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LABORATORY TESTS IN CYBER-PHYSICAL MODE FOR AN ENERGY MANAGEMENT SYSTEM INCLUDING RENEWABLE SOURCES AND INDUSTRIAL SYMBIOSIS

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ABSTRACT

The aim of this paper regards the laboratory validation of an energy management system (EMS) for an industrial site on the Eigerøy island (Norway). It will be the demonstration district in the ROBINSON project, for a consequent concept replication. This activity in cyber-physical mode is an innovative approach to finalize the EMS tool with real measurement data with prime movers available at laboratory level, considering the necessary EMS robustness and flexibility for replication on other industrial islands. This EMS was designed and developed to minimize variable costs, producing on/off and set-point signals that, through a Model Predictive Control (MPC) software, establish the system status. This smart grid includes renewable sources (e.g., solar panels, a wind turbine, and syngas) and traditional prime movers, such as a steam boiler for the industry needs. Moreover, an energy storage device is installed composed of an electrolyzer with a hydrogen pressure vessel.

The main results reported in this work regard 26-hour tests performed in cyber-physical mode thanks to the real-time interaction of hardware and software. So, a real microturbine and real photovoltaic panels were managed by the EMS in conjunction with software models for components not physically present in the laboratory. Although the optimization target was cost minimization, significant improvement was also obtained in terms of efficiency increase and CO_2 emission decrease.

Keywords: Renewable energy, intelligent control, plant integration, energy storage

NOMENCLATURE

AD	Anaerobic Digester
BES	BioElectrochemical System
CHP	Combined Heat and Power system
DLQR	Discrete Linear Quadratic Regulator
DMPC	Discrete Model Predictive Control
EL	Electrical
EMS	Energy Management System
EU	European Union
IES	Innovative Energy Systems
LNG	Liquefied Natural Gas
MPC	Model Predictive Control
O&M	Operation & Maintenance
PC	Personal Computer
PI	Proportional Integral controller
PV	PhotoVoltaic
RES	RenEwable Source
TH	Thermal
TRL	Technology Readiness Level
UDP	User Datagram Protocol
Variables	
a	plant inputs for the MPC
c	cost [€]
c_p, c_v	specific heats [J/(kg*K)]
E	Energy [J]
J	cost function [€]
k	Number of the component [-]
LHV	Low Heating Value [J/kg]
m	mass flow rate [kg/s]
M	mass [kg]
N_{st}	start-up number [-]
Nc	control horizon [-]
Np	prediction horizon [-]
p	pressure [Pa]
P	Power [W]
Q, R	weight matrixes for the MPC
r	set-points by the Decision maker [W]
Sell	Selling/buying ratio for electricity [-]
SP	Set-Point [W]
t	time [s]
T	Temperature [K]
u	set-points for the components [W]
x	system state in the MPC
y	measurements for the EMS [W]
η	efficiency [-]

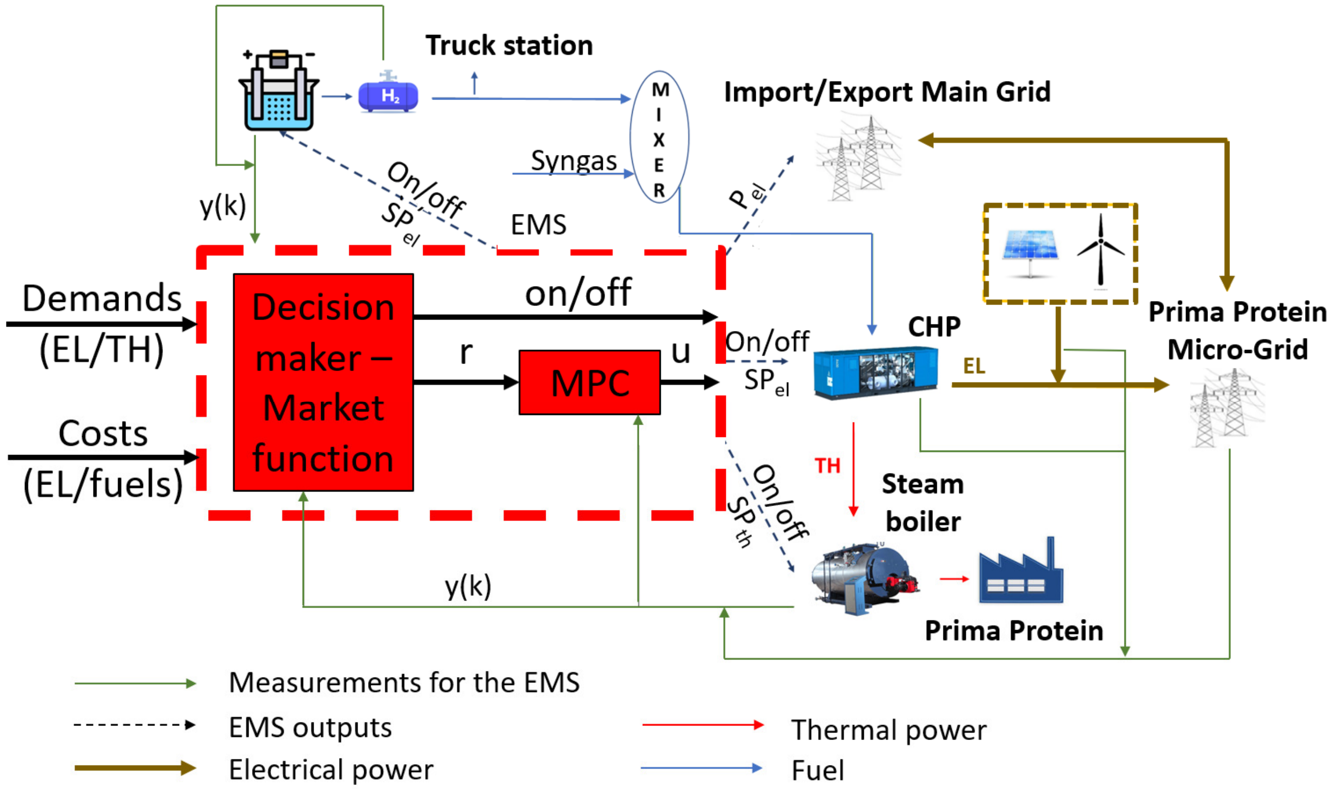

FIGURE 1: PLANT LAYOUT AND EMS INTEGRATION

Subscripts

amb	ambient
CHP	Combined Heat and Power
Electr	Electrolyzer
el	electrical
in	inlet
O&M	Operating and Maintenance
out	outlet
th	thermal

1. INTRODUCTION

The advanced integration of different energy systems and their optimization requires real-time software, which is usually called Energy Management System (EMS) [1]. Due to the ongoing and future energy transition aspects [2], this is also very important technology for integration with energy storage devices [3][4]. Although the smart grid optimization is performed in several literature studies [5][6], including different types of tools (e.g. genetic algorithms [7]) or different approaches (e.g. multi-level or multi-objective optimizations [8]), in a real field an EMS needs to be fast (real-time performance), flexible, and robust [9]. Moreover, since experimental validation is necessary before EMS application in real fields, the aim of this work is the innovative application of laboratory tests based on a cyber-physical approach. These needs are essential for industrialized districts on islands, such as for the scenarios analyzed in the EU H2020 ROBINSON project [10]. In detail, attention is focused on the smart grid for an industrialized district on the Eigerøy island (Norway), where the energy demands from the Prima Protein company (electricity and heat in the form of steam for obtaining fish products) are coupled with electricity needs of residential buildings and hydrogen demand for truck charging operations [10].

Starting from the development and validation of component models and the implementation of an EMS able to operate in real-time mode to manage energy storage systems (compressed hydrogen), attention is focused here on the EMS validation. Considering the simulation results presented and discussed in a previous study [9], which show the benefits due to the innovative integration with Model Predictive Control (MPC) technology, experimental tests in cyber-physical mode were established. The activity was performed in the Innovative Energy Systems laboratory at the University of Genoa. Since it is not possible to have all the components at laboratory level and an experimental validation is necessary before proposing the EMS for the demonstration site (on the Eigerøy island), a cyber-physical approach was considered. This experimental solution was based on the coupling of real components in the laboratory with real-time models. This is an effective approach, as demonstrated in previous studies [12][13][14], to have a validated EMS in a flexible environment (a laboratory). So, this approach reduced the risks and the development time in comparison with a direct application of the EMS after the simulations.

The main innovation of this paper regards the application of a cyber-physical approach for polygenerative grids, as an important validation bench for the proposed EMS. It is an important and innovative step to increase the EMS robustness, removing bugs and instability problems before operations at the real sites. Moreover, the positive results obtained in this study could propose this method for further smart grid systems, as planned in the ROBINSON project for concept replication [10]. In detail, the concept replication for industrial districts was already analyzed at both simulation and experimental levels in sites located in the Western Islands (UK) and in Crete (GR). While the simulation results for these replication activities are available in [11], the tests in cyber-physical mode for the Western Islands and Crete will be available soon on the project web site [10]. In detail, thanks to simulations reported in [11], the EMS application showed significant cost decrease: -33.3% for the Western Islands and -9.4% for Crete. The results demonstrated the potential benefits and the long-term impact related to large-scale application of the concept proposed and developed in the ROBINSON project. Moreover, due to layout and component size changes, this innovative cyber-physical approach, proposed here for the Eigerøy case, is also important for the EMS validation in replication cases. So, this proposed method will be an essential intermediate step for an easy EMS validation before performing operations at real sites (for further long-term application of the ROBINSON approach and results).

2. PLANT AND EMS LAYOUTS

This section regards the presentation of the smart grid plant layout, the component size on the basis of previous choices performed on the Eigerøy island, and the EMS layout and details.

2.1 Smart grid layout

The smart grid layout is shown in Fig.1. It includes: (1) a 400 kW (electrical power) gas turbine (the A400 machine [15]) fed by a fuel mixture (about 70% syngas, and 30% hydrogen in percentage terms), (2) a 22 MW (thermal power) boiler for steam production fed by LNG, (3) two 500 kW electrolyzers (the power refers to electrical consumption), (4) a wood gasifier based on local resources to produce the 70% (in volume) of the turbine fuel, (5) a 100 kW size wind generator, and (6) 5.8 kWp photovoltaic (PV) panels.

The grid is also equipped with a hydrogen pressure vessel (40 m^3) for energy storage, and a gas mixer to produce the fuel for the microturbine. As shown in Fig.1, the turbine (named CHP for the generation of both electricity and thermal power) pre-heats the water (high temperature liquid water) upstream of the steam generation, as a thermal input for the boiler. The gasifier is not shown in Fig.1 because it is operated by internal control systems to maintain the related internal buffer pressurization. So, it is not controlled by the EMS because it has very slow response performance (it cannot follow the load changes of the grid components). Although the ROBINSON project also includes an AD-BES to mix biogas in the turbine fuel, this system and the biogas line are not included in Fig.1 because they are negligible from the EMS point of view (Eigerøy island case).

The component sizes were not calculated using an optimization process because the activity reported in this paper started from already installed components or decisions based on specific site needs. So, the boiler (already installed at the Eigerøy district) was chosen to satisfy the Prima Protein needs (thermal power for steam generation), the CHP turbine and the wind power generator were sized to provide electricity for an average site demand. Moreover, the electrolyzers were sized considering commercial devices available and to have a 6-hour safety margin to operate the A400 at its maximum load. Finally, the hydrogen pressure vessel was defined on the basis of the available space and to ensure 12 hours of continuous autonomous operation for the A400 machine considering the hydrogen need of 30% (in volume) [9].

2.2 EMS layout

As already described in [9], the EMS is not a tool for scenario optimization with the availability of all the input data, but it needs to be a tool able to operate in real-time mode. This means that the demand values are the actual inputs from the field, not known in advance, but second by second (the general software time step). Considering this aspect, the EMS was designed coupling an optimization with the scheduling of the hydrogen storage system. This approach for the hydrogen vessel is necessary because the demands are not known before the operations (as in several previous works). However, considering electricity costs forecasted on the basis of the previous day, it is possible to implement the management of this component. The entire tool (the EMS plus the models of components not available in the laboratory) runs in MATLAB-Simulink with a 1-second general time step. Since the tool simulates 1 real second in a time shorter than 1 second using a standard PC, real-time performance is obtained activating the “pacing” function in the Simulink window.

TABLE 1: CONSTRAINTS OF THE OPTIMIZATION TOOL

Parameter	Min value	Max Value	Unit
CHP EL Power	70	400	kW
Grid EL Power	-2000	2000	kW
Boiler TH Power	2200	22000	kW

The EMS is composed of two blocks, as shown in Fig.1: a Decision maker (including the Market function) and a Model Predictive Control (MPC) software. The Decision maker performs the minimization of the cost function (Eq.1), with a 15-minute time step, to calculate the values of preliminary set points (r in Fig.1). The time step change (from the general to the optimizer) is obtained using the Simulink rate transition components. As reported in [9], the optimization is based on a constrained, non-linear algorithm (the “patternsearch” function from MATLAB) that minimizes the variable costs including fuel (Eq.2), electricity and Operating and Maintenance (O&M) costs. The decision variables are: the electrical power set-point values for the CHP and the amount exchanged with the grid (including the possibility of decreasing the selling cost in comparison with the buying costs, as in Eq.3). The constraints are the electrical

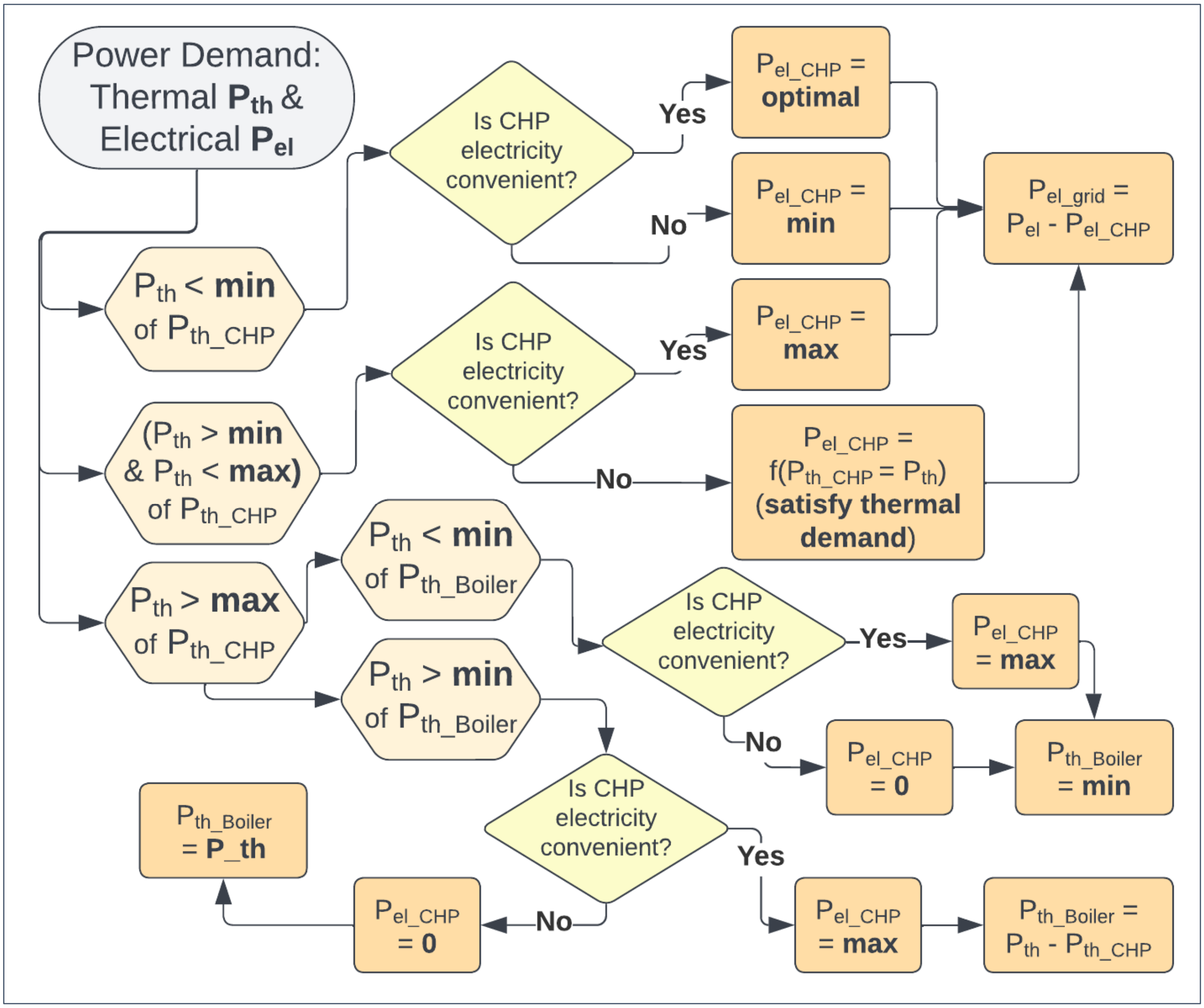

FIGURE 2: FLOWCHART OF THE EMS LOGIC

balance equation (the missing electrical power or its excess is the power exchanged with the grid) and the minimum/maximum ranges reported in Table 1.

Moreover, three cases were implemented from the thermal generation point of view (Fig.2): (a) thermal demand lower than the CHP minimum, (b) intermediate condition, (c) thermal demand higher than the CHP maximum thermal generation. For all three cases, two options are included: if the electrical generation is profitable, the turbine is managed at its optimal condition (usually at its maximum), in the opposite case the CHP is operated at its minimum load (for case a), to supply the thermal power needs (case b) or switched off (case c) [9].

$$J_{cost} = (c_{el} + c_{O\&M}) \cdot P_{el_{grid}} + c_{fuel_{CHP}} \cdot m_{fuel_{CHP}} + c_{st} \cdot N_{st} \quad (1)$$

$$m_{fuel_{CHP}} = f\left(P_{el_{CHP}}, LHV_{CHP}, \eta_{CHP}, T_{amb}\right) \quad (2)$$

$$c_{el} = \begin{cases} c_{el} & if\ P_{el_{grid}} > 0 \\ c_{el} * Sell & if\ P_{el_{grid}} < 0 \end{cases} \quad (3)$$

The second tool is a controller that includes predictive technology for the calculation of the actual component set-points. Since the components have their own control systems, the EMS produces only the on/off signals and the set-point values. The control operations on the internal components (e.g. actuation of the fuel valves) is performed by the specific commercial controllers of each device. This is an important approach, already considered in previous studies, taking into account the different dynamic response performance of the devices (e.g. the difference between the CHP fast electrical response with the long time necessary for the boiler dynamics). This is an MPC tool that was developed on the basis of the procedure by Wang [16]. An initialization defines the time window for the prediction horizon (N_P = 40 steps) and the control horizon (N_C = 1 step). This MPC was developed with information related to the components (the CHP and the steam boiler), using a linearized state-space representation. So, the architecture of this MPC includes the following functions: one regards the discrete model predictive control (DMPC) and the second one regards the observer [16]. The model (for control implementation) uses an augmented state-space approach, i.e. Non-Minimal State Space [16]. The observer estimates the state of the system that is provided to the DMPC dynamic software. The MPC integration is performed with the Laguerre network (to simplify computations with tunable parameters). One of the MPC advantages regards the possibility of response tuning operating on weights associated with control variables. In this work, cost function is based on Discrete Linear Quadratic Regulator (DLQR) architectures, as in Eq.4. The tool includes the following elements: Q and R are weight matrices, x is the state of the system, and a is the control signal. The DMPC algorithm includes constraints on plant inputs (a) and their rate of change Δa.

$$J = \frac{1}{2}x^T Q x + a^T R a \quad (4)$$

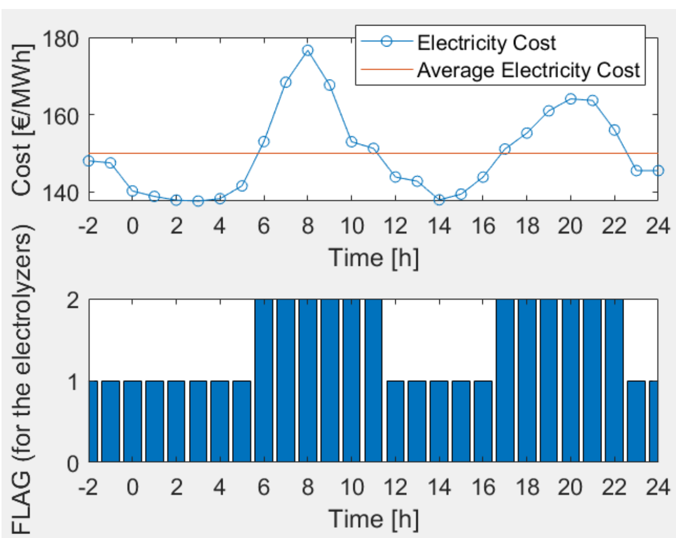

FIGURE 3: ELECTRICITY COSTS CONSIDERED IN THIS ARTICLE AND FLAGS FOR THE MANAGEMENT OF THE ELECTROLYZERS

In agreement with the issues mentioned to manage a storage device in a real-time environment, the electrolyzers are operated at maximum load when the electricity has a price lower than the average value (FLAG = 1 in Fig.3). On the other hand (FLAG = 2 in Fig.3), they are operated by a devoted controller in the opposite case, with a pressure set-point at its minimum value. In this case, the target pressures for the hydrogen vessel were: 40 bar (in case of low electricity price) or 22 bar (in case of high electricity price). These values were defined to obtain a good compromise between the necessity to avoid overpressure conditions and to provide a good margin for energy safety. They are not definitive for the real application, but represent reasonable values.

3. TEST RIG AND EXPERIMENTAL APPROACH

To validate the EMS with real interactions with hardware components, as planned in the ROBINSON project [10], attention was focused on laboratory activities. This is an important step to check the EMS behavior in terms of stability and performance with data coming from a real environment.

3.1 Test rig

The experimental plant is a test bench installed in previous activities in the Innovative Energy Systems (IES) laboratory at the University of Genoa [17]. This is a local grid including the following generation devices: a T100 gas turbine in CHP mode, a 20 kW heat pump, thermal solar panels (10 kWp), photovoltaic panels (1.1 kWp), an absorption chiller, two thermal energy storage tanks for hot water (5 m^3 for each device), a thermal grid based on two distribution ducts and equipped with fan coolers (local thermal load generation), and an electrical grid connection. Since in this work attention regarded the Eigerøy site, the tests were carried out using only the following laboratory components: (a) the T100 turbine, (b) the PV panels, (c) the connection to the electrical grid, and (d) the thermal grid.

3.2 Tests in cyber-physical mode

Due to the fact that the laboratory is not equipped with all the components of the Eigerøy site, the tests reported in this work were carried out in cyber-physical mode. This means that software and hardware operated connected, communicating in real-time mode. This allows one to introduce experimental aspects (e.g. typical measurement oscillations), avoiding additional costs and risks related to the planned application at the real site. This cyber-physical mode was important to produce experimental results for the EMS validation and possible improvements (if necessary). The software/hardware interaction is reported in Fig.4. The software input data are four measurements: electrical power from the T100 generation (affected by ±1% accuracy), thermal power from the turbine generation (affected by ±3% accuracy), fuel mass flow consumed by the turbine (affected by ±1% accuracy), and power value generated by the PV panels (affected by ±1% accuracy). To complete the cyber-physical approach, the hardware input data are two values calculated by the software in real-time mode: turbine on-off (activation) signal and its set-point values (electrical power). Due to the different sizes of the components, a data conversion system was implemented to use the T100 turbine for tests related to a 400 kW turbine. In detail, the size ratio between the two machines was used in the conversion gains for the electrical values. Moreover, the measured thermal power from the T100 was multiplied by the ratio between the design thermal power of both devices. The PV panels also included a re-scaling due to a different amount of PV area available in the laboratory, in comparison with what is installed at the Eigerøy site. So, the measured power was multiplied by a scaling factor (the ratio between the panel areas in the Eigerøy and the laboratory sites).

In conclusion, the cyber-physical approach proposed and used in this study does not include complex tools, but a direct real-time communication between the EMS (and the rest of the software) and the laboratory hardware. Depending on the smart grid layout and the available devices at laboratory level, the connection with other hardware is simple. Due to the necessity to have real-time interaction, the hardware/software communication is obtained with UDP channels based on the available components in Simulink and in the laboratory data acquisition software (LabVIEW).

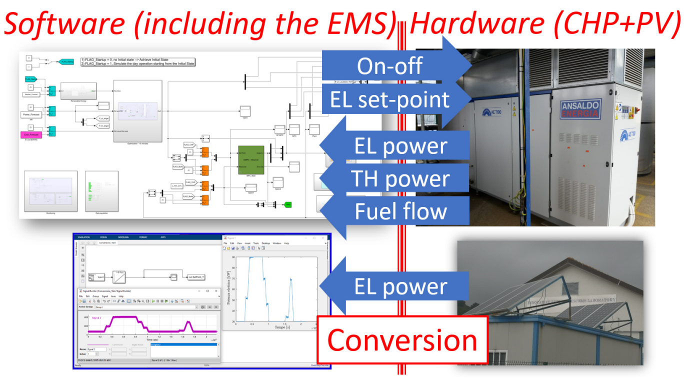

FIGURE 4: HARDWARE/SOFTWARE COMMUNICATION FOR THE CYBER-PHYSICAL APPROACH

3.3 Component models

For the tests performed in this study, detailed tools were not necessary because the EMS needed just the global performance values (e.g., electrical and thermal power). So, the boiler, the wind turbine, and the electrolyzers were modeled with black-box solutions including design, off-design and dynamic calculations. In detail, the time-dependent behavior was calculated including dead-time and first-order delay tools on the basis of manufacturers' data or literature information. This is a good compromise between fast calculation performance and reasonable accuracy.

The wind turbine model was based on the performance curve from the manufacturer. The model received the wind speed in real-time mode and calculated the electrical power generated.

For the electrolyzers the simulation was performed with two models including part-load performance curves and dynamic behavior from literature data [11]. In detail, the dynamic response of these components was calculated with first order delay, as confirmed by the manufacturer.

Specific attention was necessary for the hydrogen storage vessel and the fuel mixer. To use a physical-based dynamic approach (mainly continuity and energy equations in dynamic conditions – Eqs.5 and 6), the TRANSEO tool models were used [20]. Moreover, the adiabatic plenum concept was integrated with the 0-D approach for heat exchanges, as previously developed and validated in TRANSEO for the component named "pipe" [20]. These tools also calculate the outlet composition (and the related properties), using mass balances for each mixture component and a thermodynamic library of functions for the other properties, such as the specific heat of the mixture. For instance, in [26] the pressurization time was correctly calculated using the TRANSEO pressure vessel (the results were in good agreement with the data measured). Moreover, in [21] the composition management (the same approach used here) showed results matching the experimental data well.

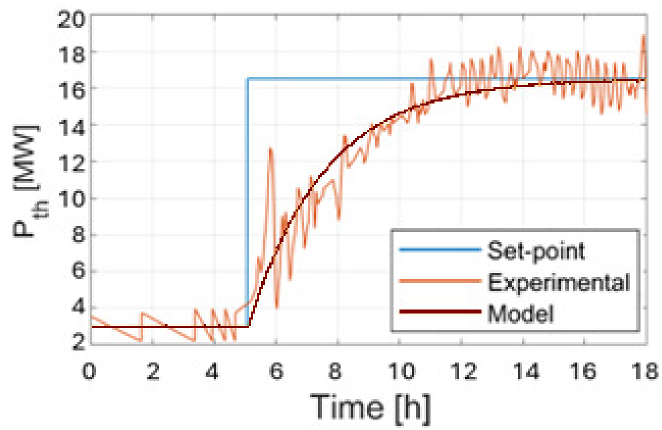

FIGURE 5: BOILER MODEL VALIDATION

$$\frac{dM}{dt} = \sum m_{in} - \sum m_{out} \tag{5}$$

$$\frac{d(M \cdot T_{out})}{dt} = \frac{c_{p\_out}}{c_v}\left[\sum (m_{in} \cdot T_{in}) - \sum (m_{out} \cdot T_{out})\right] \tag{6}$$

Finally, it is important to mention that the real-time models used in this work (for components not available in the laboratory) were fully validated in a previous study [9] against experimental data or considering literature information (e.g. in [19]).

The boiler model was validated against experimental data provided by Prima Protein (Fig.5) with ±3% accuracy, considering a set-point step from 3 MW to 16.5 MW. The model was able to reproduce the general dynamic trend of the proposed data with good agreement. Since no experimental data are available for the hydrogen pressure vessel or for the mixer, the related models are considered validated on the basis of the results obtained in previous studies (e.g. in [20] where good agreement was obtained between a dynamic model including pressure vessels and experimental measurements).

4. RESULTS AND DISCUSSION

In spite of the long duration of the experimental tests (26 hours plus the start-up/shutdown phases), two different 26-hour tests were performed in the laboratory. It is important to highlight that the results reported here were obtained after preliminary tests that highlighted the necessity to stabilize the tool better. So, this showed the importance of tests because, although the EMS was stable in just simulation mode [9], oscillations coming from measurements required improvements to have stable behavior.

Due to a completely different behavior depending on the syngas cost values, these results were performed considering two cases for the cost of syngas produced by the gasifier: €80/MWh and €5/MWh. Since no real data are available at this development stage of the activity, two different opposite values were considered. While the €5/MWh case is close to realistic values, the opposite situation was considered with high cost condition. The high cost case (€80/MWh) generated special interest in the laboratory test because this condition produced load changes in the CHP, while a low syngas cost moved the optimizer to maintain the CHP at maximum, exploiting the benefits in selling electrical energy. As performed in [9], in both syngas cost conditions, the results obtained with the EMS were compared with the related "No EMS" case. This reference was obtained with simulations considering a simple approach that did not require any intelligence or optimization. So, in the "No EMS" curves: the CHP was operated to satisfy the missing electrical demand (electricity demand minus the production by the RES that was significantly present mainly due to wind turbine operations in the late afternoon hours), the boiler was controlled through a Proportional-Integral (PI) tool to produce the missing thermal power (Fig.6), and the electrolyzers were maintained at the minimum load for the entire test. It is important to highlight that, instead of using the thermal demand directly as boiler set-point, the PI in Fig.6 was included to properly consider the slow boiler response performance. Since there are no specific results or simulations for a reference case (or cases), this approach was chosen to have something simple and reasonable considering the necessity to satisfy the demands.

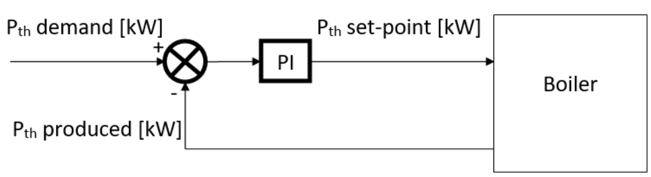

FIGURE 6: PI TOOL FOR THE BOILER SET-POINT CALCULATION IN THE "NO EMS" CASES

Finally, it is important to highlight that for all cases reported in the paper the selling/buying ratio was equal to 1 because, due to the preliminary condition of the Eigerøy site, no data are available for this aspect at the current development stage. Moreover, the following syngas composition was used: 3% CH_4, 44% N_2, 12% CO_2, 20% CO and 21% H_2. These values were chosen on the basis of typical syngas flows produced from wood gasification, because site data on this are not available at the current development stage.

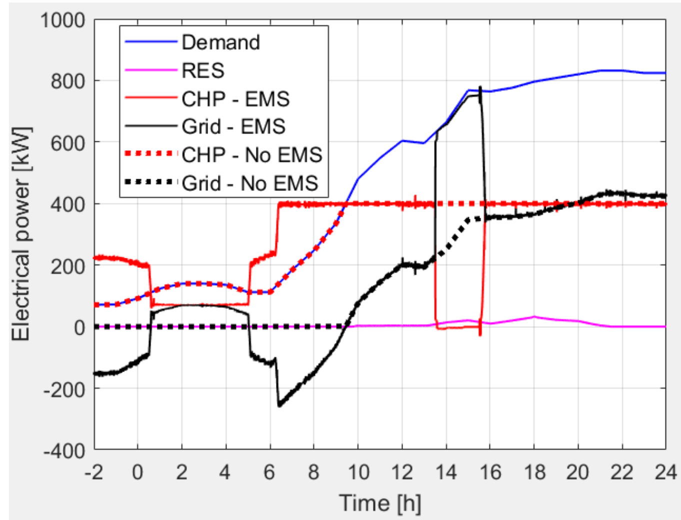

FIGURE 7: ELECTRICAL POWER COMPARISON (EMS VERSUS NO EMS CASES) FOR THE €80/MWh SYNGAS COST

3.1 €80/MWh syngas cost

The €80/MWh case for the syngas cost was chosen because, in the 26 hours, this produced different conditions: situations when it was profitable to reduce or switch off the CHP due to low electricity price to sell and conditions that moved the EMS to operate the CHP at maximum load (to produce earnings from electricity selling to the grid). In detail, this aspect is clear in Fig.7 for electrical power management. While in the "No EMS" case the CHP followed the demand trend and the missing power was provided by the grid, the EMS decided to maintain the CHP at low load when electricity selling was not profitable and increased the load at high electricity costs. Moreover, when the electricity selling was not profitable and the boiler was active (close to the hour number 14 in Fig.7) the CHP was switched off (a minimum negative power regarded the ventilation or the start-up consumptions of the CHP).

From the thermal generation point of view, Fig.8 shows that the boiler was activated when the thermal demand started to be significant and higher than the maximum thermal generation by the CHP. While the predictive performance of the MPC was able to properly manage the boiler to cover the thermal demand, the PI tool produced significant oscillations with missing or excessive power situations. Due to the PI-based approach in the "No EMS" case and the slow boiler response, following the boiler activation there are zones with excessive thermal generation because the PI tried to increase the set-point to compensate the error. Although this additional generation is nullified in long-term operations, the error in load change following highlighted the importance of the MPC tool. The gap between the demand and the boiler generation was the thermal power produced by the CHP. So, a demand-boiler matching was present when the CHP was switched off.

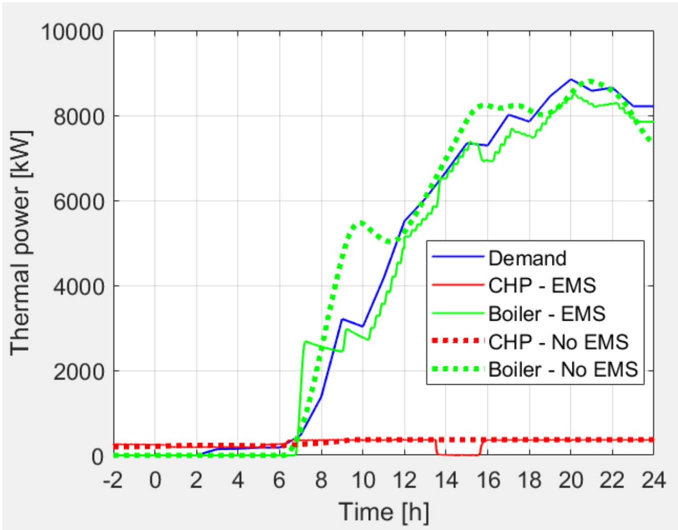

FIGURE 8: THERMAL POWER COMPARISON (EMS VERSUS NO EMS CASES) FOR THE €80/MWh SYNGAS COST

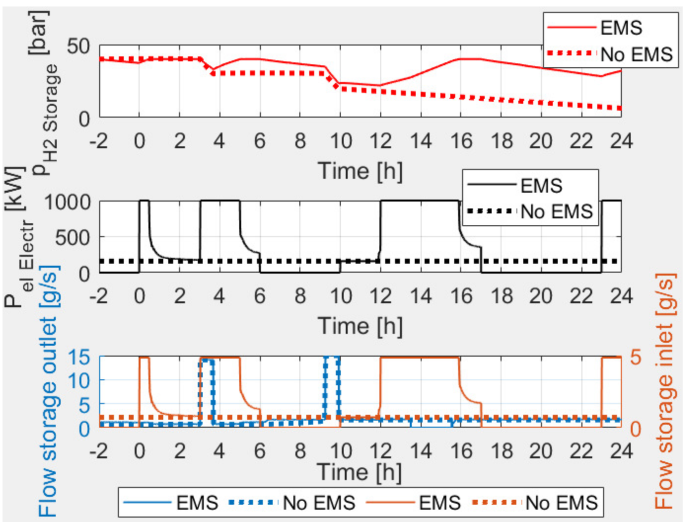

FIGURE 9: COMPARISON (EMS VERSUS NO EMS CASES) FOR THE HYDROGEN GENERATION, STORAGE AND UTILIZATION (€80/MWh SYNGAS COST)

For the hydrogen management side, Fig.9 shows the vessel pressure, the electrolyzer power and the inlet/outlet flows. While a base hydrogen consumption was present due to the CHP need, two truck charging phases of 13.3 g/s are visible (2,400 s duration in both cases). The initial charging operation was at 3:00 a.m. while the second one was at 9:15 a.m. Since no data are available for such hydrogen consumption because this will be related to future operations at the Eigerøy site, this could be representative of a typical consumption for large vehicles. Different operations could also be implemented in future studies considering statistic data.

The results reported in Fig.9 show that the EMS was able to manage the electrolyzers performing proper charging operations during the FLAG = 1 situations. So, the EMS was able to re-charge the hydrogen vessel obtaining a final pressure close to the initial one. On the other hand, a non-managed approach (e.g., the "No EMS" case) produced a final hydrogen tank pressure significantly lower than the initial one. Since this is linked with missing stored energy at the end of the period, this is taken into account in the result comparison section for the calculation of the global system performance.

3.2 €5/MWh syngas cost

This second case, although more realistic from a cost point of view, was less significant for laboratory operations because for the EMS it was always profitable to operate the CHP at maximum load to sell the possible electricity excess to the grid. So, while Fig.10 shows the same behavior as Fig.7 for the "No EMS" case, the application of the EMS tool produced a CHP behavior at 400 kW (electrical power) for the entire 26-hour test.

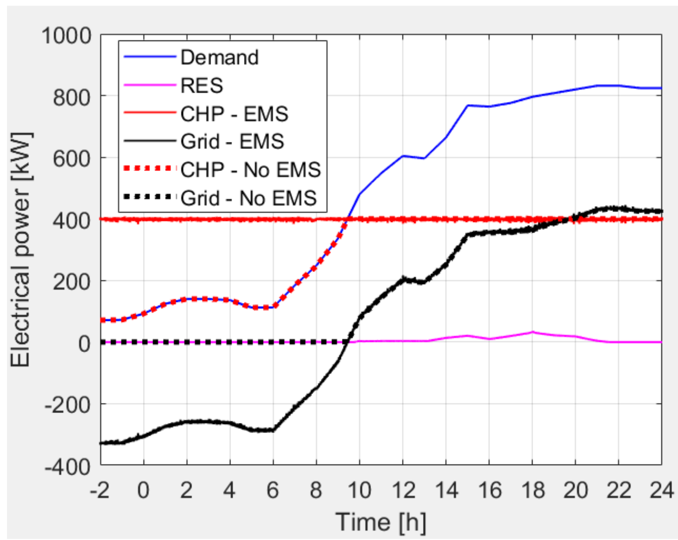

FIGURE 10: ELECTRICAL POWER COMPARISON (EMS VERSUS NO EMS CASES) FOR THE €5/MWh SYNGAS COST

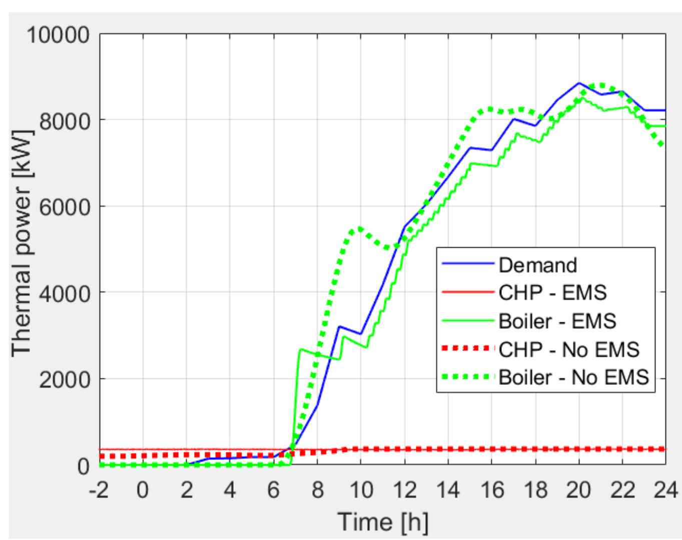

FIGURE 11: THERMAL POWER COMPARISON (EMS VERSUS NO EMS CASES) FOR THE €5/MWh SYNGAS COST

On the thermal side (Fig.11), this test with €5/MWh syngas cost produced a constant thermal generation at the CHP maximum. As in the previous case, the EMS was able to manage the boiler to properly cover the thermal power demand.

From the hydrogen management point of view, Fig.12 shows similar aspects to that presented and discussed for Fig.9. However, a constant outlet hydrogen flow is visible (except for the truck charging phases) due to the constant 400 kW set-point on the electrical side.

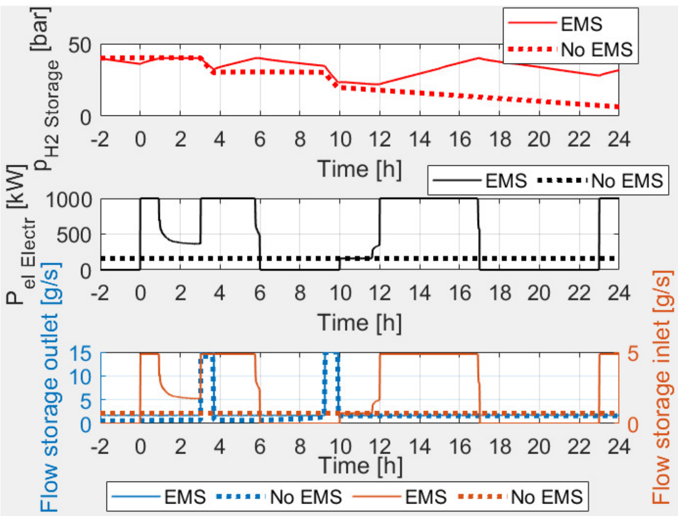

FIGURE 12: COMPARISON (EMS VERSUS NO EMS CASES) FOR THE HYDROGEN GENERATION, STORAGE AND UTILIZATION (€5/MWh SYNGAS COST)

3.3 Comparison of global parameters

To finalize the EMS validation in cyber-physical mode, a comparison of global parameters was performed for all 26 hours. The variable costs significantly decreased in comparison with the "No EMS" cases (Fig.13) due to the fact that the cost minimization is the objective chosen here. In Fig.13, it is important to include the two different costs of the "No EMS" cases due to different syngas costs. The bars for the €5/MWh case show, obviously, a lower global cost in comparison with the results obtained with €80/MWh in respective conditions. The cost decrease performance was significant due to the utilization of the EMS tool: -6.8% for the test with €80/MWh syngas cost and -8.3% for the €5/MWh case.

$$\eta_{el_{CHP}} = \frac{E_{el_{CHP}}}{E_{fuel_{CHP}}} \tag{7}$$

$$\eta_{el_{system}} = \frac{E_{el_{CHP}} + E_{H2_{users}} + \Delta E_{H2_{storage}}}{E_{fuel_{CHP}} + E_{el_{grid}}} \tag{8}$$

A second parameter discussed here and reported in Fig.14 is the electrical efficiency for the CHP alone and the integrated system (as defined in Eqs.7 and 8 respectively). The terms in Eqs.7 and 8 refer to total energy (produced, consumed or stored) for all 26 hours. In detail, the term $E_{H2users}$ is the energy (produced hydrogen mass for truck charging in the 26 hours per hydrogen LHV) and the term $\Delta E_{H2storage}$ is the energy difference in the hydrogen tank between the -2 hour and the 24 hour (it is positive in case of more hydrogen available at the end of the test in comparison with the beginning, and it is negative in the opposite case). For the CHP electrical efficiency, no benefits were obtained because it decreased (-7.6%) for the syngas cost value of €80/MWh (due to the fuel consumption during the restart phase) and the increase obtained for €5/MWh syngas cost was not significant (+0.9%). However, the benefits obtained for the system electrical efficiency were more important and significant: +13.6% for the €80/MWh syngas cost and +29.7% for the other case.

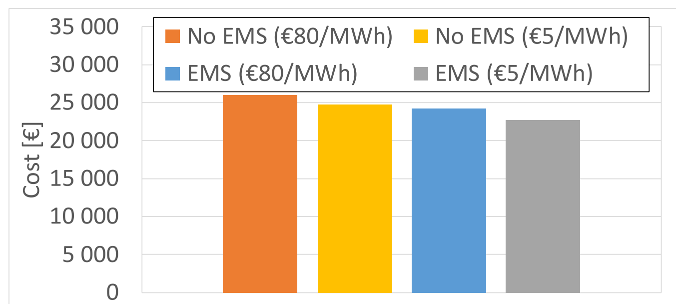

FIGURE 13: COMPARISON OF GLOBAL VARIABLE COSTS FOR THE CASES DISCUSSED IN THIS PAPER (FULL 26-HOUR DURATION)

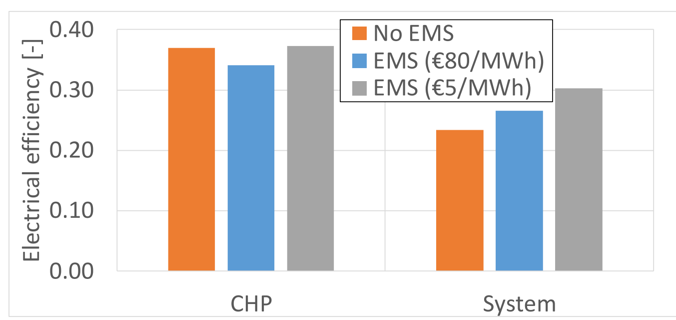

FIGURE 14: COMPARISON OF SYSTEM ELECTRICAL EFFICIENCY FOR THE CASES DISCUSSED IN THIS PAPER (FULL 26-HOUR DURATION)

Although not optimized by the EMS, it is also important to report the comparison of mass of CO_2 emitted for these 26-hour tests. The values reported in Fig.15 were calculated using Eq.9, as already presented in [9]. For these 26-hour tests, significant emission decrease was obtained with the EMS application:

-8.3% for the syngas cost equal to €80/MWh case and -8.9% for the second test.

$$M_{CO2_{system}} = M_{CO2_{boiler}} + M_{CO2_{electrolyzers}} + M_{CO2_{grid}} + \Delta M_{CO2_{H2\ storage}} \quad (9)$$

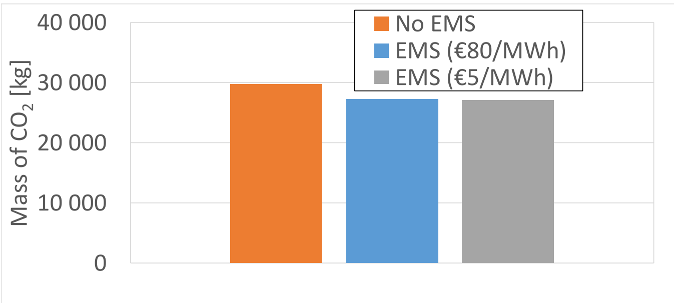

FIGURE 15: COMPARISON OF CO_2 EMISSIONS FOR THE CASES DISCUSSED IN THIS PAPER (FULL 26-HOUR DURATION)

5. CONCLUSION

The experimental results (in cyber-physical mode) obtained in this study validated the proposed EMS for polygeneration grid operations. Following the simulation results in [9], this experimental campaign was essential to confirm the software robustness and its performance considering Eigerøy island (the demo site for the ROBINSON project). So, this innovative approach for these kinds of smart grid applications was considered for two 26-hour tests producing the following performance results:

- Significant cost decrease (the objective of this optimization tool) for both syngas cost scenarios (-6.8% for €80/MWh and -8.3% for the €5/MWh case).
- The EMS also produced important system efficiency increase for the electrical side (as in Eq.8): +13.6% for the €80/MWh syngas cost and +29.7% for the other case.
- The efficiency increase also generated a positive impact on CO_2 emissions: -8.3% for the syngas cost equal to €80/MWh case and -8.9% for the second test.

Considering the positive results of this study, this EMS is ready for application in the real demo site and for its replication in the following sites proposed by the ROBINSON project [10]. Moreover, further applications will be considered for a long-term development of the proposed concept including the innovative cyber-physical approach.

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