12’594 € and an overall saving of 46.34 % with respect to the current approach. However, as far as the NG is concerned, it is important to underline that the relative costs only concern the consumed amount that can actually be controlled within the plant.

Figure 86 shows the specific costs of each energy media: in particular, the top diagram shows the costs for each day, while in the bottom diagram shows the total costs for the mission of 22 days.



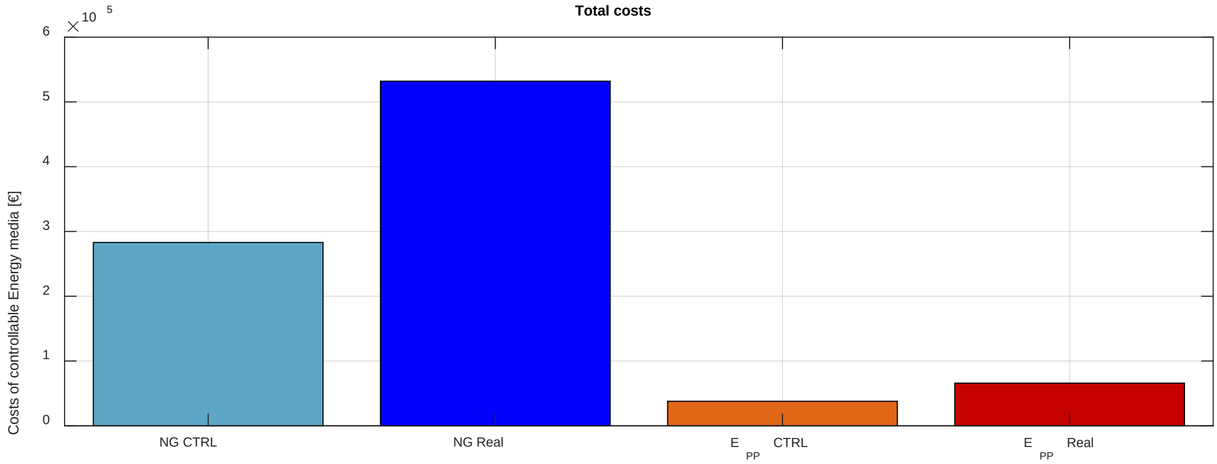
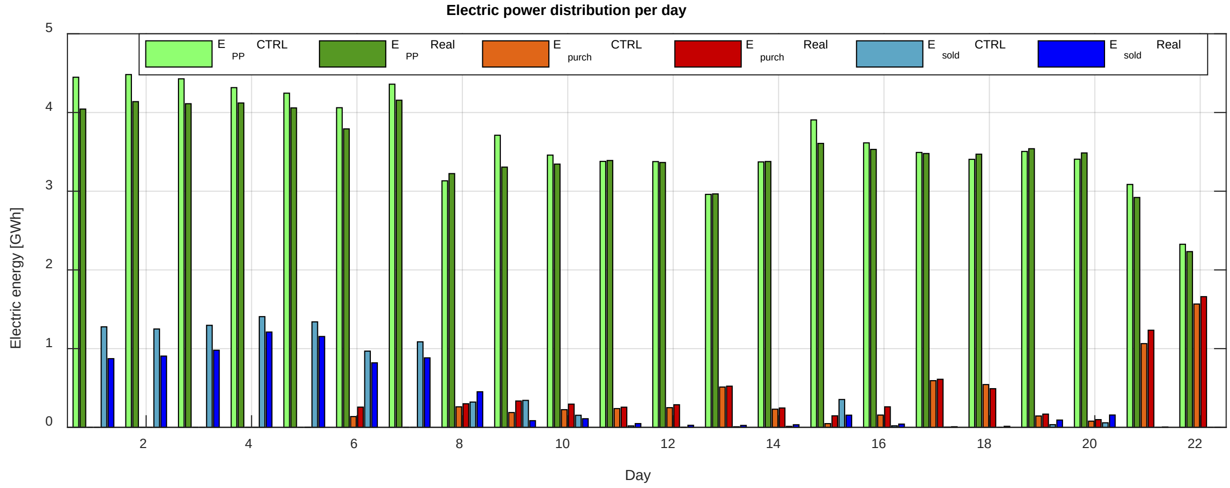


Figure 86: Mission 2: Costs analysis in the case of optimal distribution of POG and NG and in the Real case; costs related to NG and Electric energy per day (top diagram), total (bottom diagram)

The proposed strategy allows an average daily saving of NG and Epp of 11’319 € and 1’275€, respectively, and an overall saving of 46.81% and 5.27% with respect to the current approach. The optimized control approach allows to efficiently distribute POGs, such as to produce more electricity and consume less NG, with significant savings in economic terms.

Figure 87 shows the electric energy production in the internal power plant, the purchased and sold electric energy. In the figure on top is shown the electric energy for each day, while in the figure below is shown the total electric energy for the 22 days.



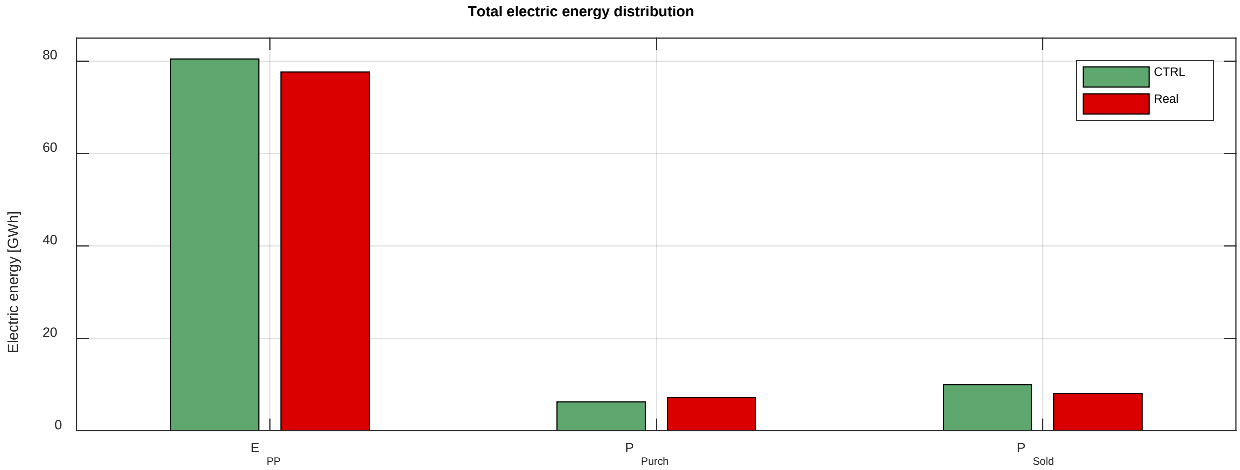
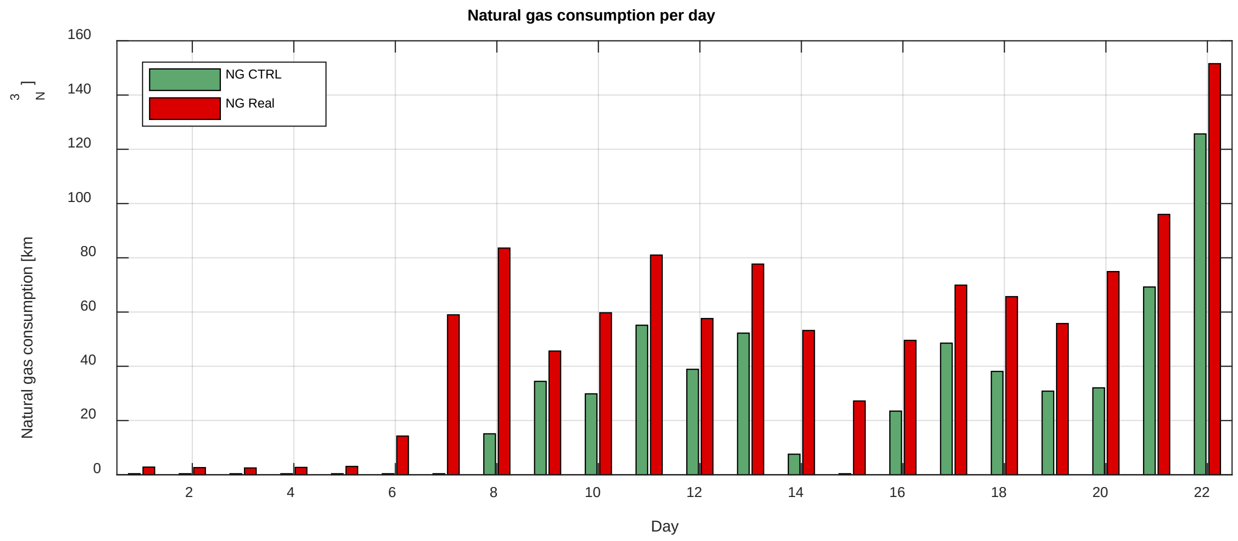


Figure 87: Mission 2, electric energy distribution between generated, purchased and sold, comparison between the optimized POG and NG distribution and the real case; Per day (top diagram), total (bottom diagram).

The proposed strategy allows an average daily variation of electricity production, electricity purchased and electricity sold of 127.73 MWh, -42.50 MWh and 85.23 MWh, and an overall variation of 3.62%, -13.04% and 23.22% with respect to the current approach. An optimal distribution of POGs allows to produce internally more energy and consequently to buy less from the external network. Furthermore, in this case the electricity sold to the external grid is increased.

Figure 88 shows the total controlled consumption of NG for each day (top diagram) and the total costs for 22 days (bottom diagram); the application of the optimization strategy is shown in green, the actual non-optimized strategy in red.



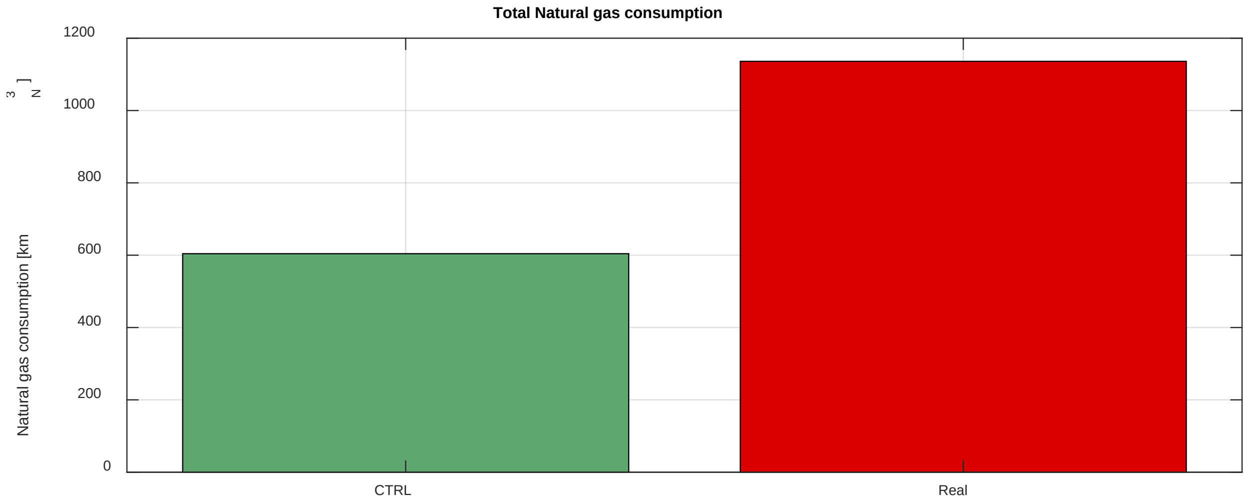


Figure 88: Mission 2, NG consumption in the controlled processes: consumption per day (top diagram), total consumption (bottom diagram)

The proposed strategy allows an average daily saving of NG of 24.17 [km^3_N] and an overall saving of 46.82 % with respect to the current approach. The control action, due to the prices of the NG and electricity, where is possible, gives higher priority to the lower consumption of NG compared to the use of POGs for the electricity.

Figure 89 shows the energy content of the POG burned in each torch (top diagram) and the total for each day (central diagram), while the bottom diagram shows the total energy loss in the torches; the application of the optimization strategy is shown in green, the actual non-optimized strategy in red.

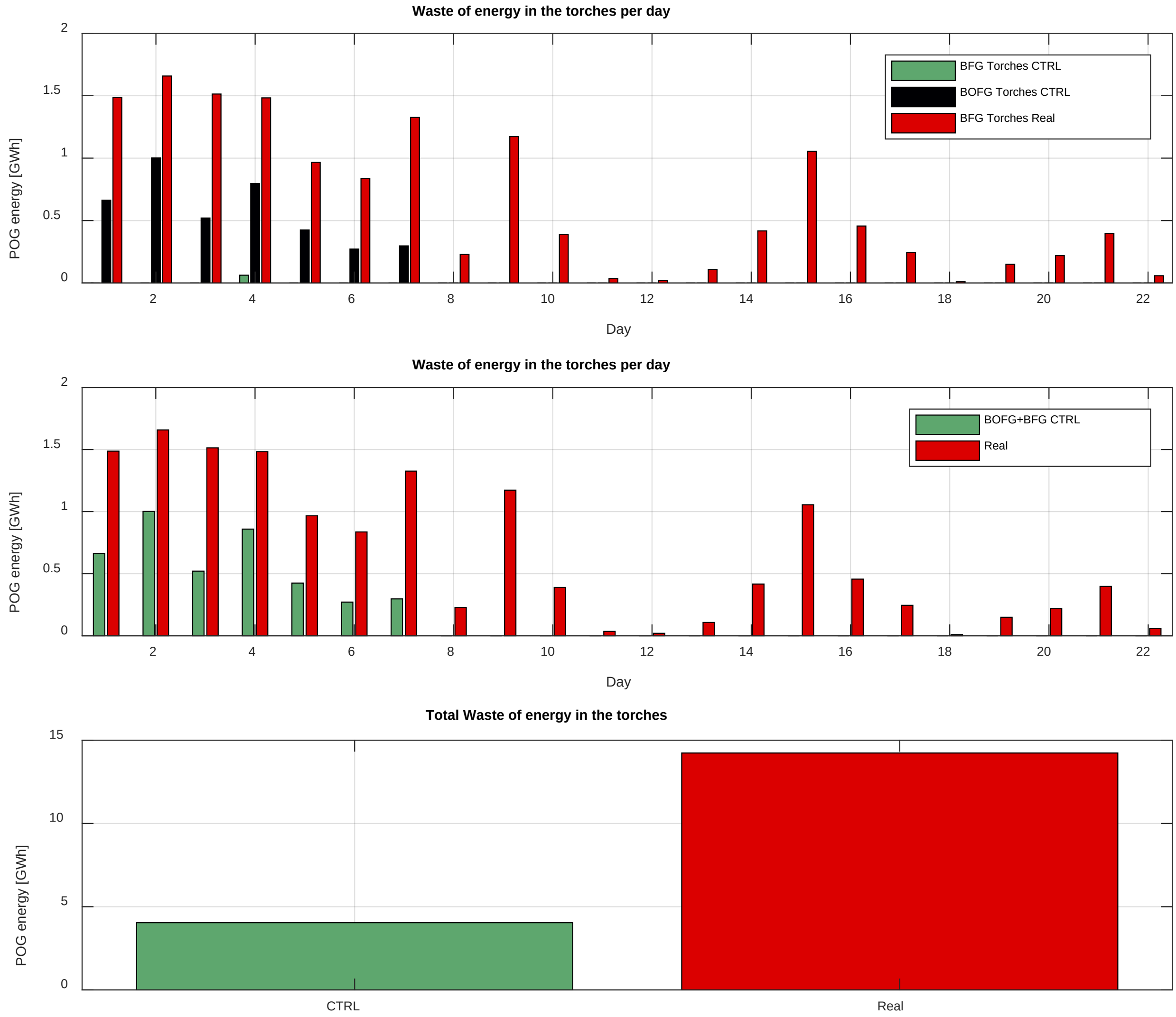


Figure 89: Mission 2, waste of energy in the torches (BOFG and BFG): per day (top and central diagrams), total (bottom diagram)

Noticeably the proposed control strategy allows significantly reducing the use of torches, apart from the first week, with a decrease of 71.62 % with respect to the current approach and an average saving of 463.4 MWh of valuable energy resources. The optimized approach allows distributing the BOFG and BFG excess to the power plant, in order to produce more electricity respect to the current approach, with a greater economic advantage and a huge decrease of the environmental impact.

Figure 90 shows the BOFG distribution among the users for each day (top diagram) and the total distribution for the 22 days (bottom diagram).
The proposed strategy optimizes the BOFG used in the WBFs to decrease the NG use. In particular, it allows an average daily saving of NG of 20.14 $[km_N^3]$ and an overall saving of 42.65% with respect to the current non-optimized approach. The optimized control approach allows efficiently distributing BOFG to the WBFs, with an increment of 24.15 % with respect to the current approach.

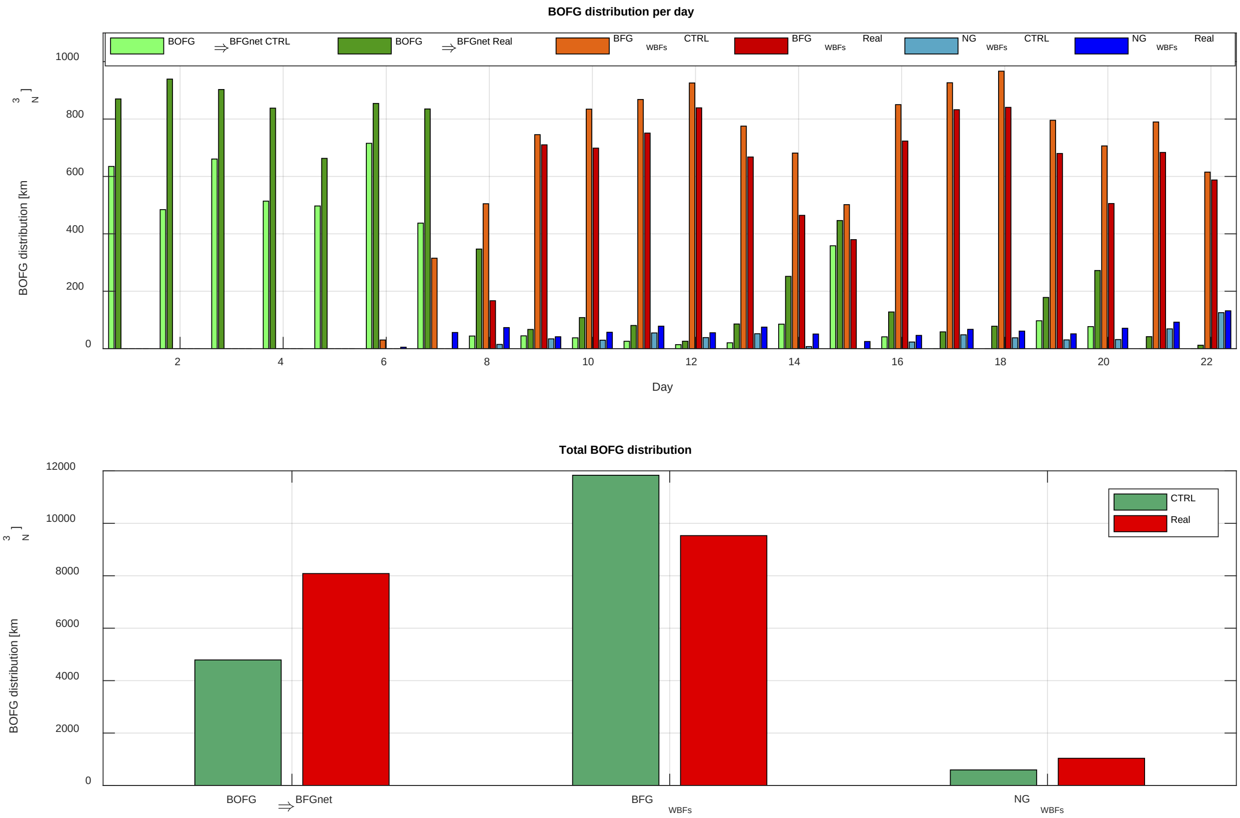


Figure 90: Mission 2, BOFG distribution among users: per day (top diagram), total (bottom diagram)

Figure 91, 92 and Figure 93 show the results related to the steam network. In particular, **Figure 91** show the condensed steam for each day (top diagram) and the total condensed steam for 22 days (bottom diagram). **Figure 92** shows the gas consumption on the auxiliary boilers for each day (top diagram) and the total gas consumption for the whole mission duration of 22 days (bottom diagram).
The proposed strategy allows managing the steam network with a noticeable saving in terms of condensed steam, with an average daily saving of 106.72 tons, and an overall saving of 98.96%. An optimized use of the condenser and a different timing of steam production also allows decreasing the production of steam in the boiler auxiliaries by 23.89 % in total.
The achieved balance in the steam network allows obtaining an overall decrease of BFG in the auxiliary boilers of 17.76%.

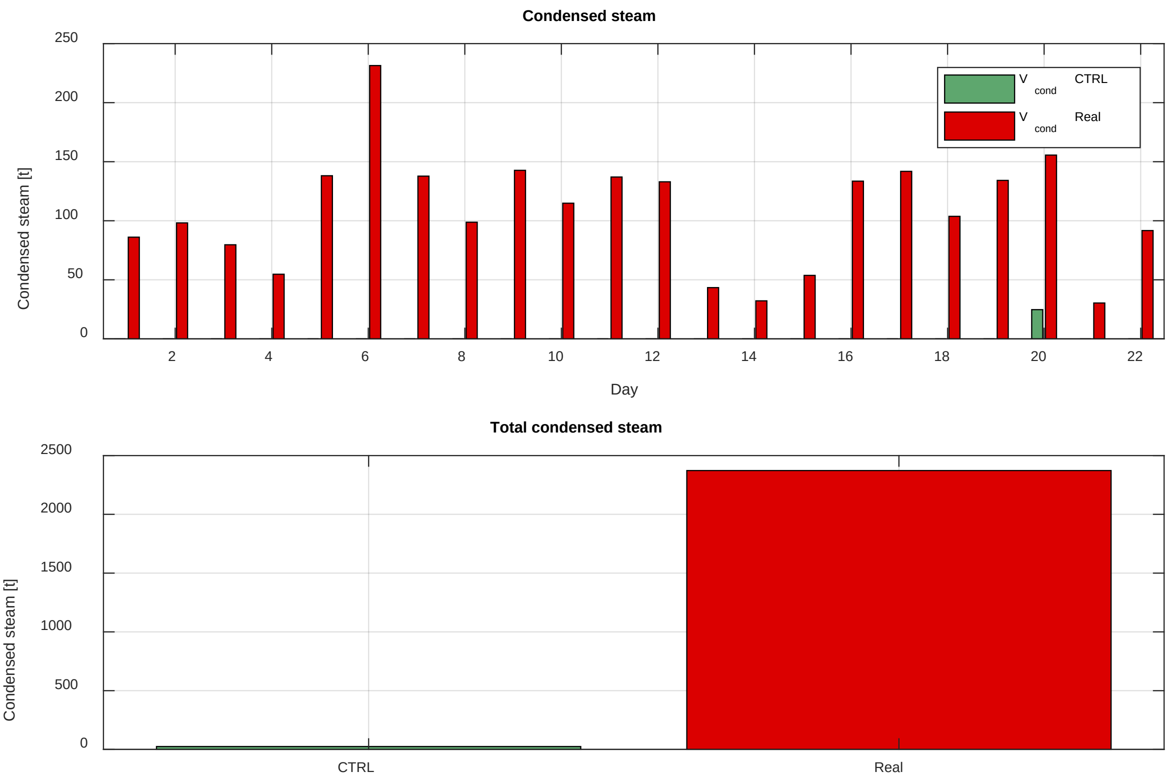


Figure 91: Mission 2, condensed steam: controlled case (top diagram), real case (bottom diagram)

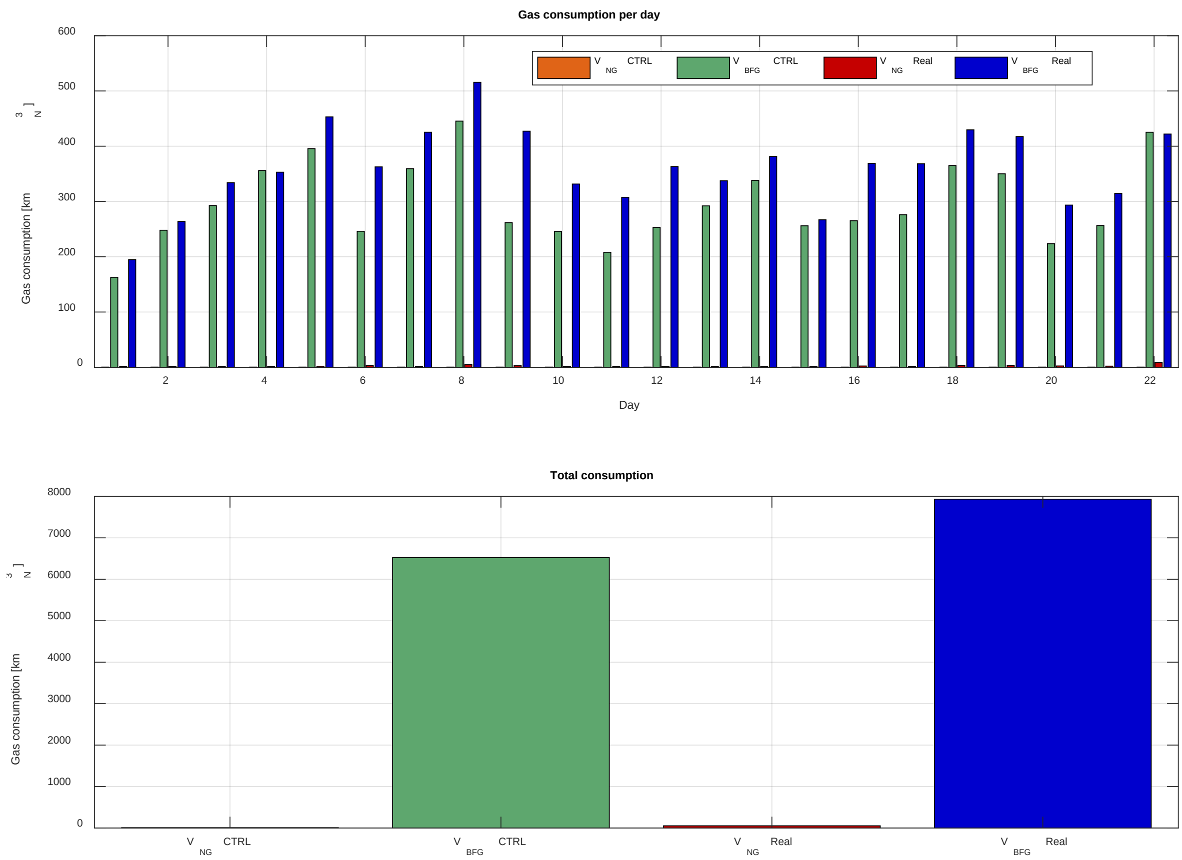


Figure 92: Mission 2, gas consumption: per day (top diagram), total (bottom diagram)

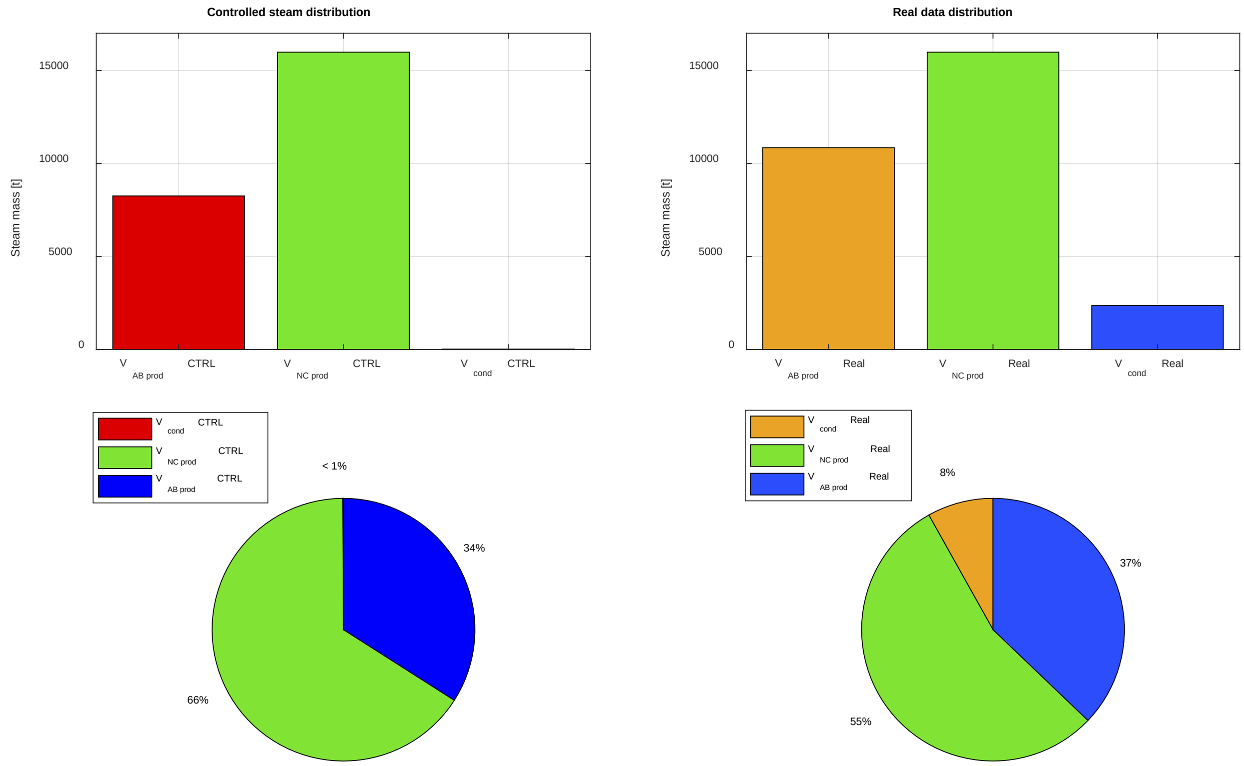


Figure 93: Mission 2, steam network, steam distribution: controlled case (left diagrams), real case (right diagrams)

4.6.3 Task 6.3 Evaluation and validation

The results achieved in the industrial tests have been deeply analysed by all the partners in order to outline the advantages of the developed approach with respect to current gas network management strategies.
The off-line gas and steam network optimization module proved to be easy to use and capable of providing meaningful although very preliminary indications on the potentials for improvements of the networks management. As such module provides a stationary optimized distribution of gas (or steam) inside the network, it can or suggest the convenience or viability of layout modifications (i.e. pipe dismantling or construiction). Moreover, such tool can be exploited in the first step of the deployment of the overall system, in order to highlight bottlenecks and critical issues in the gas network management and to define a list of priorities, issues to be solved or improvements to be reached. Following the identification of such priorities, a gradual application and adaptation of the different components of the GasNet system can be developed by avoiding misleading or confused procedures that can lead to lower advantages (see also the guidelines for exploitation for the exploitation of the integrated decision support tool, which represents **Deliverable D.3** in **Appendix A**). The computational burden of the optimization and, as a consequence, the time required to get the solutions strongly varies depending on the platform on which the software is run and on the complexity of the simulated network, ranging from a few minutes to about half an hour. However, there are margins for improvement of this aspect by the exploitation of other commercially available optimizers.
The on-line monitoring, management and optimization module proved to be efficient and easy to use: once suitably configured, the models provide a sufficiently accurate forecast of the concerned quantity over a time horizon of 2 hours, which is efficiently visualized together with the actual value. The availability of a wide library of models, the possibility to customize or include ad-hoc designed models and the possibility of incremental development of the different models, by adopting variable levels of complexity depending on the available information concerning each process as well as on its impact on the overall off-gas or steam network, provide a further element of flexibility for the overall system, which contributes to improve its potential for transferability.
As far as the high-level optimization is concerned, the performance are quantified in terms of the KPIs whose formula is provided in **Subsection 5.6.2**.
The previously presented results show that it is possible to optimize the distribution of POGs with a significant advantage from both an economic and an environmental point of view.

Table 9 summarises the main results referred to Mission 1, by reporting the KPIs calculated on the outcomes of the adopted optimization strategy.

$KPI_{€}$ [k€]	$KPI_{€\%}$ [%]	KPI_{EPPint} [GWh]	$KPI_{EPPint\%}$ [%]	$KPI_{Torches}$ [GWh]	$KPI_{torches\%}$ [%]	KPI_{NG} [GWh]	$KPI_{NG\%}$ [%]
175.1	27.49	0.67	2.46	1.43	96.9	3.72	41.56

Table 9: KPI for the evaluation of the HL optimization approach on Mission 1

The economic costs have been significantly reduced, through a larger internal production of electricity that is enabled by an optimized distribution of POGs, and mostly through a significant reduction of NG consumption. The optimal distribution of the gases allows producing more electricity that can be sold to the external grid, by thus decreasing the amount of purchased electrical energy. In addition, the costs associated with the management of the steam network are significantly improved. The predictive capabilities of an MPC-based approach allow effectively forecasting the needs of each consumer and identifying the best possible strategy for meeting the energy needs of the plant, while taking into account the constraints on the gasholders to prevent the imbalance between gas demand and production. In this way, the hierarchical control system allows almost entirely avoiding situations in which there is a large excess or shortage of POG, with the consequence of minimizing the use of torches or avoidance of production slow down. This is certainly a relevant advantage from the point of view of the environmental impact but it is also beneficial for the production.
The steam network also benefits from the predictive action of the hierarchical controller, as it allows significantly reducing the waste of gas in the condenser, and therefore jointly decreasing the production of steam through the ABs, which are synchronized with the real needs of the users.

Table 10 summarises the main results referred to Mission 2, by reporting the KPIs calculated respect to the adopted optimization strategy.

$\mathrm{KPI}_{€}$ [k€]	$\mathrm{KPI}_{€\%}$ [%]	$\mathrm{KPI}_{\mathrm{EPPint}}$ [GWh]	$\mathrm{KPI}_{\mathrm{EPPint\%}}$ [%]	$\mathrm{KPI}_{\mathrm{Torches}}$ [GWh]	$\mathrm{KPI}_{\mathrm{torches\%}}$ [%]	$\mathrm{KPI}_{\mathrm{NG}}$ [GWh]	$\mathrm{KPI}_{\mathrm{NG\%}}$ [%]
277.1	46.34	2.81	3.62	10.2	71.62	6.07	46.81

Table 10. KPI for the evaluation of the HL optimization approach on Mission 2.

The adoption of the proposed optimization approach allows to significantly reduce the costs through a greater internal production of electricity thanks to the optimized distribution of POGs. Moreover, a significant reduction in the NG consumption is observed as well as a clear reduction in the use of torches, as the developed control system is capable to synchronize and balance the energy demands of the users of the system and the production of the required energy, with greater efficiency and a considerable reduction in waste.
In particular, **Figure 87** shows in the first 7 days an increase in the production of electricity for external usage compared to the real case, which is obtained through the use of the excess of BOFG that cannot be consumed in its network, due to the fact that the main consumer, the WBFs, are not scheduled. **Figure 89**, however, shows that it is not possible to entirely use this energy content, due to the constraints relating to the maximum flow rate of BOFG towards the BFG network. This fact therefore entails a waste of excess energy, which must therefore be disposed through the torches of the BOFG system.
In **Figure 90**, on the other hand, an interesting behavior is shown in the third subplot. In order to optimize the costs associated to the use of NG in WBFs, the control system prefers to decrease the transfer of BOFG to the BFG network (and therefore to the power plant), certainly due to a higher energy yield from the use of BOFG in WBFs.
Figure 92 and **Figure 93** show a different balance of the steam network between the optimized control strategy and the real case. The figures show a huge saving in steam production thanks to an almost total reduction of the condensed steam in the network, probably due to an previously incorrect pressure setpoint for the condenser and an incorrect management of the auxiliary boiler scheduling.
To sum up, the proposed optimization strategy proved to be powerful in improving the overall efficiency of the management of off-gas and steam network, by leading to considerable savings in terms of both economic and environmental costs. A fundamental aspect to underline is that the achieved results must to be considered a maximum limit of the actual achievable optimization. In the first place, the depicted performances are obtained in the hypothesis of the application of the closed loop control action, in which the process operators synchronously implement - through appropriate actions - the references suggested by the control system with very small delay compared to the suggestion itself. If the process operators decide not to implement the control action, optimality cannot be obtained. In the hypothesis of acting in a closed loop, the performance therefore depends primarily on the delay in the execution of the control actions by the operators. Secondly, the performances obtained substantially depend on the accuracy of the process models. The proposed approach is based of availability of trustable forecastings of the future behaviours of the producing and consuming processes, therefore the model accuracy plays a relevant role. The models currently used are characterized by an accuracy that depends on the prediction distance with respect to the current control instant. The control system takes this information into account, trying to optimize the control action as soon as possible, by efficiently weighing the contributions related to the first minutes/hours ahead of prediction, and by providing a gradually decresing weight to the contribution of the farer instants of the prediction horizon. This allows obtaining a certain robustness of the results compared to the decreasing accuracy of the models. Furthermore, given that the control action at each instant is calculated starting from the real state of the processes, and that each prediction of the models is recalculated starting from the real state, the control action is to be considered reliable and robust to the uncertainties of modelling.

4.6.4 Task 6.4 Transferability issues and dissemination

Based on the poutcomes of the tests, some general guidelines have been developed for the analysis and optimization of gas networks inside integrated steelworks and for the application of the developed decision support tool. Such guidelines represent **Deliverable D6.3**, which is included in **Appendix A**.
Moreover, a user manual for the software tool has been developed by SSSA, which represents **Deliverable D6.4** and has been uploaded as a separate document on the CIRCABC.
As far as the dissemination is concerned, the partners have been deeply committed to publish the outcomes of the project through papers published in international journals as well as through presentations in international conferences and workshops. Overall, 14 papers have been generated so far, which presents some results of the project, among which 3 papers have been published in International Journal (indexed both on ISI and on SCOPUS), 11 papers have been published on proceedings of international conferences. The complete list of the publications originated by the project is provided in **Section 5.9.1**.
Two further presentations have been given within relevant international Workshops, namely

- the Workshop entitled "Digital Twin technology in the steel industry: from concept to operational benefits," which was organised by the European Steel technology Platform (ESTEP) on November 21-22 2018 in Charleroi (Belgium);
- the Workshop of the RFCS Dissemination project entitled *"Dissemination of results of RFCS-projects in the field of Integrated Intelligent Manufacturing and public discussion of a roadmap in this field" (DissI2M)*, which has been held in Pisa on May 22nd 2019. In particular, in this occasion the discussion has been focused on showing how Machine Learning and advanced control techniques, which belong to the field of Integrated Intelligent Manufacturing can be applied also in order to improve the environmental and economic impact of the steel production cycle.

The GASNET Workshop has been organised as a Special Session of the European Steel Days 2019 (ESTAD 2019), which took place in Dusseldorf on June 24-28 2019, in order to widen the audience and ensure a higher level of visibility to the project outcomes. This special session, which was entitled: *"Efficiency increase and CO_2 mitigation in iron and steelmaking: Efficient and safe management and expoitation of off-gases in the steel sector"*, has been held on June 27 2019 and included five papers which presented different aspects of the work developed within the project. The papers presented in this special session have been collected in a volume of Proceedings of the GASNET workshop, which represents **Deliverable 6.2** and has been sperately uploaded on the CIRCABC.
A group named "GASNET" has been established by SSSA on the ResearchGate platform at the beginning of the project to the aim of coming into discussion with other interested researchers and increasing the visibility of publications produced throughout the project.
Finally a logo has been elaborated for the GasNet system, to be used in future communication and dissemination activities, and a flyer depicting the GasNet DSS. They both represent **Deliverable 6.5**: the logo is included in **Appendix A**, while the flyer is uploaded as a separate document on the CIRCABC.

4.7 WP 7: Coordination and Reporting

The objectives of WP7 are:

- Coordination of project activities, control of project progress;
- Preparation and presentation of progress and final reports.

4.7.1 Task 7.1: Coordination work and meetings

A fruitful and continuous information exchange has been established among the project partners via email exchange and many conference calls. Moreover 10 physical partners' meetings have been organised:

- 1st Partners' Meeting on 06.07.2015 in Pisa (Italy), hosted by SSSA;
- 2nd Partners' Meeting on 18-19.02.2016 in Bremen (Germany), hosted by ABG;
- 3rd Partners' Meeting on 17-18.10.2016 in Ijmuiden (The Nederlands), hosted by TATA STEEL;
- 4th Partners' Meeting on 14-15.02.2017 in Maiziéres (France), hosted by AMMR;
- 5th Partners' Meeting on 20.03.2018 in Pisa (Italy), hosted by SSSA;
- 6th Partners' Meeting on 03-04.12.2018 in Bremen (Germany), hosted by ABG;
- One extraordinary meeting on 23.05.2018 in Metz (France), hosted by AMMR during the 12th Society and Material Conference SAM 12, where a paper treating part of the work developed within the project was presented;
- 7th Partners' meeting on 03.12.2018 in Bremen (Germany), hosted by ABG;
- One restricted meeting on 23.05.2019 in Pisa (Italy), hosted by SSSA during the DISSI2M workshop, where part of the work developed within the project was presented and discussed;
- 8th and final Partners' meeting on June 26.06.2019 in Dusseldorf (Germany), hosted by BFI during the 2019 ESTAD Conference, when the GASNET Workshop took place.

Furthermore, SSSA's personnel was hosted at ABG and ILVA/AMI for extensive periods both during the development phase and for the intermediate and final tests of the system, and BFI personnel organised regular visits to ABG during the models development phase.

4.7.2 Task 7.2: Documentation

The minutes of all the Partners' meeting and conference calls were sent via email. Tables and documents were shared by the partners in order to exchange useful information for the completion of the different activities.

4.7.3 Task 7.3: Reporting

All the periodic reports have been issued in due time. The Final Report is being delivered by 31/03/2020.

4.8 Conclusions

The European Steel industry is ever more committed to improve the socio-economic and environmental sustainability of its processes by promoting any development, which can increase resource efficiency and lower the environmental footprint of the steel production. The European Steel Technology Platform gives the highest priority to the topic of Sustainable Steel Production within its Strategic Research Agenda since 2013. Several projects have been developed both at corporate level, as well as by associations of companies and research institutions in order to investigate new processes, retrofit actions and apply innovative combinations of existing technologies that can allow to improve the energy and resource efficiency.

This project targeted the optimal management of the off-gas network in integrated steelworks starting from the consideration that such ambitious objective can contribute to jointly environmental and economic sustainability of the integrated route. In effects, poor economic valorization of by-product gases as well as flarings into torches represent both an economic and environmental waste.

The project showed that the capability to forecast at least on a short time horizon (2 hours) the production and demand of process off-gases plays a fundamental role for their optimal management. In effects, this allows avoiding challenging situation, such as gasholders saturation, which is generally solved by flaring of useful gases into torches, or unnecessary use of costly natural gas by some users.

The project also demonstrated the potential of Machine Learning-based approach for the development of holistic, data-driven computationally sustainable and accurate models of the different processes involved in the off gas and steam networks, as consumers and/or producers of the considered resource. A particular kind of neural networks, the ESN, has been applied in order to reproduce the dynamic behavior of the most complex processes, being the models clearly limited to the aspects that are relevant for the network management, such as, for instance, the volumes and energy content of the produced gases.

The forecasting capability provided by the advanced models has been exploited by means of an optimization strategy based on Model Predictive Control. In particular a hierarchical approach composed of two levels have been applied: the first one, named high-level control strategy for the optimal scheduling of power generation, computes a set of references for the main energy consuming processes in terms of gas exploitation for meeting specific needs on a daily horizon. In particular, this level mainly acts on the consumption of POGs for the production of electricity through the internal power plant and for the process heat of the walking beam furnace, a large consumer of natural gas and POGs. The second control level, called hybrid continuous and event triggered online control, computes the control action for each controllable process on a time horizon of two hours, with a time resolution of 1 minute. In this way it is possible to respect all the constraints through an online control of the main process variables, starting from the references calculated in the higher-level controller.

The overall achievable advantages in terms of economic and environmental costs are very relevant and extremely encouraging. The required resources for industrial implementation of the proposed solution, in terms of hardware and software as well as personnel efforts needed, e.g. for establishing the database, customizing and maintain the models heavily depend on the existing IT infrastructure and data collection system and might be not negligible at least in the first stages of the deployment. However, they appear to be well balanced by the achievable saving in terms of natural gas purchase (over 40% of savings have been achieved in the tests) and drastic reduction of wasted energy and resources.

Finally, a not easily quantifiable but relevant benefit is related to a deep involvement of the company’s technical personnel at different levels, which comes from the provided possibility of easy on-line and almost real-time monitoring and forecasting of the environmental performance of the system. This awareness can be enhanced through suitable training and information activities aiming not only at showing the main functionalities of the system but at raising the confidence of the operators toward advanced also AI-based approaches and systems.

To sum up, the project showed the relevant potential of advanced also AI-based tools and techniques for modelling, control and improvement of the environmental performances of the steelmaking processes. The ever increasing availability of data collection and storage systems and of computational resources is going to pave the way to the application of this kind of systems throughout all the European steel industry and the energy-intensive industry in general. In this sense, the project provided also a well-structured (although preliminary and limited to the gas and steam management) proof of concept that AI and BD tools and techniques are a fundamental and powerful enabler in order to implement practical solutions of circular Economy and Industrial Symbiosis.

4.9 Exploitation and impacts of the research results

The project aimed at improving the management of process off-gases in integrated steelworks through the exploitation of an ad-hoc developed simulation and decision support tool. This tool, thanks to the two included modules (and their internal packages), allows firstly gaining a greater consciousness of actual management gas and steam networks and related possible improvements and then giving suggestions to optimize continuously the distribution and the use of off-gases inside the steelworks according also to the production plan.
In effect, the tool is provided with of an off-line module and on-line one. The two modules are exploitable individually and are both independent on the availability of software licences. The off-line module can be easily installed and used without specific skills in all the industrial facilities where there are gas and steam networks (not only in steelworks). It requires some basic inputs and it provides preliminary insights about possible stationary optimizations of gases distribution in existing networks or modifications of networks layout in order to improve their management. In this way, the bottlenecks and the improvements margins can be easily visualized by the industrial staff and a list of priorities can be developed that can be addressed through the installation or the deletion of pipes or through the exploitation of the online module of the DSS. This last module requires the involvement of the facility IT services in order to establish the connection between field data (through a dedicated DB) and the software. Furthermore, it can be tailored according to the needs: for instance, models can be adapted or new ones can be developed and included. Moreover, as the KPIs are implemented as a particular class of models, new KPIs can also be included. Obviously, some of these modifications can be carried out without difficulties and following only the suggestions provided in the user manual; on the other side more complex adaptations (e.g. the development of a new complex model) need specific skills but the tool is conceived to allow this possibility. Apart from the previously listed modifications, also in this case (such as for the off-line module) the exploitation of the online module can be carried out by all the industrial users thanks to an easy to use GUI that is a simple interface to use models and optimizers. In addition, thanks to the presence of the KPI section and of an easy to understand visualization system for the simulation and optimization results, no specific skills are required in order to understand the results and to recognise how the production plan affects the production and demand of gas, steam and energy and which economic and environmental advantages can be obtained through the gas distribution optimization.
All the features of the GASNET DSS (i.e. license free, modularity, adaptability, simplicity) are added values, because they enhance its transferability also outside the companies which participated to GASNET and pave the way to the application of similar approaches or tools also in other energy intensive industries with high production of valuable process off-gases. The deployment of GASNET DSS has the hard goal to increase the awareness that advanced tools based on forefront techniques can be a very valuable help to target actions that can give significant impacts to process industries in terms of environmental and economic sustainability by “just” suggesting new management actions.
For this reason, the industrial partners are committed to exploit the project outcomes within their facilities considering not only the ones which have been involved in the project but possibly other facilities belonging to the same industrial groups.
On the other hand, the research partners are also committed to deploy the results of the project in future research project involving the steel sector as well as other sectors of process industry. As already stated, the problem of off-gas management and, even more in general, of optimal exploitation of different energy-conveying media, is common to many energy intensive industries. Therefore, the overall structure of the DSS developed within the project as well as some of its general purpose components (e.g. AI-based models and hierarchical Model-predictive control and optimization approaches) have a huge potential for transferability and adaptation outside the steel sector for similar applications targeting energy efficiency and allegedly emissions reduction.

4.9.1 List of publications originated by the project

[1] V. Colla, I. Matino, S. Dettori, A. Petrucciani, A. Zaccara, V. Weber, S. Salame, N. Zapata, S. Bastida, A. Wolff, R. Speets, L. Romaniello: “Assessing the efficiency of the off-gas network management in integrated steelwork,” *Matériaux et Techniques*, Vol. 107, No. 1, 2019.

[2] I. Matino, S. Dettori, V. Colla, V. Weber, S. Salame: "Application of Echo State Neural Networks to forecast blast furnace gas production: pave the way to off-gas optimized management," *Energy procedia*, Vol 158, pp. 4037-4042, 2019.

[3] I. Matino , S. Dettori, V. Colla, V. Weber, S. Salame: "Two innovative modelling approaches in order to forecast consumption of blast furnace gas by hot blast stoves" *Energy procedia*, Vol 158, pp. 4043-4048, 2019.

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[5] I. Matino, S. Dettori, V. Colla, V. Weber, S. Salame: "Forecasting Blast Furnace Gas Production and Demand through Echo State Neural Network-based Models: Pave the Way to Off-Gas Optimized Management," *Applied Energy*, Vol. 253, 2019.

[6] I. Matino, S. Dettori, V. Colla, N. Zapata, S. Bastida, J. Bartel: "Forecasting of Basic Oxygen Furnace Gas Production Through Echo State Neural Networks*", 8th European Oxygen Steelmaking Conference - EOSC 2018*, Taranto (Italy), 10-12 October 2018.

[7] V. Colla, I. Matino, S. Dettori, A. Zaccara, A. Petrucciani, V. Weber, S. Salame, N. Zapata, S. Bastida, A. Wolff, R. Speets, L. Romaniello, "A way to quantify the efficiency of the gas network management in integrated steelworks" *4th European Conference on Clean Technologies in the Steel Industry CLEANTECH 4*, Bergamo (Italy) 28-29 November 2018.

[8] Colla, V., Matino, I., Dettori, S., Cateni, S., Matino, R. “Reservoir computing approaches applied to energy management in industry,” *Communications in Computer and Information Science*, 1000, pp. 66-79, 2019.

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[10] I. Matino, S. Dettori, V. Colla, A. Zaccara, A. Petrucciani, V. Weber, S. Salame, N. Zapata, S. Bastida, A. Wolff, R. Speets, L. Romaniello: "Quantification of the impact of an optimal gas network management in integrated steelworks: the GASNET performance indicators", *European Steel Days ESTAD 2019*, Dusseldorf (Germany), June 24-28, 2019.

[11] I. Matino, S. Dettori, V. Colla, A. Zaccara, A. Petrucciani, V. Weber, S. Salame, A. Wolff: "Advanced modelling for forecasting off-gas, steam and electricity production and demand in integrated steelworks: the GASNET model library" *European Steel Days ESTAD 2019*, Dusseldorf (Germany), June 24-28, 2019.

[12] A. Wolff, F. Mintus, S. Bialek, S. Dettori, V. Colla: "Economical Mixed-Integer Model Predictive Controller for optimizing the sub-network of the BOF gas," *European Steel Days ESTAD 2019*, Dusseldorf (Germany), June 24-28, 2019.

[13] R. Speets, D. Berghuis, P. Pronk: "Advanced Energy Management System at Tata Steel in Ijmuiden," *European Steel Days ESTAD 2019*, Dusseldorf (Germany), June 24-28, 2019.

[14] S. Dettori, I. Matino, V. Colla, R. Speets: “Deep Echo State Networks in Industrial Applications,” accepted for presentation at *16th International Conference on Artificial Intelligence Applications and Innovations*, Halkidiki (Greece), June 5-7 2020.

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6 LIST OF FIGURES

7 LIST OF TABLES

8 LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation	Name
AI	Artificial Intelligence
AMI	ArcelorMittal Italia
BF	Blast Furnace
BFG	Blast Furnace Gas
BOF	Basic Oxygen Furnace
BOFG	Basic Oxygen Furnace Gas
BOFGIS	BOFG injection station
BOFGIP	BOFG injection point into BFG
BPF	Boiler Penalty Factor
CCS	Carbon Capture and Storage
COG	Coke Oven Gas
CRM	Cold Rolling Mill
CWPx-BF2-NGIP	Natural gas injection point into BF2G before the BF2 cowper
CWPx-BF3-NGIP	Natural gas injection point into BF3G before the BF3 cowper
DSS	Decision Support System
EAF	Electric Arc Furnace
EMPC	Economical Model Predictive Control
ESN	Echo State Networks
FCM	Fuzzy C-means
FIS	Fuzzy Inference System
GA	Genetic Algorithms
GHG	Greenhouse gas
GMS	Gas Management System
GPF	Gasholder Penalty Factor
GUI	Graphical User Interface
HDGL	Hot Dip Galvanizing Lines
HRM	Hot Rolling Mill
HSM	Hot Strip Mill
HSM-NGIP	Natural gas injection point into BOFG
HSM-NGIS	Natural gas injection station into BOFG
HSM-MG	Mixed gas (natural gas+BOFG) for the walking beam furnaces of HSM.
LD	Linz-Donawitz
LSSVM	Least Square Support Vector Machine
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
ML	Machine Learning
MOO	Multi-Objective Optimization
MPC	Model predictive Contol
NARX	Nonlinear Autoregressive Network with exogenous inputs
NCV	Net Calorific Value
NG	Natural Gas
OLAP	On-Line Analytical Processing
PCI-NGIP	Natural gas injection point into POG before PCI
PCI-NGIS	Natural gas injection station into POG before PCI
POG	Process Off Gas
POGMP	Process off-gases mixing point
PP-NGIP	Natural gas injection point into POG before power plant
PP-NGIS	Natural gas injection station into POG before power plant
TDNN	Time Delays Neural Networks
WBF	Walking beam furnace

9 APPENDIX A: DELIVERABLES OF WP6

9.1 D6.1 Final version of decision support tool

The integrated simulation and decision support tool is articulated into two modules, which can be installed and run separately: the former one is devoted to on-line monitoring, management and optimization of the gas and steam networks, by collecting data from a database linked to the steelworks IT systems and fed with real data coming from the different plants. The latter on is devoted to off-line network optimization and allows developing optimization studies and scenario analyses on how the off-gases are distributed inside the network including the possibility to dismantle or build new pipes. The data are fed manually by the user, but it can also be linked to the former module, as the data related to the simulated network can also be stored and loaded from some configuration files.
The reason for keeping the two modules independent on each other is mainly twofold: firstly, it allowed independent testing and running of the two components of the software by the partners of the GasNet project, within which the software has been developed. On the other hand, such separation seemed more fruitful in order to pave the way to future dissemination and exploitation actions. In effects, the installation of the on-line monitoring tools requires a set of actions involving also the IT services of the facility in order to establish the database for on-line collection of field data, therefore it cannot be done individually, for instance, by an industrial researcher, who whishes to somehow study the potentials for improvements on the off-gas management. On the other hand, the off-line optimization tool can be installed and run on a PC and needs some basic inputs, which can be fed by the single user. Although the results that are provided in such a case have a validity, which is limited to a stationary optimized distribution of gas (or steam) in the network, they can allow an insight of the possible improvements as well as to define an initial list of priorities for the management of the network, including layout modifications. In other words, the second module can be distributed in test or demo versions in order to raise the interest in the scientific and technical community toward the outcomes of the GasNet project as a whole and to pave the way to the deployment of the overall system.

On-line monitoring, management and optimization module

The on-line optimization module of the GasNet DSS is used to work on process variables, coming from a database filled with factory sensors readings and defined set points, in order to obtain predictions and decision support information.
The users can analyze the time trend of relevant variables in a convenient chart representation and can intervene in the predictions subsystem, tuning models parameters, to fit their needs.
This software module is organized into 3 different interconnected applications, according to the architecture schematically depicted in **Figure A.1**: the server, the viewer and the modeler. Each one is a stand-alone software, that user can launch from Windows Desktop, after installation.

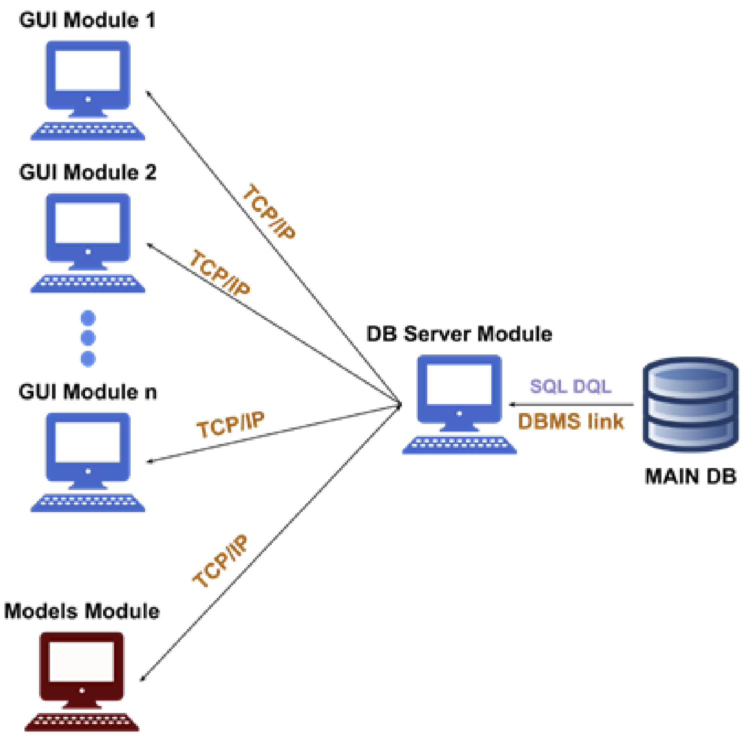

Figure A.1: Software architecture

The *viewer* is the application for users who want to monitor the variables evolution in the plant. It requires a running instance of the server. The *modeler* is the application for users who want to select which models to turn on and how they must be configured. It requires a running instance of the server. The *server* manages the connection with the data source and provides the data to the other two applications.
Each application is stand-alone and can be run from a different machine in the network as they communicate with TCP/IP network protocol. The user can exploit this feature by installing the most computationally intensive application (i.e. the modeler) on a performant machine and the visualization tools (several instances of the viewer) on less efficient machines.

<u>*GasNet Wiewer*</u>
The **viewer module** shows process variables evolution in time. Such module is organized in two tabs: the former one is devoted to process variables, while the latter one is focused on KPIs.
Once connected, the viewer awaits updates from the server. Every minute a snapshot of data is transferred from server to viewer and is ready to be examined (see Errore. L'origine riferimento non è stata trovata.).

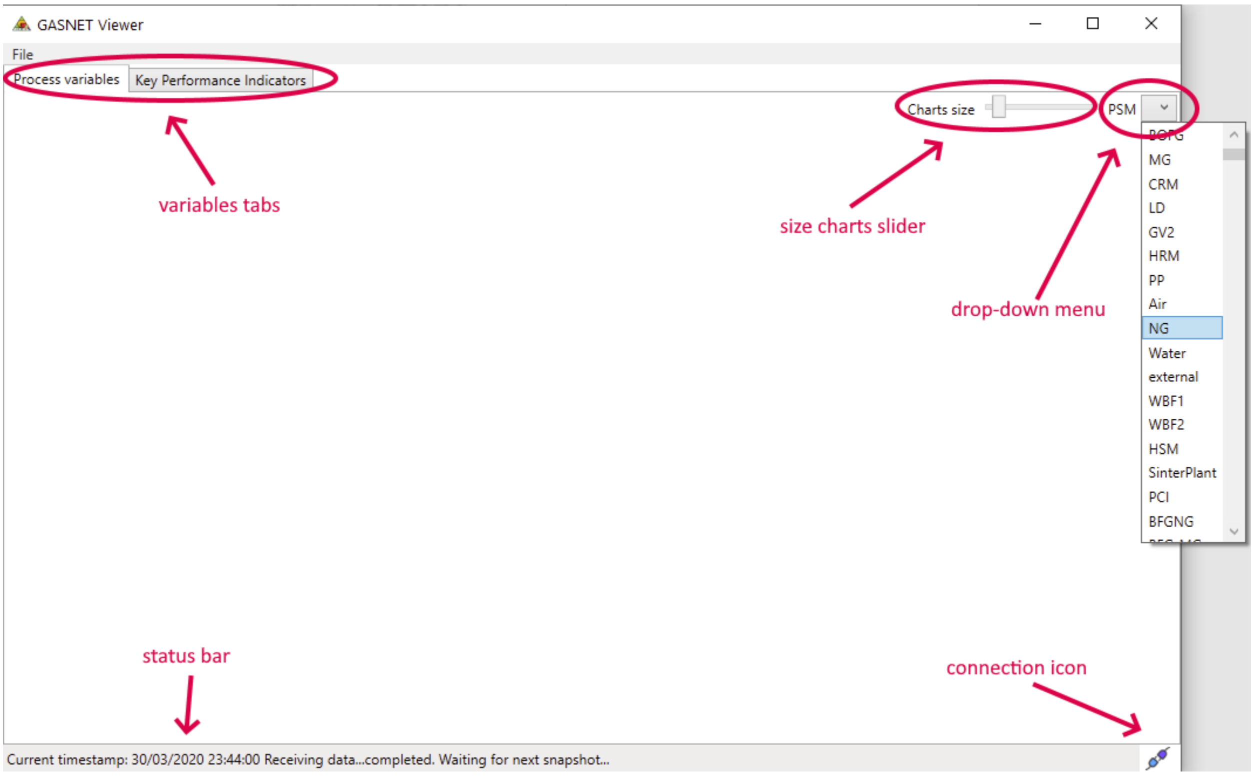

Figure A.2: GASNET Viewer main window after successful connection

The user can select which group of variables he wants to monitor among process variables and KPIs. The selection is made by clicking on the desired variables tab in the upper left corner.
If process variables are selected the user needs to select which PSM he wants to monitor by clicking on the drop-down menu in the upper right corner. After the first snapshot of data has been received (this fact is signaled with a message in the status bar) all the charts associated with the PSM will appear in the main window. A chart size slider is available to resize charts for user convenience. Please refer to Errore. L'origine riferimento non è stata trovata. to identify the various above-described components.
Figure 71 shows variable charts with values picked from the database. Leaving the mouse cursor on a point allows reading the sample value in the associated tooltip. For variables that have associated predictions a blue overlay is drawn on the chart (see **Figure 72**), in order to show the predicted evolution of the variable samples. Those values are obtained from the models, which are implemented in the modeler software, the third component of the whole solution.
Under the Key Performance Indicators (KPIs) tab there is a section dedicated to that kind of charts (see **Figure A.3**). A similar chart size slider helps the user to adjust the data presentation. This section contains only data picked from database, without models' contribution.
Multiple instances of the viewer can be run on multiple machines and can connect to the same server module. This gives the flexibility to view the data from different workstations provided with network access.

Figure A.3: Exemplar KPI charts.

GASNET Modeler

This software is the core of the system since it provides the implementations of all models and executes them to obtain predictions from input data.

Once it is connected to the database, the modeler downloads the models list from the server and for each of them searches for a suitable implementation into its library. All the models are shown in the main window (see Errore. L'origine riferimento non è stata trovata.): they are displayed in red if they miss implementation, in green if they are ready to start, in yellow if, even having an implementation, they stll miss a full configuration.

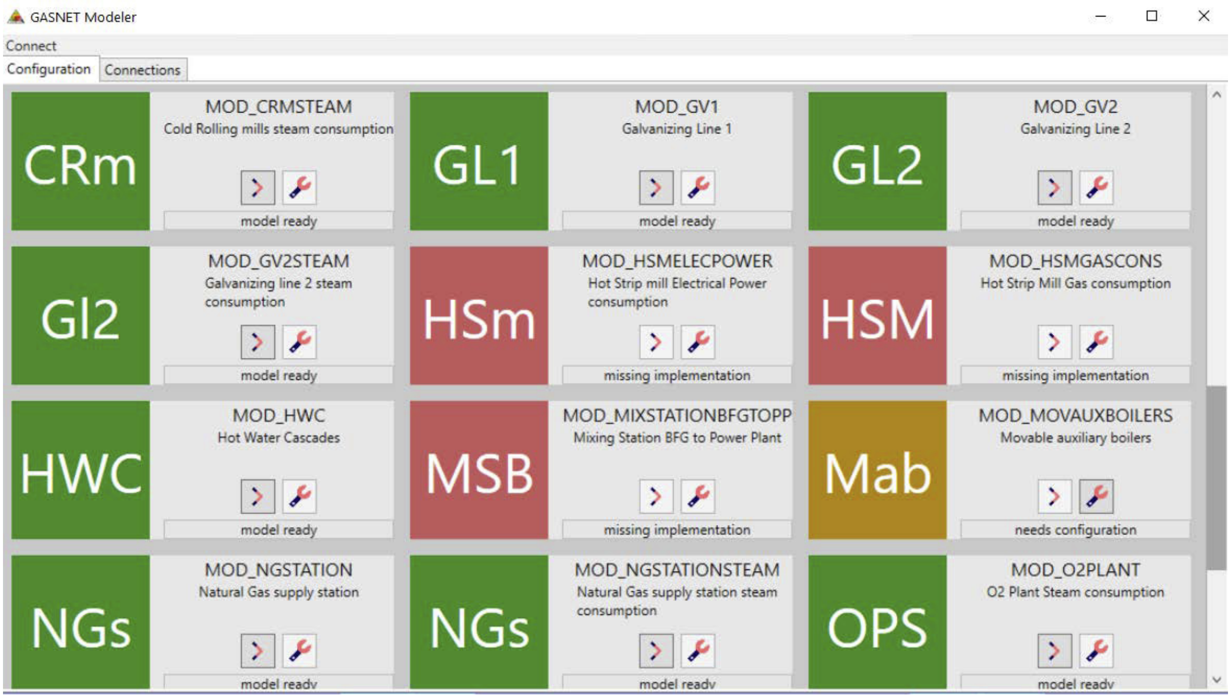

Figure A.4: Modeler main window: status after connection

When ready, a model can be started by clicking on its “play” icon. From this point on, the model will catch its input variables from the next snapshot received from the server, and will execute its computations, returning its output to the server. Afterwards, the model will update its internal database cache making available the received data to the viewer and, periodically, dumping the new data to .csv files, passed to database updating scripts.

When a model needs configuration, or if user wishes to fine tune the configuration of a runnable model, the wrench icon button must be clicked. This opens a configuration window in which user can set proper parameters. This configuration environment depends on the class of the model selected: every model belongs to a specific class of models and needs different parameters to be set. Some models have fixed parameters and, therefore, show a greyed-out wrench icon in order to inform the user.

The software is equipped with a configuration system for the model tuning. This kind of models allows the connection of several components, from the simplest adder and multiplier to the most complex, such as the ones based on ESNs, passing through the conditional blocks that simulates if/then constructs. Mouse hovering over blocks shows useful information for user convenience.

As far as the configuration of the ESN-based models is concerned, which forecasts the evolution of some relevant variables based on a pre-built knowledge, acquired through the training stage, a configuration interface is available, which allows the user to fine tune the parameters and retrain the block (see **Figure A.5**). In this section user can configure global ESN numerical parameters and can add or remove layers, by also changing their local parameters with a double click on them. The process is straightforward. As the ESN also requires a training stage, the configurator allows for input/target datasets disk loading.

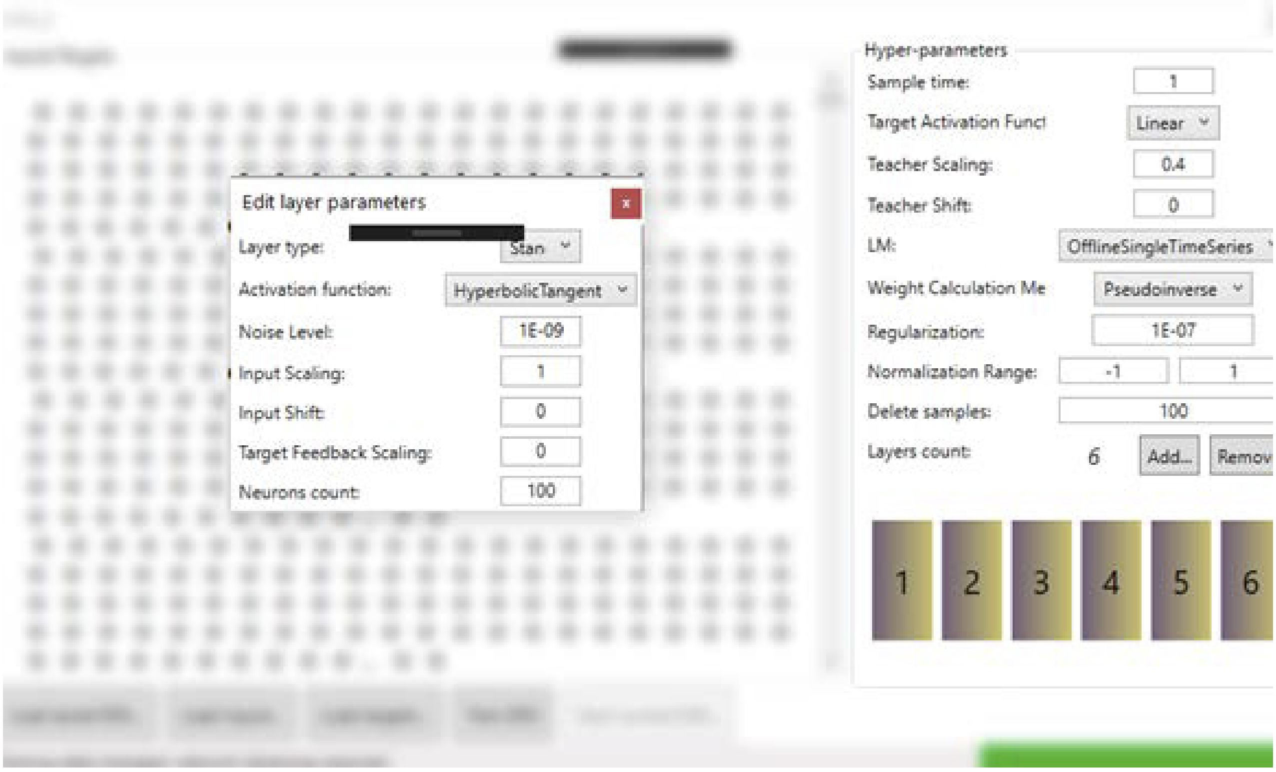

Figure A.5: ESN component configurator (only parameters section visible).

GASNET Server

This component manages database queries and serves the other modules by sending data and storing results. It needs to be run on a computer located on the same network of the database. In other words, the computer running the server needs to have direct access to the database. To start the server the user must launch it from the command line.

The server module has a textual interface and, once launched, does not require interactions with the user; it only shows a log of the most important events. The connection between server and clients (modeler and viewer) is not encrypted, therefore the security is demanded to the underlying network.

Off-line optimization module

The main window of the GUI which allows running the offline optimization tool for the network structure is displayed in **Figure A.6**.

The first step to be accomplished by the user in order to establish the network to simulate is the input of the information about the gas or steam network. This operation can be performed by using the set of fields in the right bottom corner area of the main window. In these fields the number of producers, consumers, torches, gasholders, natural gas providers, nitrogen providers must be input. Moreover, the total number of gases to be considered must be also be input here. If some structure is not present, for instance, if there is no nitrogen provider, the box must be filled with a null value.

The network can be created by using the buttons, which are located on the central bottom part of the main window depicted in **Figure A.6**.

The network is represented as a graph which includes a series of nodes interconnected by edges. Such graph can be created by inserting manually each vertex ("Add Vertex"), where a name or a number can be used to distinguish the vertices. The id number of vertices are generated in ascending order, i.e. the first generated vertex has id number $N_{id}=1$, the second vertex generated has id number $N_{id}=2$, etc. The connections can be created by clicking on "Edges".

To generate the network constraints, several parameters must be input in the tabs, which are placed on the top part of the window reported in **Figure A.6** and can be selected by means of the mouse.

After the vectors tab is filled, The adjacency matrix is automatically generated with the network construction, it contains a 1 in correspondence to the entry placed in the *i-th* row and *j-th* column if there is an arc connecting vertex *i* to vertex *j*, otherwise it contains an infinite value *inf*.

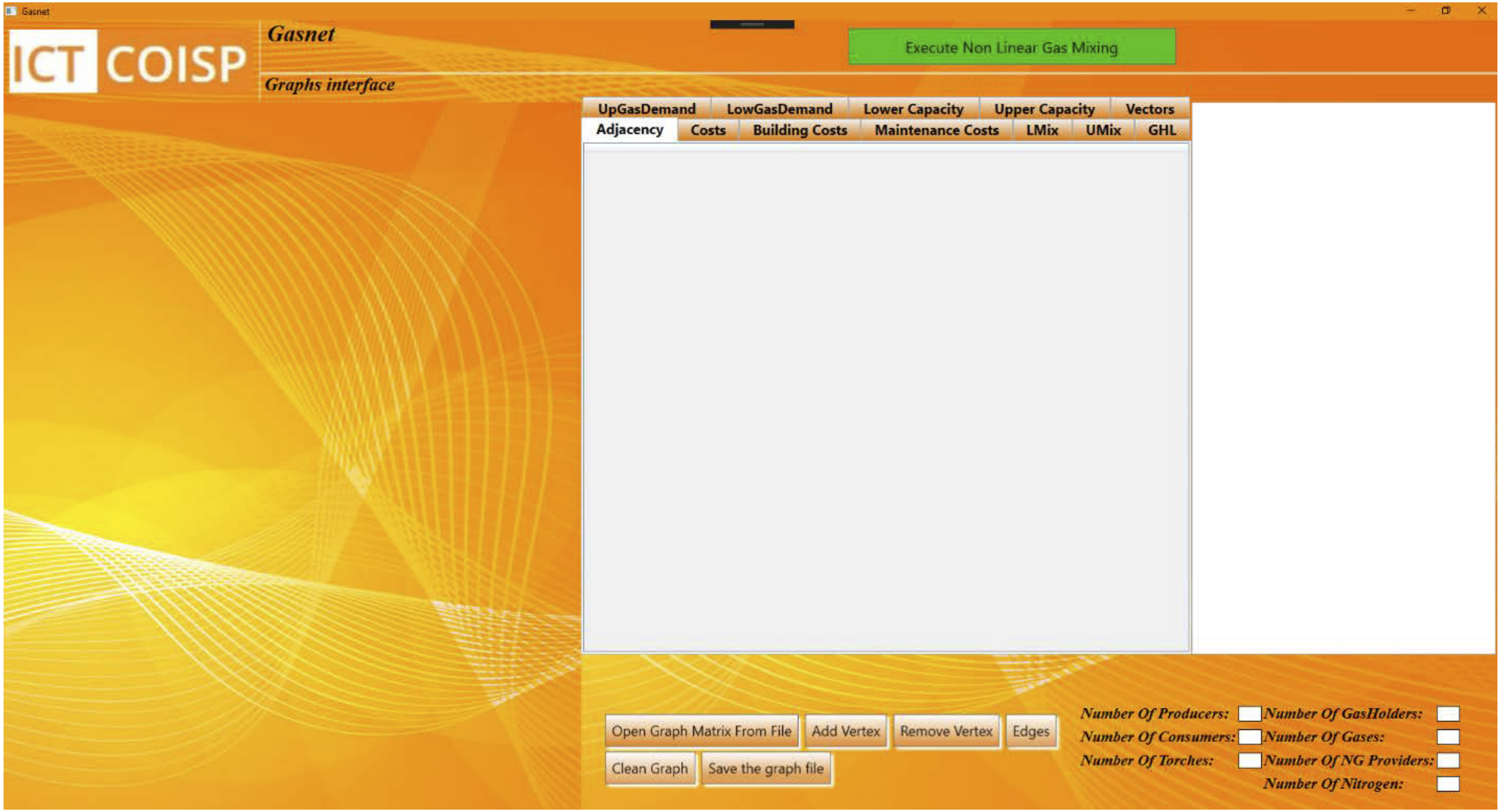

Figure A.6: main window of the off-line network optimization tool

Other tabs, which are included in ten matrices, must be filled by the user. Among the proposed matrices, five matrices (*Lower Capacity* and *Upper Capacity*, *Building Cost*, *Maintenance Costs* and *Costs*) refer to properties or costs associated to the edges connecting the different couples of nodes (or vertices) of the network. **Figure A.7** present an example of a compiled Upper Capacity matrix.

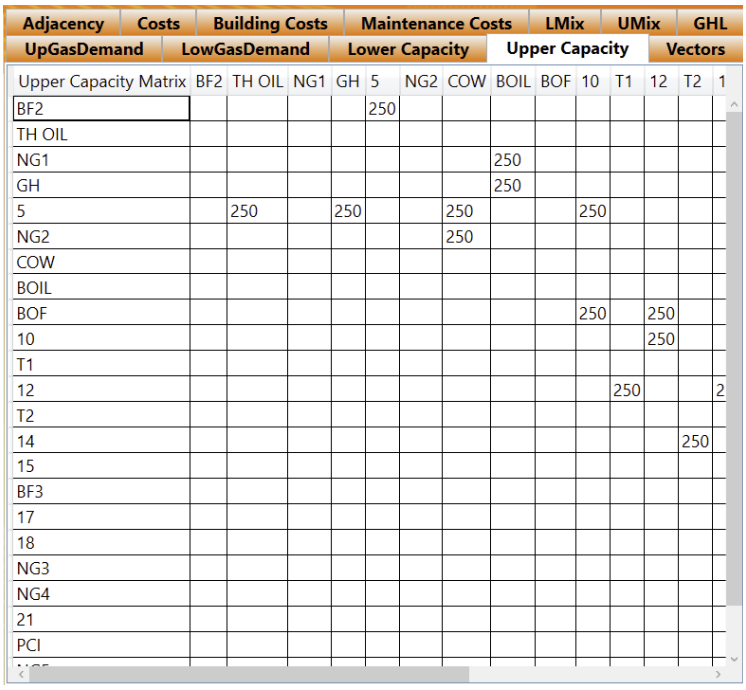

Figure A.7: Example of compiled Upper Capacity matrix

Other five matrices (*Lmix*, *UMix*, *LowerGasDemand*, *UGasDemand* and *GHL*) allow setting to the properties of the *g-th* gas that can flow through the *i-th* node (or vertex) of the network.
In order to save the data that have been input within the previously depicted matrices, the used must click on the button entitled *"Save the graph file"*. So doing, all the excel files containing the network data will pop up and can be saved.
After all the network parameters are set, in order to run the simulation, the user must click on the green button entitled *"Execute Non Linear Gas Mixing"*, which is located in the top of the main window The solver performs optimization of a Mixed Non-Linear Integer Programming (MINLP) according to what discussed in **Section 5.4**. The searched solution is a vector of real and binary variables. The real variables represent the flow of gas between pipes, while the binary variables represent the activation of a pipe.
The calculation of the solution can require some time to be executed. The duration of the computation can vary depending on the size of the network and, particularly, on the number of pipes inspected for construction/demolition, namely the number of nonzero entries in the matrix *Building Costs*. The time needed varies approximatively from a couple of minutes to one hour. The solution is displayed in the main window, such as depicted in **Figure A.8**.
On the left part of the screen, the graph of the network is shown: the amount of each gas type flowing in a pipe is displayed on the corresponding arc. For instance, in the exemplar case considered in Figure 23, 20 Nm^3 of BF gas (Gas1) and 43.56 Nm^3 of Natural gas (Gas4) are flowing from Node 21 to the Power plant (Node 24).
The possibility is also provided to load an existing network, instead of creating it from scratch. To this aim, the following steps must be followed by the user:

1. To fill the boxes in the bottom right area: Number of Gas Holders; Number of Producers; Number of NG providers; Number of Consumers; Number of Gases; Number of Torches; Number of Nitrogen.
2. To click on "Open Graph Matrix" from the "File" button and select the file .gph containing the network structure.
3. To load the excel files containing the matrices Costs, GHLmatrix, LMix, LowerMatrix, LowGasDemandMatrix, UMix, UpperGasDemandMatrix, UpperMatrix, BuildingCosts, MaintenanceCosts, and the excel file containing the vectors.
4. Once loading is complete, to click the button "Execute Non Linear Gas Mixing" and wait for the solution to be displayed.

For detailed instructions on how to use and exploit both the on-line and the off-line optimization modules, please refer to the User manual of the integrated simulation and decision support tool, which represents **Deliverable 6.4** and has been uploaded as a separate file on the CIRCABC.

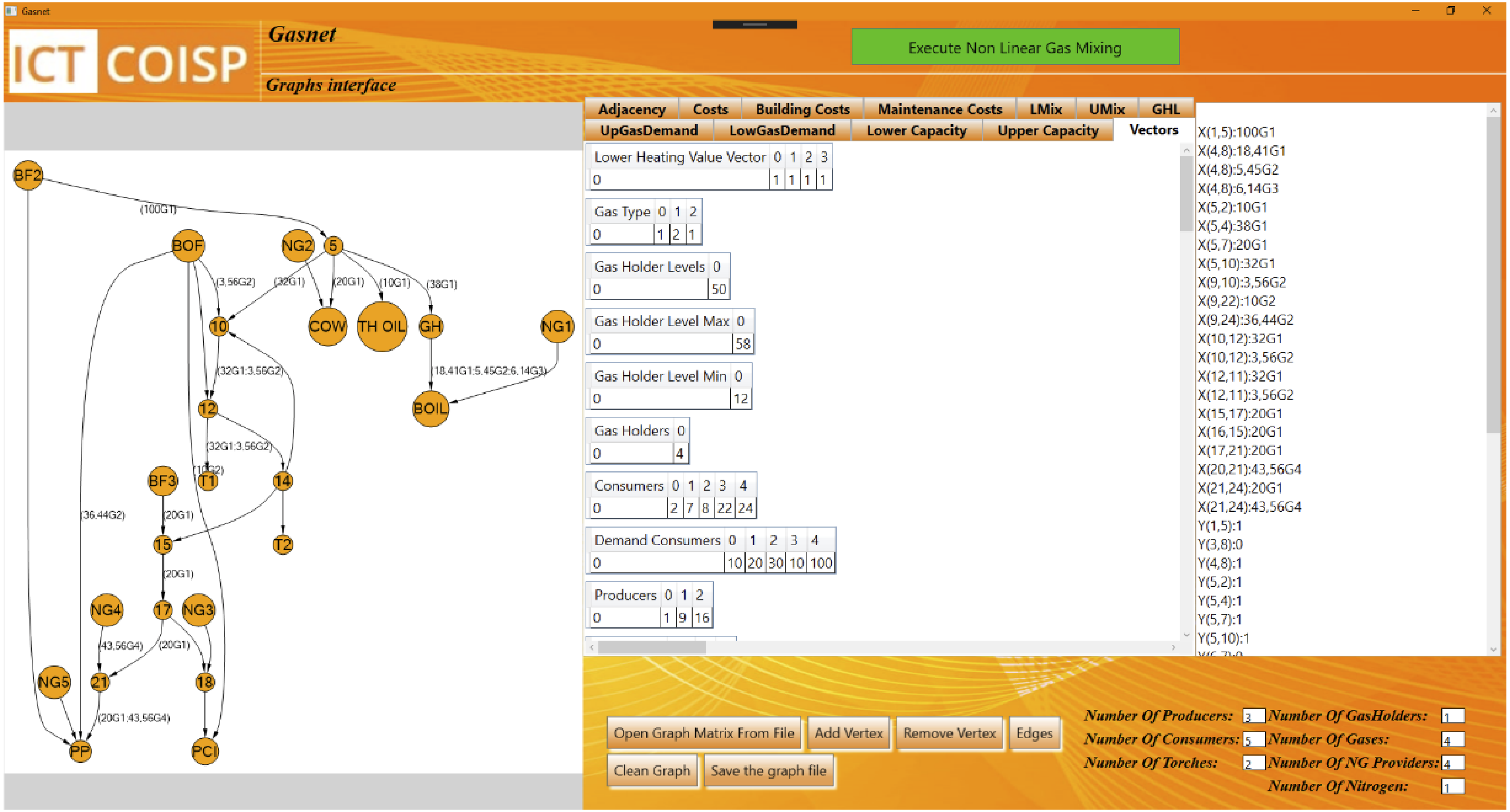

Figure A.8: presentation of the solution on the main window

9.2 D6.3 Guidelines for exploitation for the exploitation of the integrated DSS

One of the main ambitions of the EU policy is the environmental protection that is directly linked with more specific objectives such as the reduction of greenhouse gas, pollution and primary raw material exploitations or increase of energy and resource efficiencies. An adequate analysis, monitoring and management of the gas networks inside the steelworks can help reaching these ambitions, as process off-gases are valuable by-product whose optimal exploitation and distribution can lead to significant environmental and economic advantages.
The GASNET decision support tool is an instrument that has been conceived in order to address the previously described issues and it has been structured and developed in order to be tailored and applied in different integrated steelworks. In effects, different situations could be addressed, which are directly related to the degree of technological advancement of a steelworks, such as, for instance, the layout of the existing gas network, the amount of monitoring points, the structure of the actual industrial database and control system and also to the regulation constraints.
For these reasons, some general guidelines can help exploiting the GASNET decision support tool in the most efficient way.

1. **Preliminary analysis of steelworks gas network**

Preliminarily to the GASNET tool tailoring and installation, it is fundamental to pursue a deep analysis of the steelworks gas network in terms of layout, involved units as well as actual monitoring and management procedures. So doing, eventual bottlenecks and critical issues can be identified and deeply understood together with their correlation to the actual production plan. Moreover, the real needs for the considered steelworks can be identified. This is a fundamental step in order to fully understand how the GASNET tool can be adapted for the specific case.

2. **Definition of priorities**

A further step is represented by the definition of priorities to the identified, issues to be solved or improvements to be reached. Following the identification of such priorities a gradual application and adaptation of the different components of the GASNET tool can be developed by avoiding misleading or confused procedures that can lead to less accurate results and lower advantages.

3. **Exploitation of off-line gas and steam network optimization tool**

The first analyses can be assisted by the exploitation of the off-line gas and steam network optimization tool. Such tool allows the simulation and optimization of actual gas and steam networks after the insertion of some input that are own of the network to be simulated (see GASNET manual) and the definition of constraints and costs to be considered in the non-linear optimization. The results give a stationary optimized distribution of gas (or steam) inside the network or suggest layout modifications (i.e. pipe dismantling or construiction) allowing improvements of the gas management. Such results can be exploited to get a better insight of the possible improvements as well as to refine the list of priorities.

4. **Installation of new measurement devices**

The analysis of the network and the definition of priorities allow deciding if new measurement devices are needed in order to achieve the target. In the affirmative case, ideally such new devices should be installed before the definition of the dedicated GASNET DB.

5. **Definition or adaptation of industrial database and start of GASNET server**

After all the previous steps have been accomplished, all the main aspects affecting the optimal management of the actual gas networks have been identified and a priority-driven ranking of the action has been defined. Therefore, the first step for the deployment of the GASNET tool and its online usage can be performed, which is represented by the definition of a database or the adaptation of the existing one by following the indications provided by the GASNET tool developers in order to provide the required data to the different packages of the software. Before the use of the online mode of the GASNET tool, the GASNET server needs to be installed and run (see the GASNET tool manual).

6. **Start using the KPI module**

The KPI module can be directly used and a first easy monitoring of the current situation of gas networks management can be obtained, while further information can be collected in order to improve the definition of priorities and to decide which part of the network need to be simulated fol allowing an online optimization.

7. **Development or adaptation of simulation and forecasting models and start of online simulations**

Firstly, it is necessary to define two main categories of process models: the former one is related to the process and transformation equipment (such as, power plant, steam boilers, gasholders, etc.) that can be directly manipulated within the online optimization strategy; the latter on is related to the processes that cannot be manipulated within the optimization (such as, BOFs, BF, etc.). The dynamics of manipulated processes have to be modeled through linear methodologies (e.g. State space models, linear ARX, linear correlations, etc). The dynamics of the nonmanipulated processes can be modelled through adequate accurate methodologies (also nonlinear ones). The right definition of units to be simulated, according to the previously defined priorities and to the available continuous data, is fundamental in order to avoid the overload of software resources and the decrease of the “answer time” or the development of inaccurate models. After this definition, some units can be modelled by adapting existing library models (e.g. through an *ad-hoc* tuning procedure) or can be *ad-hoc* developed by using the ESN modeler, which is included in the software (see the GASNET tool Manual). Furthermore, completely new models can also be added. However, in this case a direct interaction between users and GASNET software developers could be required. The deployment of the forecasting models can provide useful information about the behaviour of different units included in the network in the future according to the production plan. Such forecasting capability is fundamental both in terms of monitoring that for optimization purposes. All the results obtained from the models can be visualized by using the GASNET viewer (see the GASNET tool Manual).

8. Adaptation and start of online optimization

A further stage is the adaptation of the online optimization tool by including ad-hoc constraints and costs and deciding the network areas or units to be considered as manipulable. Each specific plant needs to be adequately modelled, in order to describe the main constraints in terms of gas and steam network connections, limits on the equipment, etc. The optimizer results are then shown in the viewer in terms also of obtainable advantages and can give setup values for optimal management and control of the gas network.

9. Improvement of tailoring of GASNET tool according to the defined priorities

Finally, the previous procedure can be repeated, especially considering the points 7 and 8 (but sometimes some DB modification could be necessary), and the tailoring of the GASNET tool can be improved and finalized considering the defined priorities.

The previously depicted guidelines are summarized in the diagram reported in **Figure A.9**.

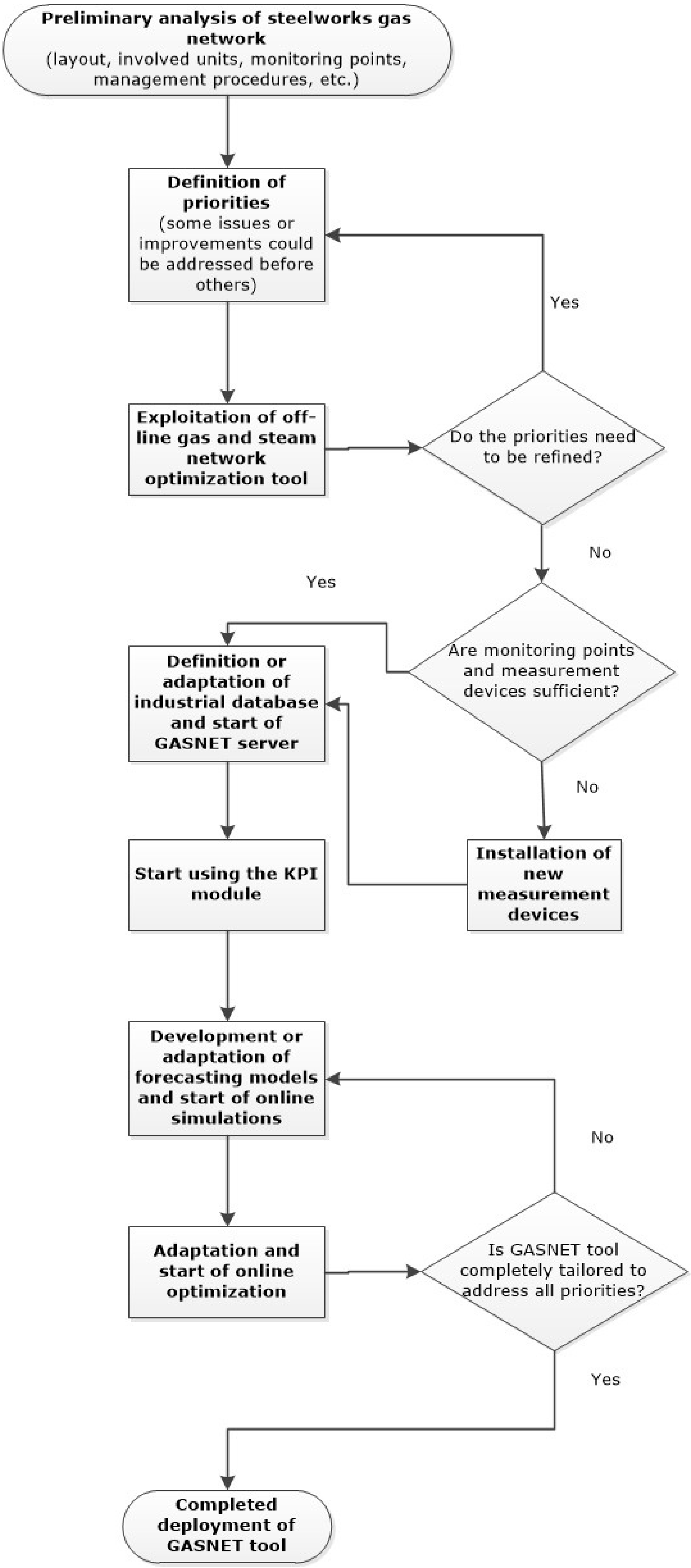

Figure A.9: GASNET guidelines Flowchart

9.3 D6.5 Dissemination material

A logo has been elaborated for the GasNet system, to be used in future communication and dissemination activities, which is depicted in **Figure A.10**.

Figure A.12: GasNet logo

Such logo is used as the icon of the off-line Gasnet optimization tool and it will be used for all the future communication activities.
Moreover, a flyer depicting the GasNet DSS has been prepared, which is separately uploaded on the CIRCABC. The flyer is organized in two pages and it is designed in order to be folded into three parts.

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The EU Open Data Portal (https://data.europa.eu/euodp/en/home) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

The project overall aim is to improve the management of process off-gases in integrated steelworks through a proper distribution and an appropriate use of these gases. This objective consists of the following major targets to be jointly reached:

- to forecast the off-gases production and the gas demand from various processes
- to meet the needing of the energy utilities of gas from the various processes (not only the productive ones, but also any facility for energy generation);
- to minimize the amount of gas that is burned in torch, to the aim of lowering the environmental impact of the integrated steelmaking route as well as the associated costs (i.e. the waste of a resource);
- to optimize the gas network inside the steelworks;
- to continuously monitor the energy and environmental performance of gas management system;
- to enhance the flexibility of the gas management system and its capability of an efficient-adaptation to processes scheduling variability.

In order to achieve the above listed ambitious objectives, the following targets have been achieved:

- investigation, at total site and individual process levels, of all the factors affecting off-gases management (such as process scheduling, gas behaviour inside the pipes, gas composition variability, etc...) and of the constraints and limitations to overcome;
- development of an easy-to-use and flexible decision support tool for simulating steelworks gas networks implementing multiple levels of optimization.
- testing of such system in order to assess its efficiency and general validity in a real industrial context as well as the possibility to transfer and further deploy its different modules throughout the European steelmaking industry.

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