Ref. Ares(2023)4262898 - 20/06/2023

This Project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 957752

Smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands

D 3.4 –Validation report of the EMS for Eigerøy island

Lead partner: NORCE

Project Contractual Details

Project Title	Smart integration of local energy sources and innovative storage for flexible, secure and cost-efficient energy supply on industrialized islands
Project Acronym	ROBINSON
Grant Agreement No.	957752
Project Start Date	01-10-2020
Project End Date	30-09-2024
Duration	48 months
Website	www.robinson-h2020.eu

Deliverable Details

Number	D3.4		
Title	Validation report of the EMS for Eigerøy island		
Work Package	3		
Dissemination level	Public		
Due date (M)	33	**Submission date (M)**	20.06.2023
Deliverable responsible	Peter Breuhaus		
Contributing Author(s)	Mario L. Ferrari		
Reviewer(s)	Rene Vijgen		
Final review and quality approval			

Document History

Version	**Date**	**Name**	**Comments**[1]
1.0	05.06.2023	D3.4_Robinson_Draft 0.docx	Document for review
1.1	10.06.2023	D3.4_Robinson_Draft 0_PB.docx	Document after review
1.2	16.06.2023	D3.4_Robinson_Draft 1.docx	Document sent for hearing
1.3			

[1] Creation, modification, final version for evaluation, revised version following evaluation, final

Executive summary

Deliverable 3.4 of the ROBINSON project is related to Task 3.4 that is entitled "Validation of the EMS for all involved islands". Although the task includes also the cases of the Western Islands and Crete, this document regards the validation of the Energy Management System (EMS) tool for the Eigerøy case. This activity has been performed in the Innovative Energy Systems (IES) laboratory of the University of Genoa (UNIGE) in cyber-physical mode. The results presented and analysed here refer to experiments based on the real-time parallel operation of hardware (a T100 microturbine and 1.1 kWp PV panels) with software (for the other devices not available in the laboratory and the EMS). The component models related to these devices (e.g. the electrolyzers, the hydrogen storage vessel, the mixer, etc.) were already presented and validated in D3.2. The activity, that is coordinated (as WP leader) and mainly involving the UNIGE partner, is the results of the component integration and the continuous support by the involved partners (with specific bilateral meetings). Moreover, the contributions by SIT (the third party of UNIGE in the ROBINSON project) was essential for support during the preliminary and especially the long term laboratory tests (26 hours of continuous operations plus the start-up and shutdown phases).
In details, the report presents the following topics:

- Description of the involved hardware.
- Description of the cyber-physical approach related to these tests.
- Preliminary experimental tests for the EMS validation in cyber-physical mode.
- 26-hour test with 80 €/MWh for the syngas cost.
- 26-hour test with 5 €/MWh for the syngas cost.
- Global performance and comparison with a standard management approach.
- Lessons learned for the replication cases (Western Islands and Crete sites).

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List of abbreviations

CHP	Combined heat and power
El.	Electrical
EMS	Energy management system
IES	Innovative Energy Systems laboratory
KPI	Key Performance Indicator
LNG	Liquefied Natural Gas
MPC	Model Predictive Control
PV	Photovoltaic
RES	Renewable Energy Source
Th.	Thermal
UDP	User Datagram Protocol
UPS	Uninterruptible Power Supply
WP	Work package
Variables	
p	pressure
P	Power

Subscripts

el	Electrical
Electr	Electrolyzer

1. Introduction

Due to the current energy scenario and the related environmental impact [1], polygeneration grids are essential for future power generation, especially considering the integration of renewable sources [2]. This type of grids could be important also for islands equipped with industrial symbiosis, such as resource recycling. In these energy systems, storage devices will be essential, starting from hydrogen technology, for energy security, optimization opportunities and to compensate the source variability of renewables, such as for wind or solar systems [3]. Considering this scenario, the ROBINSON project aims to operate devices of different generation or energy storage systems under the supervision of the Energy Management System (EMS) that has been developed and presented in D3.3. It is a real-time tool to optimize the related polygeneration grid [4]. The effectiveness of this optimization was demonstrated by previous activities based on different algorithms [5,6], mainly applied in offline mode (optimization based on available demands and costs: forecasted or based on historical data). Nevertheless, few activities considered real-time optimization on real hardware components. Since the final ROBINSON aim is the demonstration at the pilot on Eigerøy island, this report shows the experimental validation of the EMS at laboratory level (in the Innovative Energy Systems laboratory of the University of Genoa [7]). Due to a very different grid with different components from the demo site, this validation has been performed in cyber-physical mode (available hardware and software interacting in real-time mode), that is an effective approach because demonstrated in previous works [8]. So, thanks to the laboratory flexibility (in case of wrong operations the test can be stopped to perform changes without the complexity of a real site), significant validation results have been obtained before doing the demo activities. This an important step in the EMS development process to reduce the EMS refining time and to be ready in a short time for the demo site.

This report is organized in these chapters:

- Chapter 2 presents the hardware used in this work.
- Chapter 3 reports the description of the cyber-physical approach related to these tests.
- Chapter 4 presents the preliminary experimental tests for the EMS validation in cyber-physical mode.
- Chapter 5 presents details of laboratory preparation activities for tests in cyber-physical mode.
- Chapter 6 reports the results of the 26-hour test with 80 €/MWh for the syngas cost.
- Chapter 7 reports the results of the 26-hour test with 5 €/MWh for the syngas cost.
- Chapter 8 discusses the global performance and the comparison with a standard management approach.
- Chapter 9 regards lessons learned for the replication cases (Western Islands and Crete sites).

2. Laboratory hardware

The rig used to validate the ROBINSON EMS is a test bench available in the Innovative Energy Systems laboratory at UNIGE (campus located in Savona). It was designed and installed in previous activities on distributed generation for doing laboratory tests on past EMS tools [7]. This facility is a laboratory grid (both electrical and thermal) equipped with the following devices: a T100 CHP microturbine, a 20 kW heat pump, 10 kWp thermal solar panels, 1.1 kWp PV panels, an absorption chiller (lithium bromide and water), two 5 m^3 hot water vessels for thermal energy storage, a two-loop thermal grid including fan coolers for obtaining local thermal demands, and a local electrical grid (also connected to the main line). For this activity, attention is focused on the components included in the ROBINSON project (Eigerøy pilot site). So, the tests presented in this document were performed using just the following laboratory components: (i) the microturbine, (ii) the PV panels, (iii) the electrical grid, and (iv) the thermal grid.

During the experimental work, the following activities on devices used for the ROBINSON tests were financed:

- maintenance activities on the laboratory general facilities (e.g. the fire and gas detection systems, the air compressor for actuators, the battery-based UPS);
- probes necessary for the rig management and the data acquisition (e.g. re-calibration of 3 mass flow rate probes);
- natural gas consumption for the microturbine operations.

2.1. The microturbine

The microturbine is a AE-T100NG generator [9], capable of producing up to 100 kW (±3 kW) of electrical power and 167 kW (±5 kW) of thermal power through a gas/water heat exchanger for cogeneration. This machine is based on the recuperated cycle [10] and operates (at high load conditions) at constant turbine outlet temperature (918.15 K set-point) [9]. Its nominal efficiency values are: 30% (±1%) for electrical generation and 80% (±1%) as overall efficiency for operation as a CHP (including thermal production) [9]. Other design data are reported in Table 1, as from [9].

Table 1 – Main design data for the AE-T100NG microturbine.

Parameter	**Value**	**Unit**
Burner pressure	4.5	bar
Turbine inlet temperature	950	°C
Rotational speed	70000	rpm
Fuel consumption	333	kW
NOx emissions	<15	ppm(v)
CO emissions	<15	ppm(v)

Figure *1* below shows the used microturbine and its connections for natural gas supply, electrical local grid connection and thermal energy extraction.

Figure 1 - AE-T100NG microturbine in the UNIGE laboratory.

2.2. The PV panels

The PV system consist of 6 panels/modules located on the laboratory storage room (Figure 2) with in total 1.1 kWp nominal peak power. The details about the nominal data are reported in Table 2.

Figure 2 – PV panels in the laboratory.

Table 2 – Main design data for the PV panels.

Parameter	Value	Unit
Number of modules	6	-
Module peak power	185	kWp
Nominal efficiency	14.5	%
Nominal temperature	46 (±2)	°C

2.3. The electrical grid

Both the microturbine and the solar panels are connected (for the electrical side) to the campus smart grid (Figure 3) that includes also a link with the general electrical distribution grid of Savona. The connection to the local grid is at 380 V (50 Hz - 3 phases), for a maximum 200 kW power. The microturbine is connected after the rectifier and the inverter devices which are part of the T100 internal power conditioning system (power electronics). The connection of the PV panels is performed through a devoted inverter.

Figure 3 – Electrical connection to the campus smart grid.

2.4. The thermal grid

The thermal grid is based on a two-loop layout where thermal generators (the microturbine in this case) are connected to produce hot water for the high temperature line and users (two fan coolers) to provide the return water to the low temperature pipe. In case of mismatches between generation and utilization, a 5 m^3 vessel (available also to store thermal energy) is connected to both thermal lines to allow for decoupled thermal and electrical demand profiles. While more details about it are reported and discussed in [7], Figure 4 shows the thermal grid, one of the connections to the campus smart thermal grid (not used in this work) and the fan cooler necessary to generate the thermal load (visible in the upper part of the picture).

Figure 4 – Picture of the thermal grid with one of the pipe connections to the campus smart grid.

3. The cyber-physical approach

Since the UNIGE facility does not include all the components related to the ROBINSON project (Eigerøy site), the tests for the EMS validation were performed in cyber-physical mode. This means that real-time software was used for the components not physically present in the laboratory. Thanks to real-time operation and the connection with the hardware, communicating with UDP channels, they were able to produce reliable results in connection with the hardware. As in previous works, this is an effective solution to obtain experimental results, without the costs and risks of damaging a complete prototype. In the ROBINSON project, thanks to the cyber-physical approach, it has been possible to improve and validate the EMS before the demonstration in the Eigerøy pilot site, with a significantly reduced time, costs and risks.

The communication between the software and the hardware is shown in Figure 5. The software (including the EMS, the MPC, the boiler, the mixer with the syngas/biogas inputs, the electrolyzers, the hydrogen storage vessel and the wind turbine) receives four measured signals from the field: the turbine produced electrical power (±1% accuracy), the turbine produced thermal power (±3% accuracy), the turbine fuel mass flow rate (±1% accuracy), and the power produced by the photovoltaic panels (±1% accuracy). On the other hand, the hardware receives (as input) two values from the software: the turbine signal for the machine activation and the related electrical set-point.

Since the turbine size is different, a data conversion was implemented to use the 100 kWel T100 microturbine for a system including a 400 kW turbine (lookup tables to scale the signals in both communication senses). The T100 microturbine was limited to the 30 kW – 90 kW range to avoid problems due to ambient temperature change. Moreover, the photovoltaic panels were operated with a signal re-scaling because the installed panel area in the laboratory is different from the configuration in the Eigerøy site.

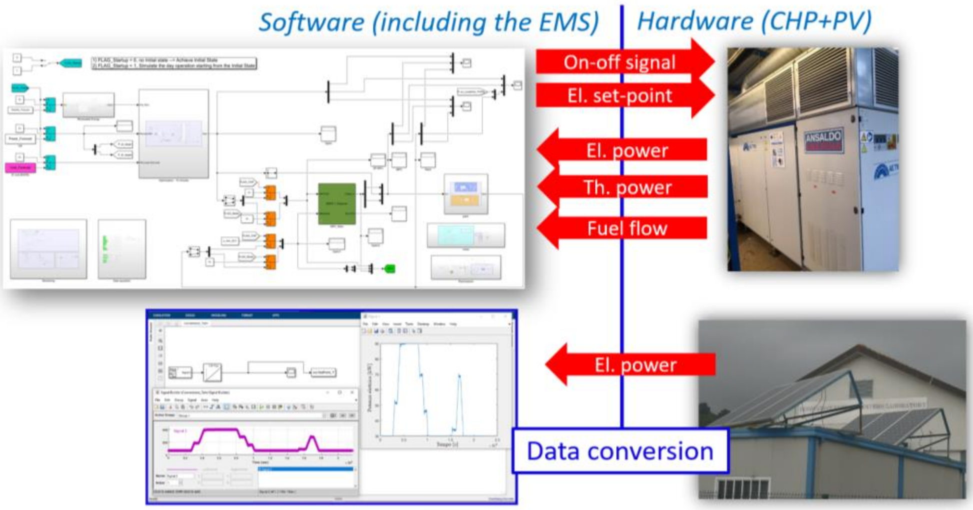

Figure 5 – Data communication between the software and the hardware (tests in cyber-physical mode).

4. Preliminary experimental tests for the EMS validation

In this section, attention is focused on a specific part of the day proposed in [11] and in D3.3 of the ROBINSON project. It is a working day of November 2021 when the Prima Protein facilities were started-up and for which measurements are available. Details about the electrical cost are shown in Figure 6 with the flag values for the operations with the electrolyzers (all the details about the EMS structure are reported in D3.3 also for the hydrogen vessel management). These other costs were considered: 150 €/MWh for the LNG and 100 €/MWh for the syngas. Although maintenance and stat-up costs are included in the general description in D3.3, they were neglected for these preliminary experimental tests for the EMS validation. Although 100 €/MWh is a high value for the syngas, in these preliminary tests this high syngas cost was chosen to have CHP load changes during the operations (a low value as 5 €/MWh drives the microturbine to be at maximum load during all the test).

The results reported in Figure 6 show that the CHP was maintained at its minimum load when a low demand condition was coupled with low cost for the electrical energy. Then, the CHP load was increased to the maximum when high earning can be obtained from the electrical energy selling (the buying/selling ratio was equal to 1 for the entire test). Finally, with high thermal demand values and low electricity prices the microturbine was switched off and the thermal demand was entirely satisfied by the boiler. Figure 6 also shows a good demand matching for the boiler and the results for the hydrogen side (electrolyzers and pressure of the hydrogen storage vessel). Considering a comparison with the standard management, as proposed in [11] and in D3.3, significant benefits resulted from the EMS application: 12.9% cost decrease and 21.4% CO_2 emission decrease.

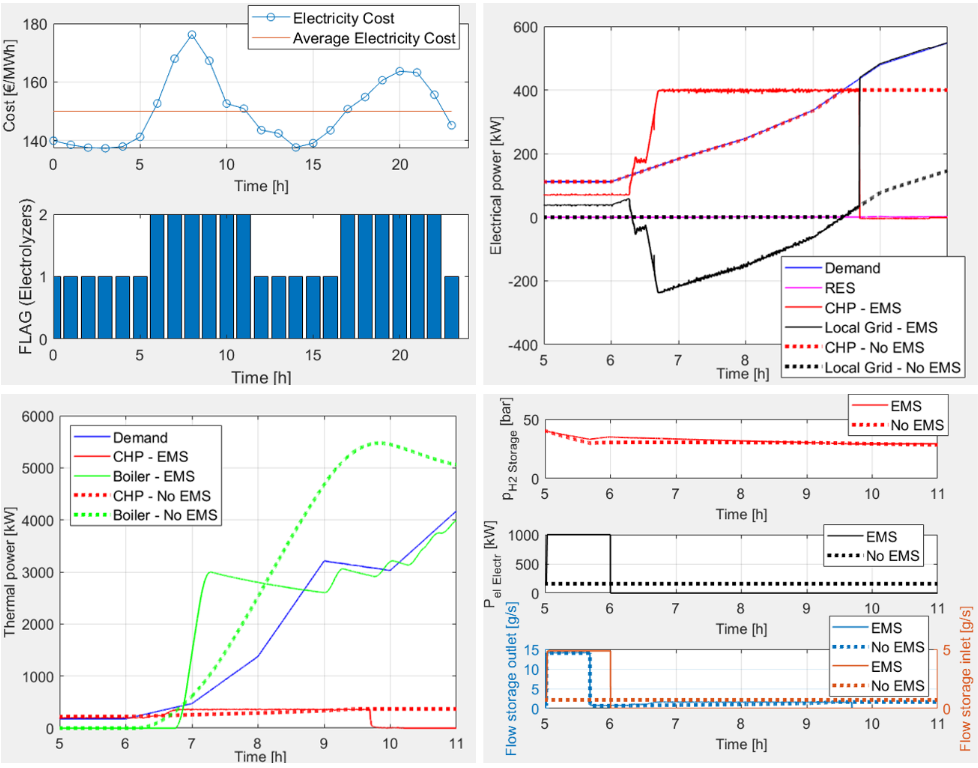

Figure 6 - Electrical costs, demands and preliminary results for tests in cyber-physical mode against simulations with a standard management approach, as described in [11] or In D3.3.

5. Laboratory preparation activities for 26-hour tests and general considerations

The laboratory preparation activities (performed in the IES laboratory in Savona) regarded meetings with the involved partners for the Eigerøy site, including discussions on the final decisions about the technology to be installed or used in the planned demonstration. Moreover, on the laboratory side, it was necessary to carefully plan the tests due to the long duration (26-hour duration has been chosen to satisfy one of the project objectives – "continuous operations for >1 day (as measure of reliability obtained in the lab)" that regards KPI 1.1). For this reason, the support of SIT has been essential. Moreover, due to the long test duration, on both Matlab-Simulink and LabView sides (see D3.3 for the communication details) a communication check system has been implemented. The concept is that in case of communication failure of up to a few seconds, this system avoids problems on the test because it maintains the last correctly transferred values. Due to the time scale of the test transients, this system allows to prevent wrong operations (or calculations) and to secure the test.

It is also important to highlight that the following activities were necessary in preparation of the tests or to comply with the laboratory safety rules: (i) maintenance on the laboratory fire sensors and the gas detection systems, (ii) maintenance on the laboratory UPS (batteries to avoid problems on the instruments and the system control in case of blackout events), (iii) re-calibration of mass flow rate sensors for the pneumatic valve air, (iv) substitution of the laboratory air dryer, (v) maintenance on the laboratory air compressor, (vi) other preparatory activities as presented in D3.3. Finally, it is important to highlight that these tests (both preliminary and 26-h tests) produced an important consumption of natural gas (1940.65 m^3) for 74.9 hours of operation (in total) and 28 T100 start-up phases.

Another activity was the re-implementation of the inputs in terms of weather conditions, electricity costs and both electrical and thermal demands. Since the demands are reported in the following sections, here (as a general introduction of the tests presented in the following sections) Figure 7 shows the electricity cost (hour-by-hour trend and average value) and the flag for the electrolyzer management (with the approach described in D3.3).

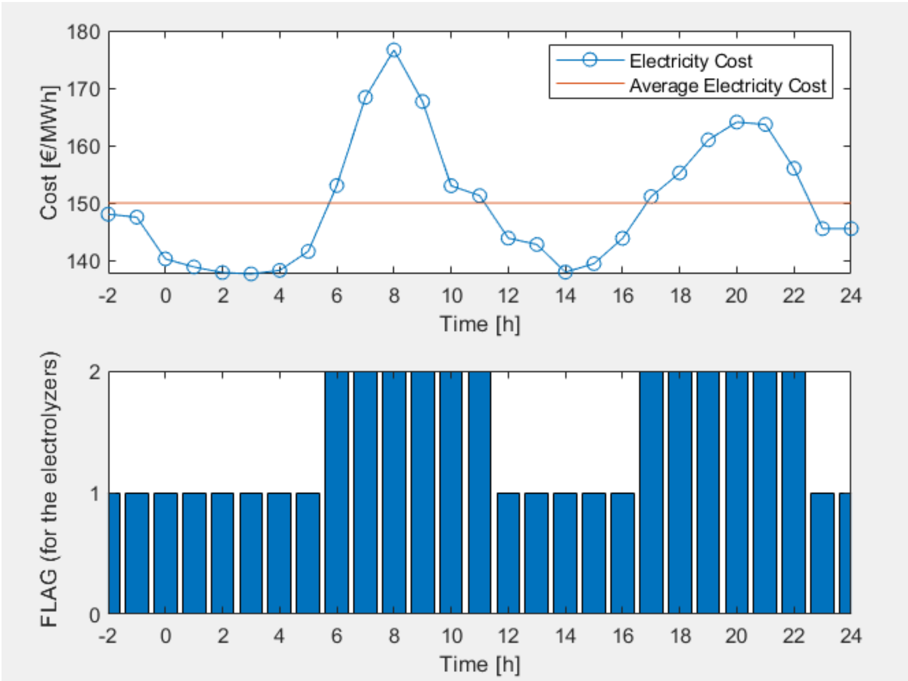

Figure 7 - Electricity cost (hour-by-hour trend and average value) and the flag for the electrolyzers.

6. 26-hour test with 80 €/MWh for the syngas cost

As mentioned before, this cyber-physical test was performed considering a cost situation that produces optimal scenarios with different loads for the microturbine, including the machine switch off. So, a test with 80 €/MWh as syngas cost was performed with the buying/selling ratio equal to 1 for the entire test. Although this is high for this renewable source, this could be representative of real conditions. In this case both maintenance and start-up costs were included. The results discussed here are on the performance for the devices of the Eigerøy site. However, the electrical set-point and generation conversion (to operate with a T100 machine) was presented in D3.3 and in previous sections. All the results presented here (and obtained from the test in cyber-physical mode) are compared with simulated results with the standard management approach presented in D3.3 and representative of a reference case ("No EMS" in Figure 8).

In the initial part of the test, Figure 8 shows that the CHP load changed due to the electricity cost change: the cost decrease produced an optimal solution with the CHP at minimum load. Then, the increase of the electricity cost changed the optimal solution calculated by the EMS and in consequence the microturbine load was increased to the maximum. Close to the hour number 14, due to an electricity cost decrease, the EMS considered unfruitful the local electrical generation. So, since at this time of the test the boiler was active, the CHP was switched off for about two hours. In the final part of the test, the CHP was re-activated and operated at its maximum load to exploit the economic benefit related to the energy selling high price.

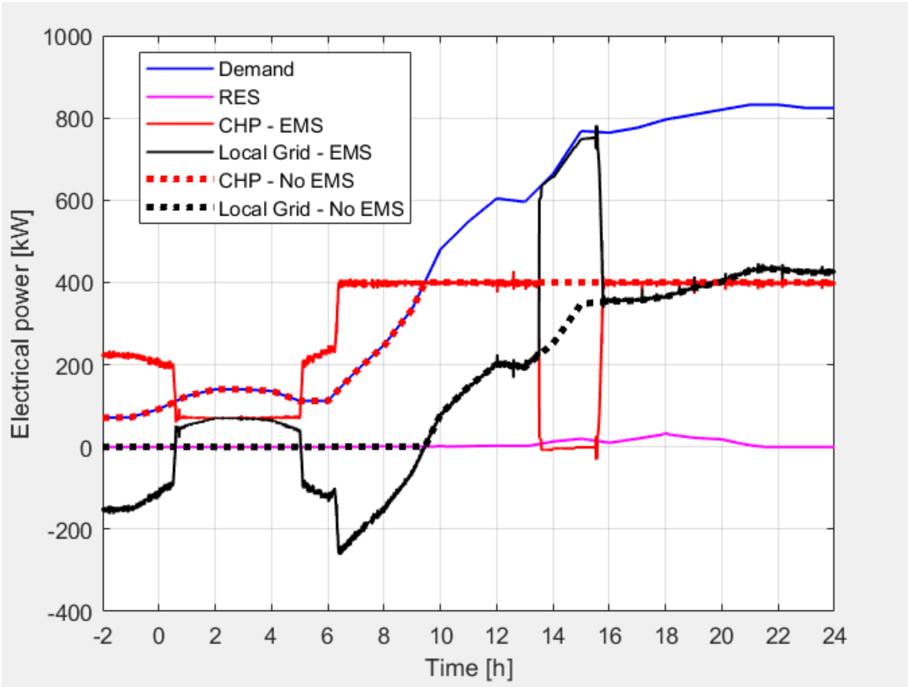

Figure 8 – 26-hour test with 80 €/MWh for the syngas cost: electrical power.

While the generation of PV panels is not visible in the scale of Figure 8, the RES impact (up to about 32 kW) is related to the wind turbine that was active in the evening. Moreover, to better show the minimum impact of the PV panels (about 3 kW at 12 o'clock) and the effect of the interaction with the laboratory microturbine, Figure 9 shows a zoomed in version of the Figure 8. Here it is possible to show the EMS robustness that, with the typical oscillations of a real plant, is able to successfully manage the system (hardware + software devices) without faults or unstable operations. Moreover, Figure 9 also shows a negative generated power during the microturbine start-up. This was the power absorbed during the initial part of the re-start operation when the alternator worked as a motor.

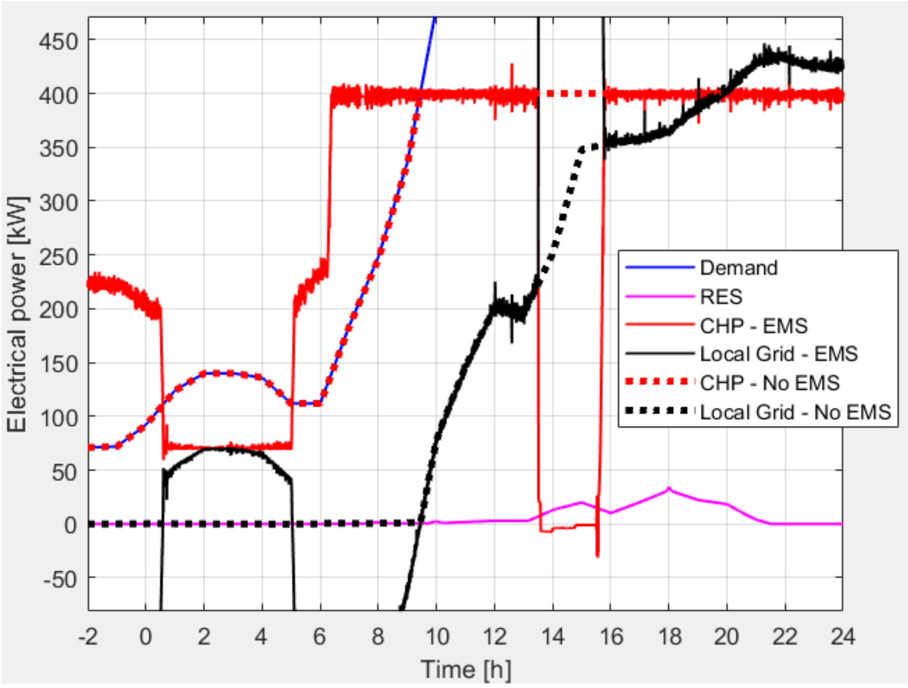

Figure 9 – 26-hour test with 80 €/MWh for the syngas cost: electrical power (zoomed plot).

The results obtained in the 26-hour test for the thermal side are reported in Figure 10. While in the initial part of the test the generated thermal power was higher than the demand (heat radiators could be necessary), at about 7 o'clock the boiler was started-up (considering the EMS logic presented in D3.3) and the related generation correctly satisfied the demand (the difference between the blue line and the continuous green line is the thermal power produced by the microturbine (the continuous red line). A matching between the demand and the boiler generation is present when the CHP was switched off. Also, for the thermal power, Figure 10 shows a comparison with the thermal power generated with a standard control approach ("No EMS" in Figure 10), as described in D3.3. Before comparing the global results, it is quite visible that the standard control system produces a significant mismatch from the demand and, in some parts of the test, missing thermal power.

Also, for the thermal side, a zoomed in plot (Figure 11) shows the oscillations related to these experimental results, highlighting the importance of this cyber-physical approach in comparison with the simulations reported in D3.3. The oscillations coming from the real hardware were correctly managed by the EMS without any problem.

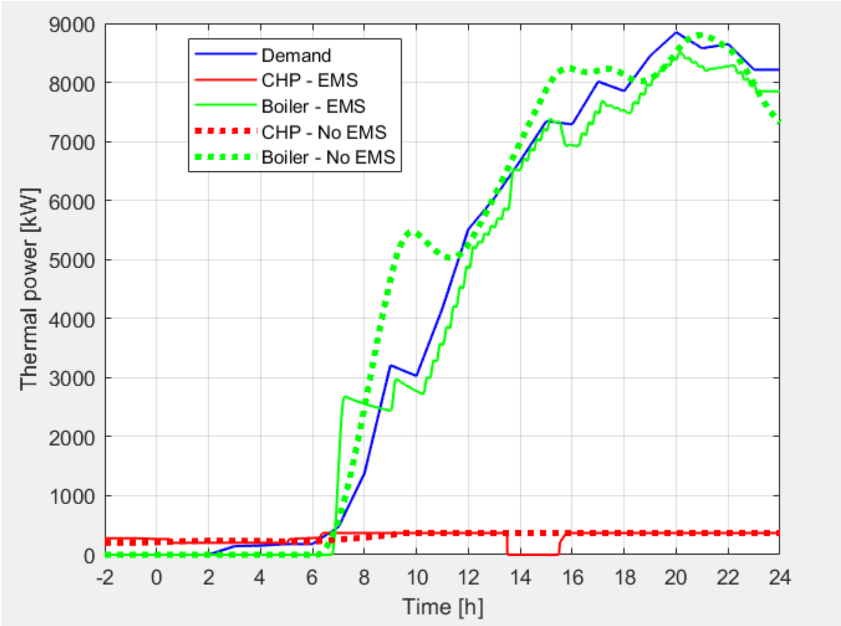

Figure 10 - 26-hour test with 80 €/MWh for the syngas cost: thermal power.

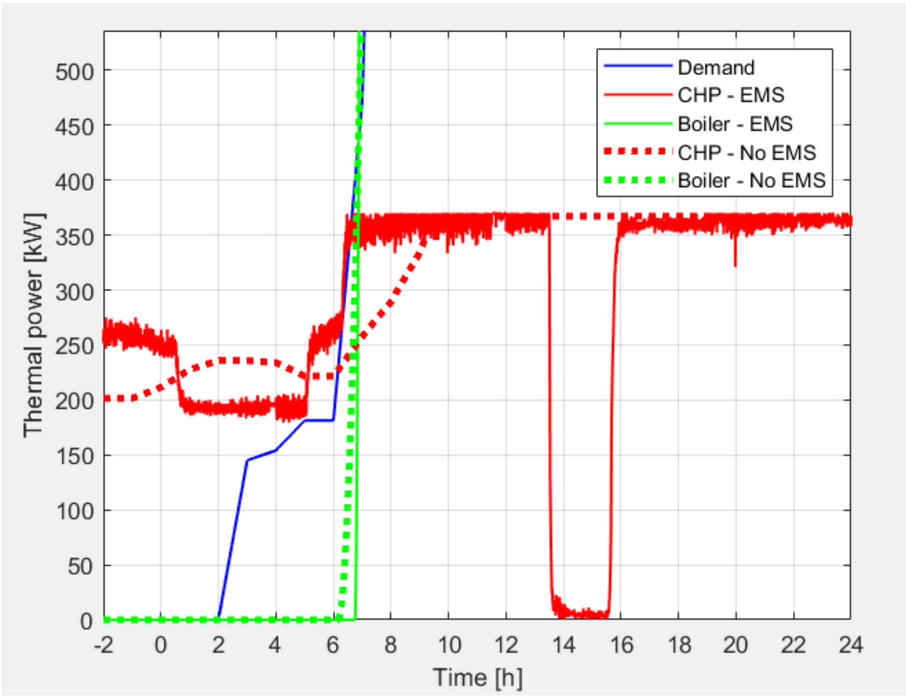

Figure 11 - 26-hour test with 80 €/MWh for the syngas cost: thermal power (zoomed plot).

As already described in D3.3, the hydrogen generation/storage/utilization is managed considering the flag values in Figure 7. Moreover, the hydrogen outlet mass flow rates (from the storage vessel) are calculated considering the utilization of hydrogen for transport and the gas mixer need (to maintain the hydrogen content in the CHP fuel at 30% in volume). For the transport, the charging of a truck tank (up to 32 kg of H_2) was considered. So, Figure 12 shows that during the truck charging operations (the first charging event was at 3 a.m. while the second one at 9:15 a.m. – both for a duration of 2400 s) the hydrogen pressure in the storage tank showed a significant decrease, while the recharging is mainly obtained during periods with the electricity cost lower than the average value (when the flag in Figure 7 was equal to 1). The reference case for the standard management ("No EMS" in Figure 12) was obtained maintaining the two electrolyzers at their minimum generation during the entire test. This is not enough to compensate the hydrogen consumption, producing a pressure decrease trend for almost the entire test.

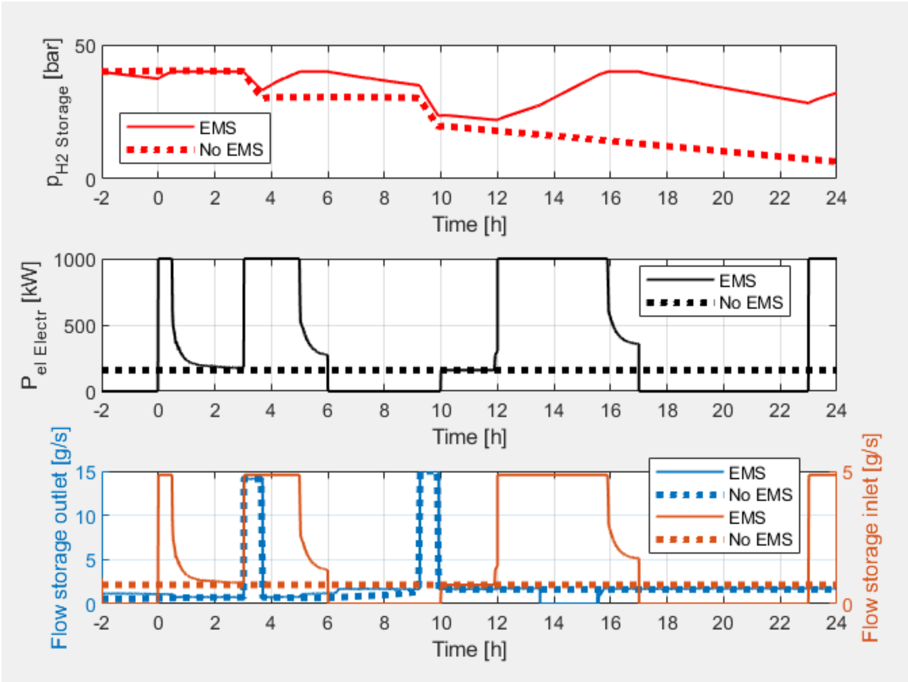

Figure 12 - 26-hour test with 80 €/MWh for the syngas cost: hydrogen generation and storage.

7. 26-hour test with 5 €/MWh for the syngas cost

To complete this analysis related to the Eigerøy site, a further test in cyber-physical mode was performed with a syngas cost of 5 €/MWh (as in the simulations in D3.3 and [11]). This is a more realistic cost and in agreement with the data from the Eigerøy site reported in D1.3 and in D3.1. No changes were implemented for the renewables, the electricity cost and for both electrical and thermal demand values during the 26-hour period. Also, the buying/selling ratio remained equal to 1 for the entire test, as for the previous cases. In this case both maintenance and start-up costs were included.

Due to this very low syngas cost, the electrical energy export and selling to the grid was profitable during the entire test. So, the EMS maintained the microturbine at its maximum (90 kW for the T100 machine that corresponds to 400 kW for the A400 turbine) for all the 26 hours. For this reason, Figure 13 shows an electrical generation at 400 kW by the CHP and a large energy selling in the initial part of the test (about 12 hours) followed by an important demand compensation by the grid. Similar to the previous section, also in this case the test results are compared with the "No EMS" management that was calculated with the simulation models.

Also in this case, a zoomed-in plot (Figure 14) is shown to highlight that the EMS produced a stable behaviour without any problems coming from the interaction with a real system that produced oscillations in the signals.

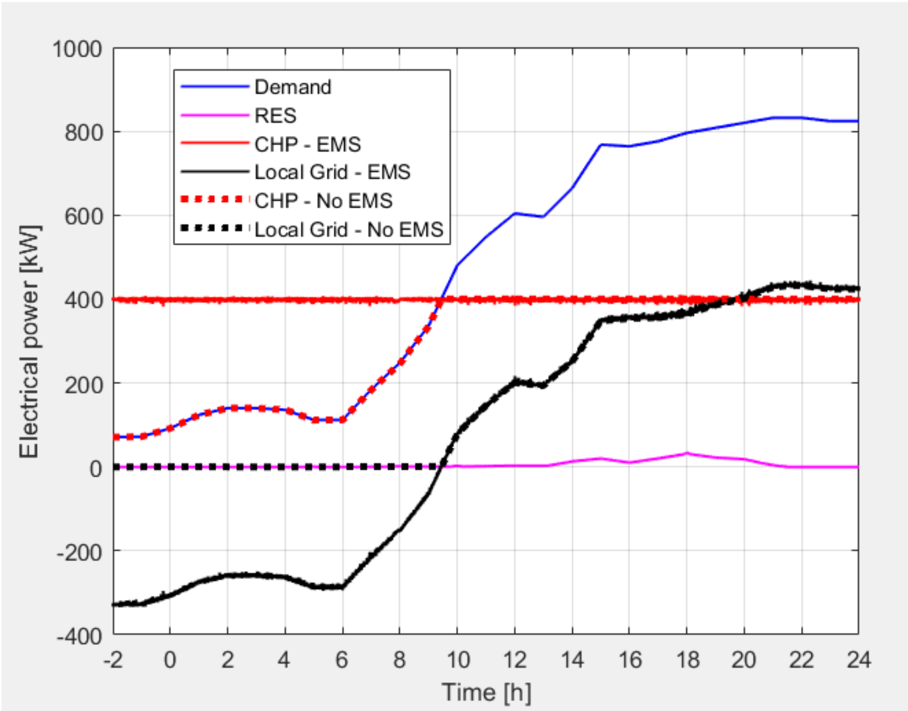

Figure 13 - 26-hour test with 5 €/MWh for the syngas cost: electrical power.

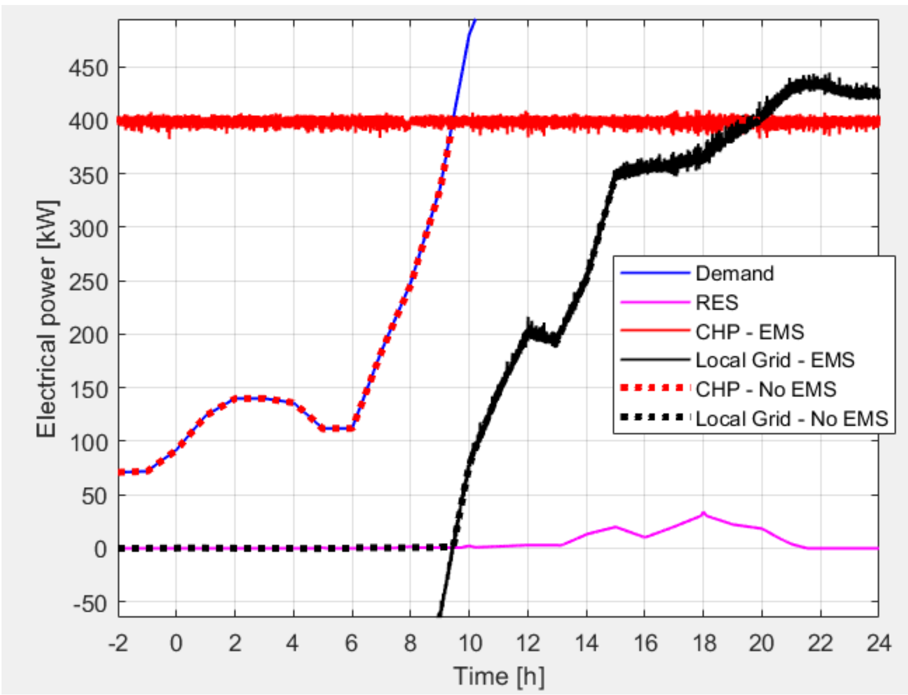

Figure 14 - 26-hour test with 5 €/MWh for the syngas cost: electrical power (zoomed plot).

From the thermal point of view, Figure 15 shows a constant thermal generation from the CHP. So, the EMS produced set-point for the boiler in agreement with the logic shown in D3.3. When the boiler was active its set-point took into account the thermal power generated by the CHP. Moreover, Figure 15 shows the comparison with the “No EMS” case for the thermal generation side.

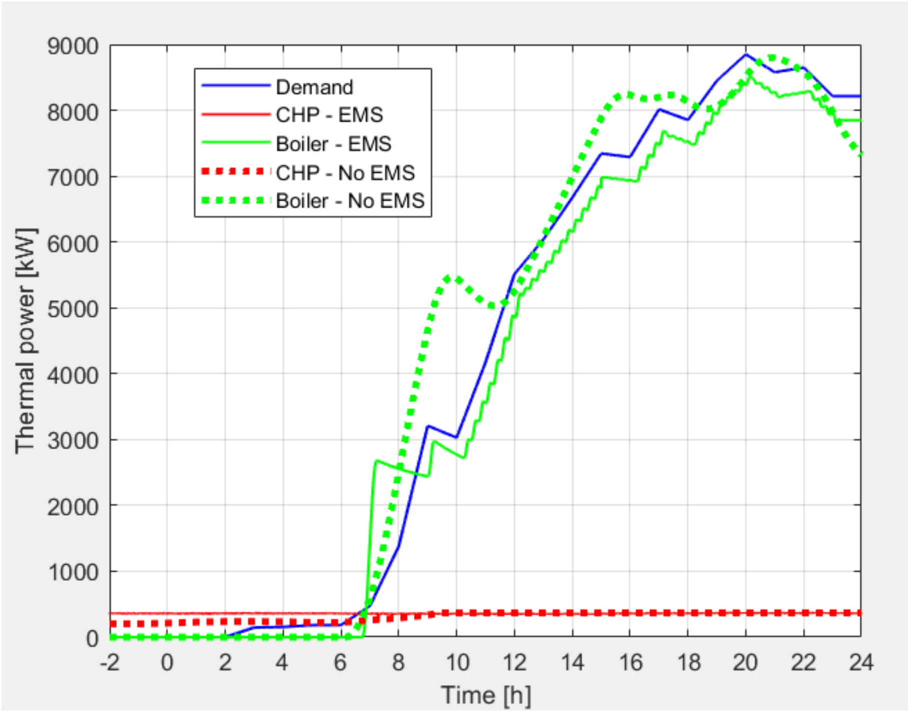

Figure 15 - 26-hour test with 5 €/MWh for the syngas cost: thermal power.

This test with the CHP at maximum load during all the 26 hours produced a constant outlet flow (from the hydrogen storage tank) except for the truck charging phases (Figure 16). So, due to a higher hydrogen consumption the electrolyzers remained active and at maximum load for additional time, especially when the flag of Figure 7 was equal to 1. Moreover, also Figure 16 shows the comparison with the “No EMS” case for the thermal generation side.

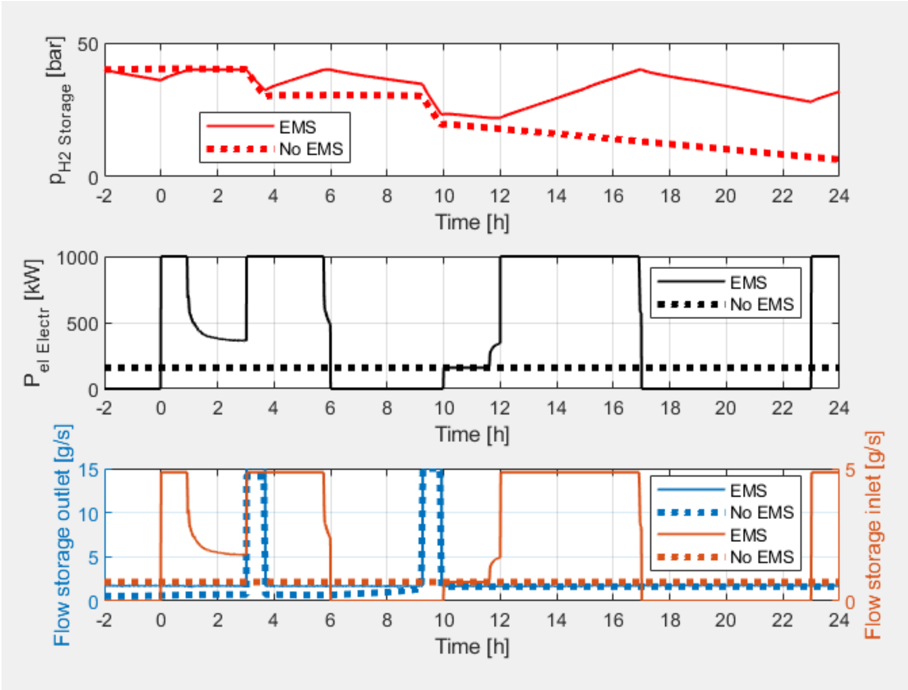

Figure 16 - 26-hour test with 5 €/MWh for the syngas cost: hydrogen generation and storage.

8. Global performance comparison

To complete the EMS validation with these tests in cyber-physical mode, it is important to do a comparison related to global parameters, that are performance indicators of the entire 26 hours. This analysis starts from the property that is optimized by the EMS algorithm, that is the variable cost function including mainly fuel and electricity costs, but also including maintenance and start-up costs. Figure 17 shows significant cost decrease with the EMS application, in comparison with the "No EMS" case. In this plot, it is necessary to report the two different costs of the "No EMS" case because two different syngas costs were considered. For sure, the bars related to the 5 €/MWh show a lower cost in comparison with the 80 €/MWh respective conditions. Moreover, it is important to highlight the cost decrease performance due to the EMS application: -6.9% for the syngas cost equal to 80 €/MWh and -8.5% for the 5 €/MWh case.

Another important parameter is the electrical efficiency for both the CHP and the system (the related definitions are reported in D3.3). The CHP electrical efficiency has not a significant benefit considering that it presents a decrease (-7.6%) for the 80 €/MWh case (due to the machine shutdown and restart phases) and the increase for the 5 €/MWh case is not significant (+0.9%). However, the system electrical efficiency shows important increase due to the EMS application: +13.6% for the 80 €/MWh syngas cost and +29.7% for the 5 €/MWh case. This final value is significant to be highlighted because it is higher than the 20% efficiency increase target related to the KPI 1.1 producing an experimental confirmation of what already obtained for the simulations presented in D3.3.

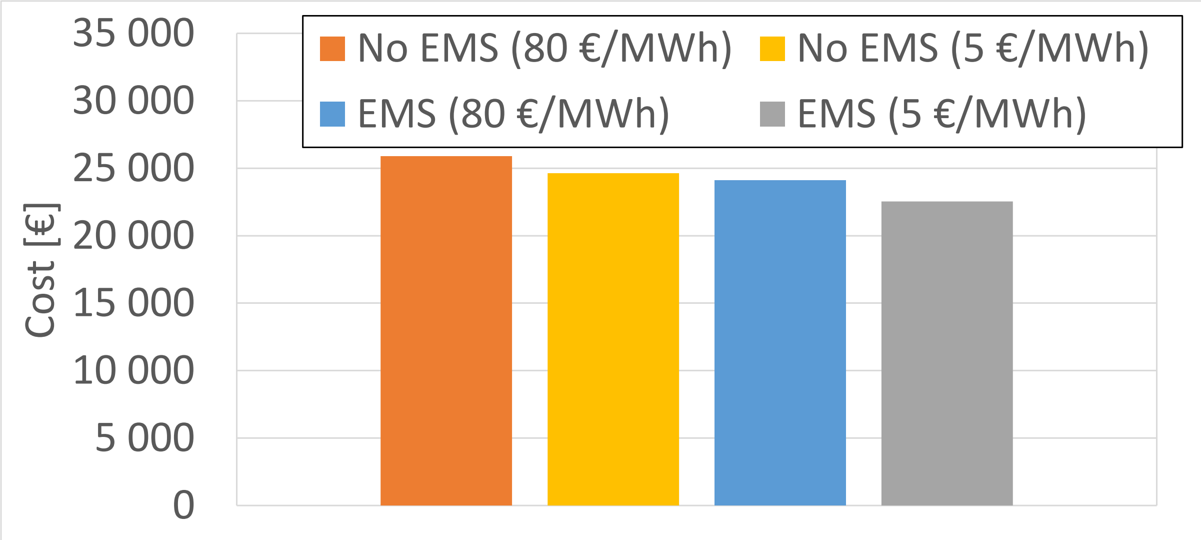

Figure 17 – Global performance comparison: variable costs.

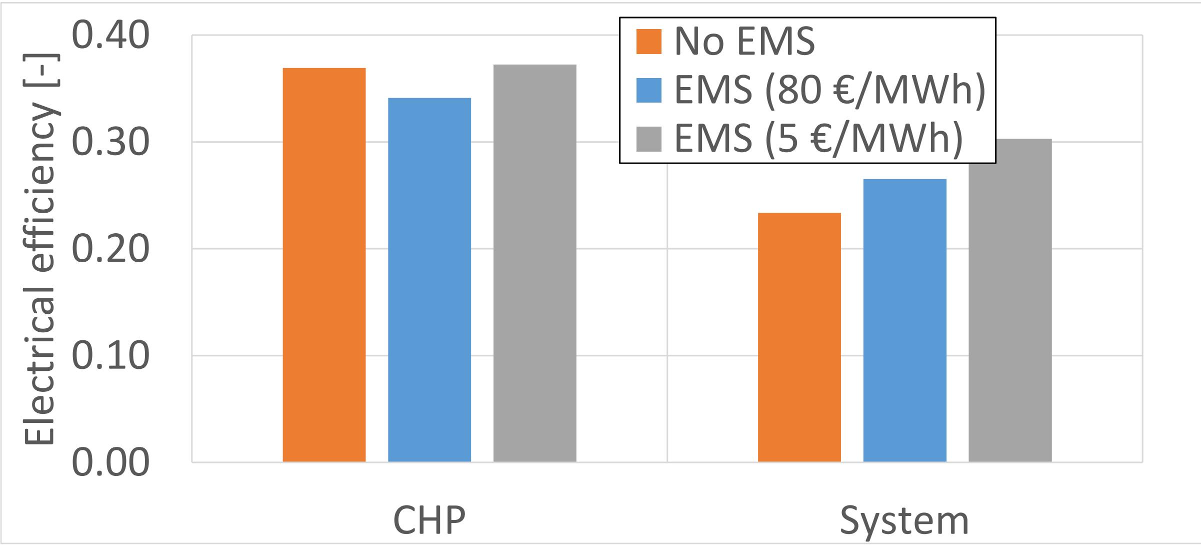

Figure 18 - Global performance comparison: electrical efficiency.

Another important parameter is the mass of CO_2 emitted during the 26-hour tests. These values were calculated considering what reported in D3.3. For these tests, Figure 19 shows a significant emission decrease with important positive impact on the environment: -8.3% for the 80 €/MWh case and -8.9% for the test with the syngas cost equal to 5 €/MWh.

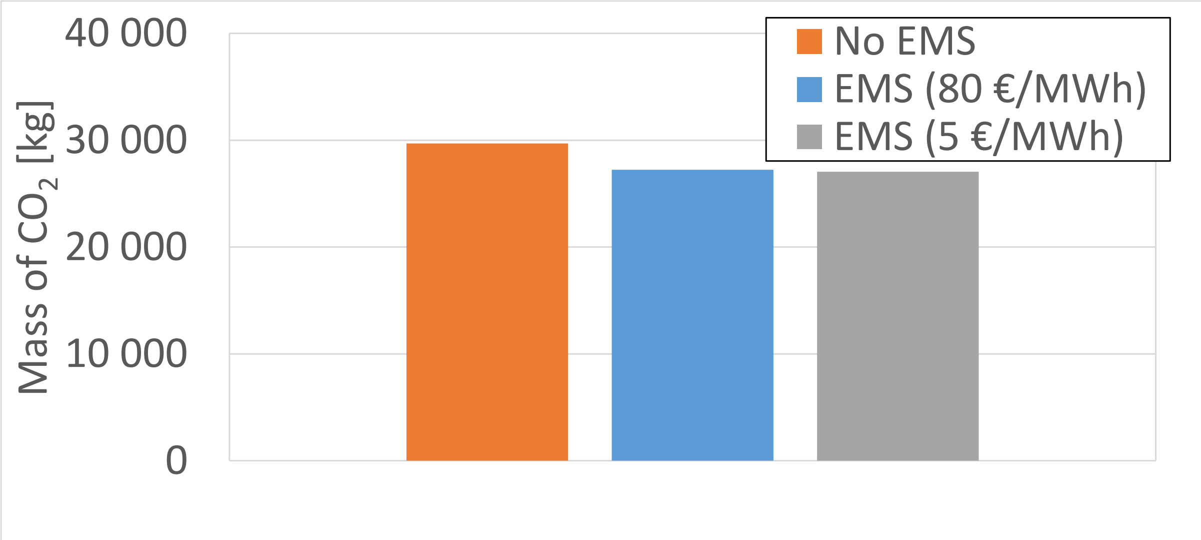

Figure 19 - Global performance comparison: CO_2 emissions.

9. Replication section

Although in this document no activities about replication are presented or discussed, the results of this report show a general approach that will be considered for the replication activities to be reported in D3.5. In detail, these tests for the Eigerøy site produced significant validation results for the EMS application for the planned demonstration and the following learned lessons to be transferred to both Western Islands and Crete cases:

- implementation of the cyber-physical approach in the laboratory;
- interaction with laboratory systems (e.g. the CHP) of different sizes in comparison with the devices installed or to be installed in the smart islands;
- laboratory organization for the planned tests considering the safety issues and the long test duration;
- analysis of results in comparison with the "No EMS" case;
- comparison of the global parameters for the experimental validation of the EMS performance.

Considering these aspects, the validation experimental approach in cyber-physical mode coupled with the tool modular approach will be essential for the replication activities with different system layouts.

10. Summary

This report, as D3.4 of the ROBINSON project, presents the experimental tests performed in cyber-physical mode in the IES laboratory of the UNIGE partner for the Eigerøy site. This activity is the final result of an intense collaboration between the partners involved in T3.4 and in the entire WP3. Considering the experimental activities presented here for the Eigerøy site the main results are reported in the following points.

- A cyber-physical approach was successfully implemented for the EMS validation tests.

- Two 26-hour tests were performed considering two different syngas costs (80 €/MWh and 5 €/MWh) that generated different CHP behaviours.
- In both cases the EMS correctly managed the system (including the hardware) without instability problems.
- The experimental results obtained with both tests were compared to the simulated results related to a standard management approach (described in D3.3).
- The analyses of the global parameters showed important performance increase obtained with the EMS application (+29.7% system electrical efficiency, -8.5% cost and -8.9% CO_2 emissions for the 5 €/MWh case).

These 26-hour tests ("continuous operations for >1 day (as measure of reliability obtained in the lab)") and the obtained +29.7% system electrical efficiency (efficiency ">20% compared to standard energy management approach") and the software stability as demonstrated in D3.3, this document (D3.4) shows that all goals related to the KPI 1.1 of the ROBINSON project were achieved.

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