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

D 3.5 –Validation report of the EMS for Crete and Western Islands

Lead partner: NORCE

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Executive summary

Deliverable 3.5 of the ROBINSON project is the final deliverable related to Task 3.4 that is entitled "Validation of the EMS for all involved islands". This document regards the validation of the Energy Management System (EMS) tool for the cases related to the Western Islands and Crete. This activity has been performed in the Innovative Energy Systems (IES) laboratory of the University of Genoa (UNIGE) in cyber-physical mode. So, as operated for D3.4, 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 boilers, 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 result 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 long laboratory tests (two tests involving 24 hours of continuous operations plus the start-up and shutdown phases and preliminary tests for the MPC stabilization). The experimental results (for tests in cyber-physical mode) reported in this deliverable are the mean of verification of MS11 ("The EMS is validated for the follower islands").
In details, the report presents the following topics (no replication session is included because all the document is devoted to replication activities):

- Description of the involved hardware and the cyber-physical approach for these tests.
- Preliminary experimental tests for the EMS stabilization for the Western Islands case.
- 24-hour test for the Western Islands case (Creed district).
- Preliminary experimental tests for the EMS stabilization for the Crete case.
- 24-hour test for the Crete case (Manna district).
- Cybersecurity aspects for EMS replication.

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List of abbreviations

API	Application Programming Interface
CHP	Combined heat and power
El.	Electrical
EMS	Energy management system
IES	Innovative Energy Systems laboratory
Kero.	Kerosene
KPI	Key Performance Indicator
LNG	Liquefied Natural Gas
MPC	Model Predictive Control
PV	Photovoltaic
RES	Renewable Energy Source
Th.	Thermal
UDP	User Datagram Protocol
WI	Western Islands
WP	Work package

Variables

p	pressure
P	Power
SoC	State of Charge

Subscripts

el	electrical
Electr	Electrolyzer

1. Introduction

Due to the current energy situation involving important environmental constraints [1] and the EU 2030 road map [2], research activities on polygeneration grids continue to be important for current and future applications. Special attention should regard the integration of renewable sources [3] including energy storage solutions in the form of fuels, such as green hydrogen [4]. Moreover, special interest is due to islands including industrial districts (industrial symbiosis), with interesting potentiality in resource recycling, such as waste utilization for biogas production [5]. In these grids, storage devices will be essential, starting from hydrogen technology to different technical solutions depending on the storage timescale (minutes, hours or days/weeks) [6]. Considering this international scenario, the ROBINSON project aims to integrate different generation devices and energy storage systems thanks to the supervision of an Energy Management System (EMS). This real-time tool was specifically developed for this project and presented in D3.3 for the optimization of the proposed polygeneration grid [7]. The effectiveness of polygeneration grid optimization was demonstrated in previous activities based on different algorithms [8, 9]. However, previous grid optimization analyses, although including important innovative aspects, were mainly applied in offline mode (calculations based on available demands and costs performed in offline mode for 24-hour scenarios). Few activities considered real-time optimization on real hardware components and they presented critical aspects and complexity in including energy storage devices [10].

Considering that the EMS experimental validation for the Eigerøy island was included in D3.4, this report shows the experimental validation results for replication cases (districts in Western Islands and Crete). As performed for D3.4, also in this report the EMS tools for Western Islands and Crete were validated at laboratory level (in the Innovative Energy Systems laboratory of the University of Genoa [11]). Also in this case (in agreement with the approach used for Eigerøy), the validation has been performed in cyber-physical mode (available hardware and software interacting in real-time mode). This is an effective approach to produce significant improvements for the EMS robustness and flexibility, as demonstrated in previous works (such as in [12]). 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 for the replication cases proposed in the ROBINSON project (the districts in Western Islands and Crete).

This report is organized in these chapters (no replication section is included because the entire deliverable regards replication activities):

- Chapter 2 presents the hardware used in this work and the cyber-physical approach.
- Chapter 3 includes preliminary experimental tests for the Western Islands (WI) case.
- Chapter 4 reports the 24-hour test that validates the EMS in the application for the Western Islands.
- Chapter 5 includes preliminary experimental tests for the Crete case.
- Chapter 6 reports 24-hour test that validates the EMS in the application for Crete.
- Chapter 7 summarises the cybersecurity interoperability tests we performed using the live API for the cybersecurity management system of the EMS in ROBINSON, adaptable (adjusting the input to the desired input or variables in the file registered in the backend) and replicable to any of the islands.

2. Laboratory hardware and cyber-physical approach

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 [10]. The tests presented in this document were performed, similarly as for D3.4, using the following laboratory components: (i) the T100 microturbine, (ii) the PV panels (1.1 kWp), (iii) the connection to the electrical grid, and (iv) the thermal grid including fan coolers.

It is important to highlight that during the experimental activities the following expenses were necessary: laboratory equipment maintenance and significant consumption of natural gas for the microturbine operations.

2.1. The microturbine

The microturbine is an AE-T100NG generator [13], 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 [13] and operates (at high load conditions) at constant turbine outlet temperature (918.15 K set-point) [14]. Its nominal efficiency values are: 30% (±1%) for electricity generation and 80% (±1%) as overall efficiency (including thermal production) [14]. Other design data are reported in D3.4 [13].

2.2. The PV panels

The PV panels are 6 modules on the laboratory storage room for 1.1 kWp as nominal peak power. The technical nominal details are reported in D3.4.

2.3. The electrical grid

Both the microturbine and the solar panels are connected (for the electrical side) to the campus smart grid that with a link to the 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 via the power electronics consisting of the rectifier and the inverter and being an integral part of the T100 CHP. The connection of the PV panels is performed through a devoted inverter.

2.4. The thermal grid

The thermal grid is based on a two-ring layout to which the generators (the microturbine in this case) are connected to produce hot water for the high temperature line and users (two fan coolers) to extract the heat and 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. More technical details are reported and discussed in [11] and in D3.4.

2.5. The cyber-physical approach

Since the UNIGE facility does not include all the components related to the ROBINSON project (for both Western Islands and Crete sites), the tests for the EMS validation were performed in cyber-physical mode. This means that real-time software was able to operate in connection with the hardware, communicating with UDP channels. As in previous works [15] and as in D3.4, this is an effective solution to obtain experimental results, without the costs and risk of damage of a complete large scale prototype. Due to the cyber-physical approach, it has been possible to improve and validate the EMS for the replication sites.

The communication between the software and the hardware is shown in Figure 1 for the WI case. However, the same approach (with differences in the software due to different simulated components) is also implemented for the Crete district. The software (including the EMS, the MPC, the boiler (or the boilers for the WI case), the mixer with the syngas/biogas inputs (for the Crete site), the electrolyzers, the hydrogen storage vessel, the thermal storage vessel (for the WI site) and the wind turbine) receives four measured data 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 at the follower islands is different from the test environment, a data conversion was implemented to use the 100 kWel T100 microturbine of the test site for a system with a 240 kW engine (for the WI case) or a 240 kW turbine (for Crete). This conversion system is based on lookup tables to scale the signals in both communication senses. Moreover, the T100 microturbine was limited to the 30 kW – 90 kW range to avoid problems due for the ambient temperature change (to avoid different maximum and minimum limits depending on the laboratory real ambient temperature that is not the one measured in the real sites). Finally, the photovoltaic panels were operated with a signal re-scaling because the installed panel area in the laboratory is different from the ones installed in each site.

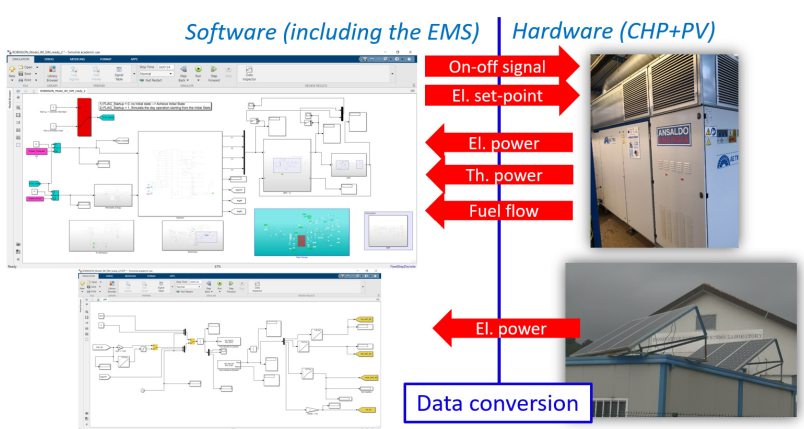

Figure 1 – Data communication between the software and the hardware (tests in cyber-physical mode) for the WI case.

3. Preliminary experimental tests for the EMS validation (WI case)

The test implemented in the mentioned cyber-physical mode refers to the layout of the Creed district (Western Islands) already presented in D3.1. It includes the following components: a 240 kW (electrical power) engine fed by biogas from waste and able to produce also 370 kW of thermal power in CHP mode, a 150 kW kerosene boiler, a 180 kW electrical boiler, 9.75 kWp photovoltaic panels, a 300 kW wind turbine, a 50 kW electrolyzer, a 30 m^3 thermal energy storage (hot water vessel) and a 1.25 m^3 pressurized hydrogen storage vessel.

The input data related to a representative 24-hour test were implemented thanks to devoted bilateral meetings with CNES. In details, Figure 2 shows the electricity cost for purchase from the grid and the flag values for the electrolyzer management that is set to 1 in case of electricity cost lower than the average value and set to 2 in the opposite case. In case of flag 1, the hydrogen vessel set point is 30 bar, while in the opposite case is 10.5 bar. This is the same management approach (implemented for the hydrogen generation/storage system) considered and fully described in D3.4. Moreover, further input data are: 47 GPB/MWh biogas cost, 400 GPB/MWh kerosene cost, 0.3 sell/buy ratio for the electricity and the demands (for electricity, heat and hydrogen) shown in the related result plots.

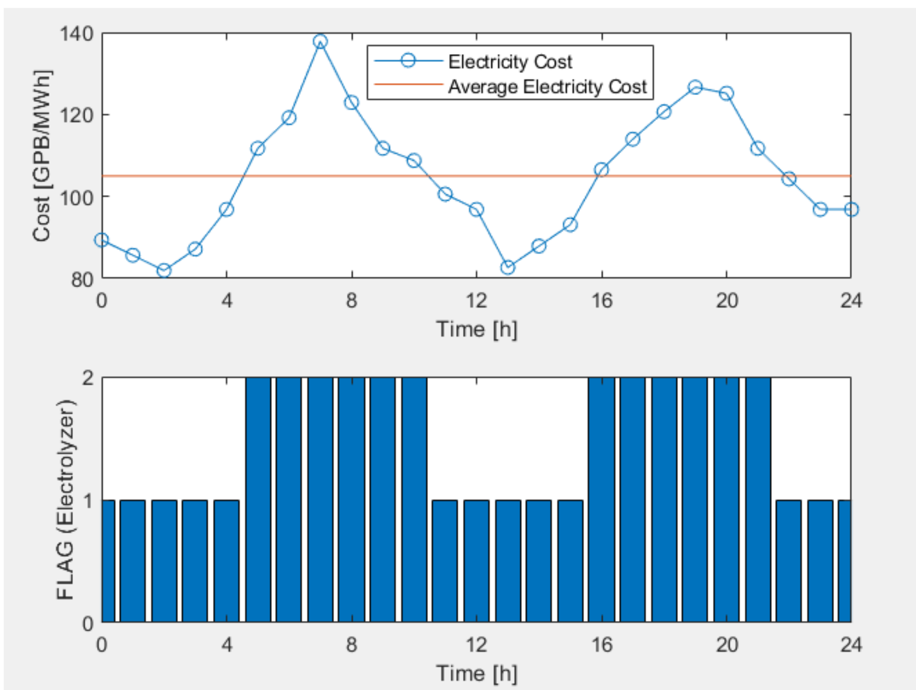

Figure 2 - Electrical costs and electrolyzer flags (WI case).

The Energy Management System (EMS) is based on the same approach described in D3.3 for the Eigerøy site. It includes the optimizer in the decision maker block and an MPC module. Both are based on the same implementing details described in D3.3 including the optimization approach. This is a minimization of a variable cost function including also the operating and maintenance costs. For the subcases related to the different thermal maximum power of the involved prime movers (as in Fig.3 of D3.3), here a similar approach is implemented depending on the component sizes. However, they are implemented with the same approach presented in D3.3 giving low priority to the kerosene boiler for CO_2 emission decrease reasons.

Starting from the defined EMS and based on the simulation results reported in D3.3, the tool was equipped with the UDP communication block for the data exchange with the hardware and the mentioned conversion system. Then, after the T100 start-up and stabilization at the initial set-point of the electrical load, the 24-hour test was started without further modifications on the EMS side. Although D3.3 shows a stable behaviour for the EMS (no oscillations around the set-points) and the energy generation, the experimental tests presented instability problems. As shown in Figure 3 for the electrical side, the EMS produced oscillations with an increasing amplitude and the trend of a divergent behaviour, starting from a stable condition. Since this is not acceptable, the test was terminated after 4500 seconds and the MPC response was slowed down before repeating the test. This is an important result justifying the importance of the experimental tests (although in cyber-physical mode): operations with real data showed the necessity to further stabilize the MPC tool, although no problem was visible with full software simulations.

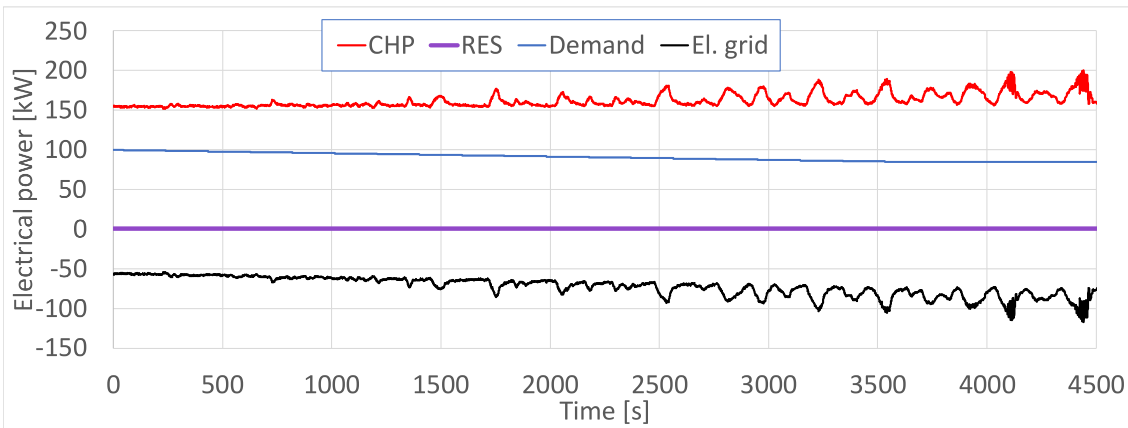

Figure 3 – Preliminary results for the WI case.

4. 24-hour test for the EMS validation (WI case)

The laboratory preparation activities (performed in the IES laboratory in Savona) included meetings and conference calls with the involved partners from the sits on the Western Iles, including discussions on the installed technology or which is going to be installed. At the laboratory side, it was necessary to carefully plan the tests due to the long duration (24-hour duration has been chosen to represent one typical day). For this reason, the support of SIT has been essential to maintain the minimum number of personnel units (N.2 units with one of them, at least, qualified for the fire emergencies – high risk level). Moreover, the communication check system presented in D3.4 has been used also for these tests and maintenance activities have been performed continuing with what presented in D3.4 (essential activities to operate the turbine T100 in the laboratory). It is important to highlight that the tests for the WI case (both preliminary and 24-h tests) resulted in high consumption of natural gas (528.94 m^3) for 34.8 hours of operation (in total) and 4 T100 start-up phases.

As shown in D3.4 for the Eigerøy site, for the WI case Figure 4 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. So, the CHP load was increased. Since the T100 microturbine had some instability problems at about 70 kW electrical load (that corresponds to about 190 kW for the CHP in the WI site) due to an interaction between a critical frequency and the fuel system (just a detailed cleaning of the fuel valves can smooth this phenomenon, as in D3.4), some oscillations are visible for the CHP generation and the power coming from the local electrical grid. However, instead of repeating the test, the results are reported here because they again validate the EMS robustness, important aspects for reaching both KPI 1.1 and 1.2. A significant presence of RES is included due to the generation by both the PV panels and the wind turbine. Figure 4 shows also the comparison with a reference "No EMS" case. Differently from D3.4, in the "No EMS" case the thermal load is fully covered by the two boilers, giving the priority to electrical generation (lower CO_2 emissions). For this reason the CHP in the "No EMS" case is not used as additional thermal energy generation is not necessary. So, the electrical demand is covered by the renewable sources and the local grid (the dotted black line in Figure 4 that includes also the power for the electrical boiler).

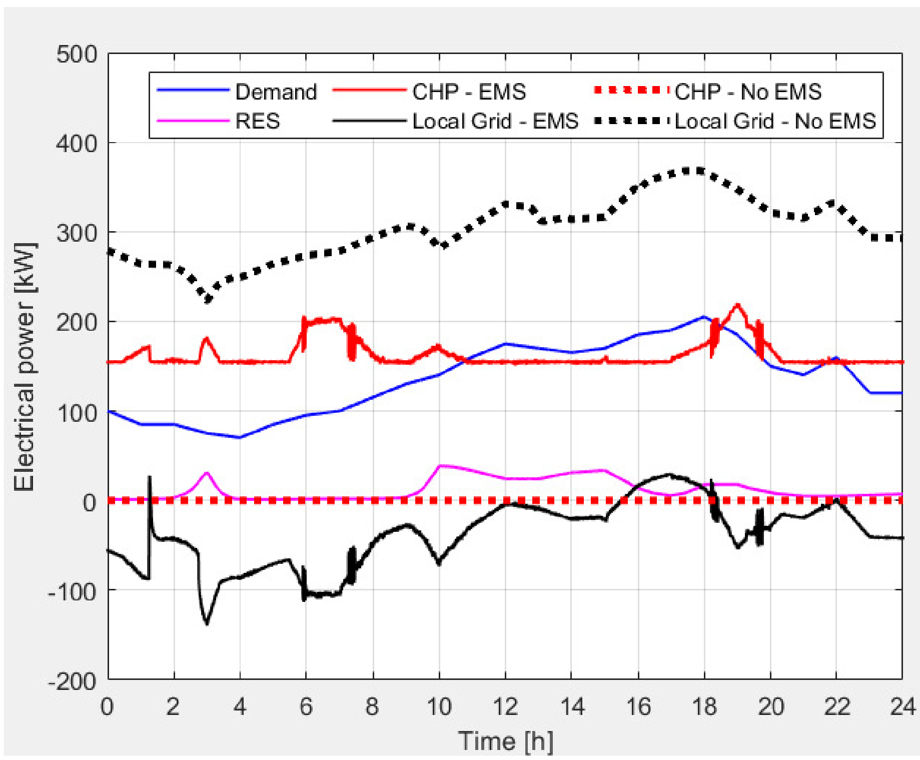

Figure 4 – 24-hour test for the WI case: electrical power.

To better highlight the EMS robustness, Figure 5 shows the electrical power produced by the T100 microturbine (that is converted to the WI CHP power) and the related set-point produced by the EMS (converted to the T100 size) for the 1000 seconds before reaching 6 hours of continuous operation (the hour number 6 in Figure 4). It is visible that while the T100 turbine produced a significant oscillation (in the ±5 kW range), the EMS remained stable without risks related to the system management. The EMS was therefore able to successfully manage the system (hardware + software devices) without faults or unstable operations even in case of the typical oscillations of a real plant.

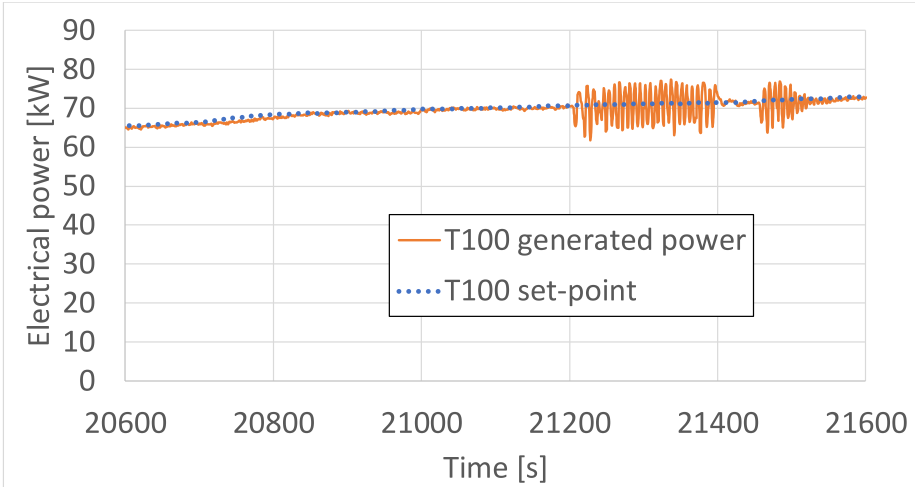

Figure 5 – Detail for the T100 microturbine (WI case).

The results obtained in the 24-hour test for the thermal side are reported in Figure 6. While for the "EMS" case the CHP covered the demand for large parts of the test, the kerosene boiler was not used and the electrical boiler was operated for a few hours during the night when the CHP generation increase was not effective from the cost point of view. Also in this case the comparison with the "No EMS" case is included. The EMS allowed to reduce to the boiler utilization with an important benefit for both cost and emissions thanks to the CHP management.

Figure 6 includes also the State of Charge (SoC) level for the 30 m^2 hot water vessel. In the "No EMS" case the SoC variation was almost negligible due to the fact that the boilers operate to cover the entire thermal demand. In the "EMS" case the CHP utilization generated conditions with thermal generation excess that increased the SoC level. To complete the discussion about the hot water vessel Figure 7 shows the temperature trends related to the 16 calculation nodes used for the vessel model in the "EMS" case. Since these values are used to calculate the SoC ("EMS" case) in Figure 6, the correspondence between the temperatures and the related SoC is evident: when the temperatures are flat the SoC is constant and when they are increasing the SoC is increasing.

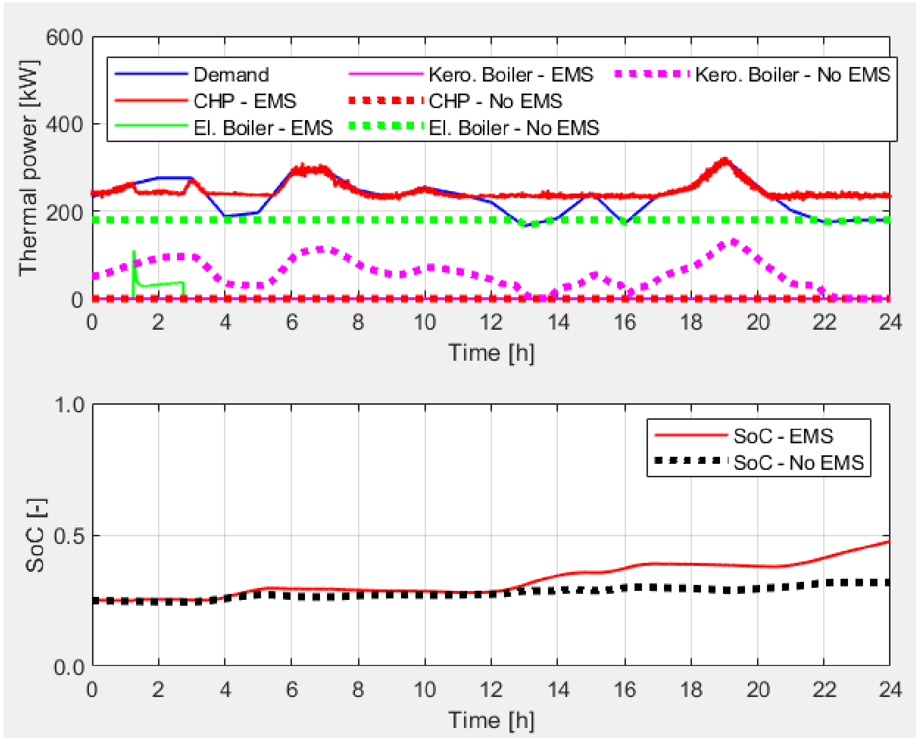

Figure 6 - 24-hour test for the WI case: thermal power.

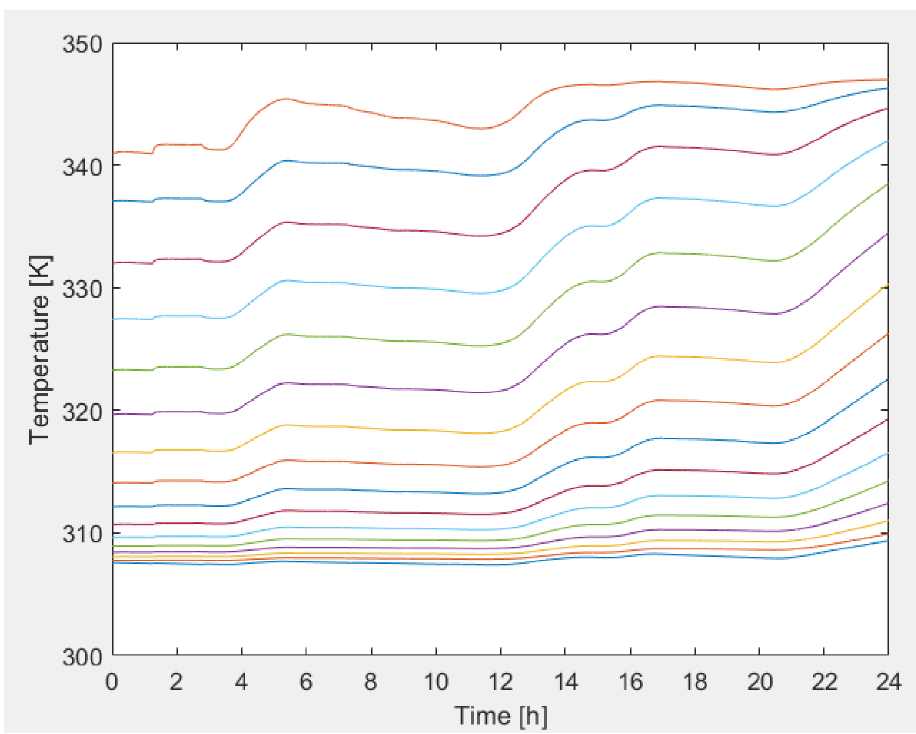

Figure 7 – 24-hour test for the WI case: 16 temperatures related to the thermal storage vessel (1D model) for the cyber-physical test operated with the EMS.

As already described in D3.3 and D3.4, the hydrogen generation/storage/utilization is managed considering the flag values in Figure 2. Moreover, the hydrogen outlet mass flow rate (from the storage vessel) is related to the utilization for transportation: the charging of a truck tank (up to 32 kg of H_2). Figure 8 shows that during the truck charging operations (the charging event was at 5 a.m. for a duration of 3000 s) the hydrogen pressure in the storage tank significantly decreases, while the recharging is mainly obtained during the periods with the electricity cost lower than the average value (when the flag in Figure 2 is equal to 1). The reference case for the standard management ("No EMS" in Figure 8) was obtained by maintaining the electrolyzer at the minimum generation during the entire test. This is not enough to compensate the hydrogen consumption, resulting in a decreasing pressure in the storage tank.

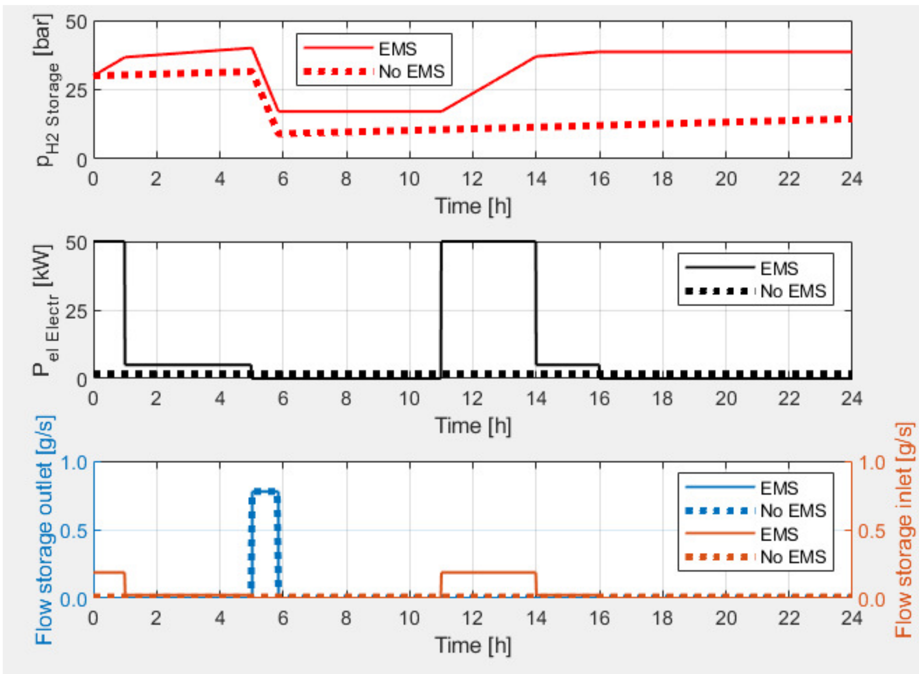

Figure 8 - 24-hour test for the WI case: hydrogen generation and storage.

4.1. Global results

To finalize the test for the WI case, this section reports the comparison of the global main parameters for the 24 hours test. Starting from the variable cost comparison (the objective of the optimization tool), Figure 9 shows that the EMS application generated about 40.8% reduction. However, the EMS application generated also positive results for other parameters. Figure 10 shows an overall efficiency increase of about 23.2% as another important confirmation of the KPI 1.1 achievement for the replication site also. Finally, it is important to highlight that switching from a system based on electricity and kerosene (the "No EMS" case) to the optimized management (the "EMS" case) that is mainly based on biogas and some electricity, the CO_2 emissions decreased more than 97.5% (Figure 11).

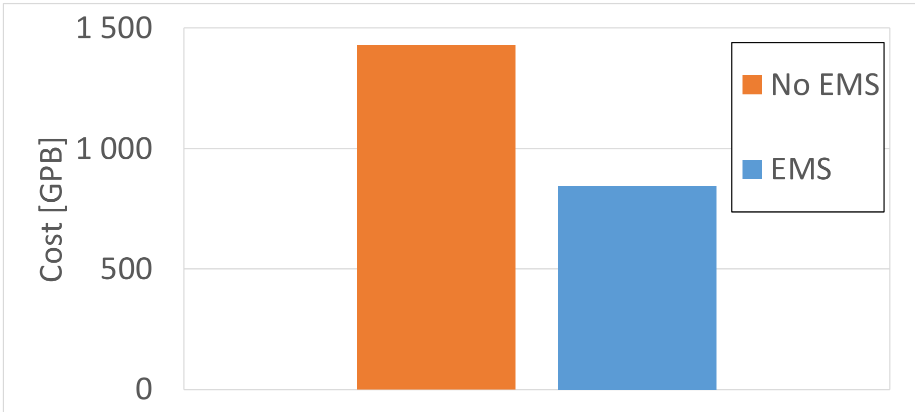

Figure 9 - 24-hour test for the WI case: global performance comparison (cost).

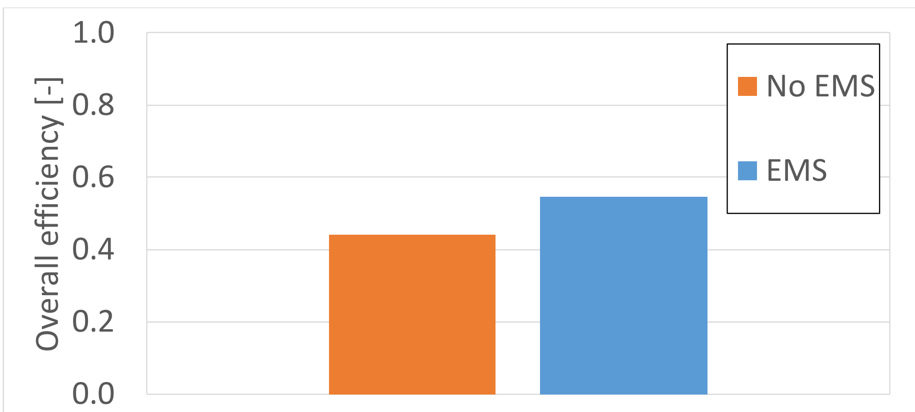

Figure 10 - 24-hour test for the WI case: global performance comparison (overall efficiency).

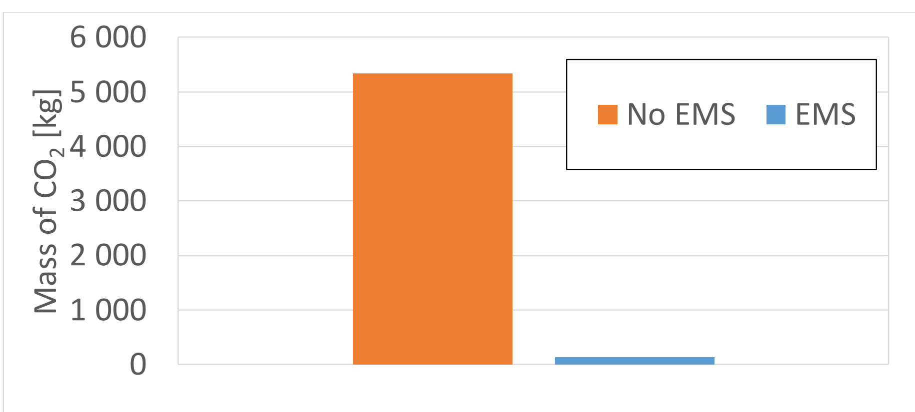

Figure 11 - 24-hour test for the WI case: global performance comparison (CO_2 emissions).

5. Preliminary experimental tests for the EMS validation (Crete case)

The test case for Crete which was implemented in the mentioned cyber-physical mode refers to the layout of the Manna district (Crete Island) already presented in D3.1. It includes: a 240 kW (electrical power) turbine fed by biogas, syngas and hydrogen (thanks to a gas mixer) and able to produce also 370 kW of thermal power in CHP mode, a 450 kW boiler fed by LNG, 240 kWp photovoltaic panels, a 60 kW wind turbine, two 500 kW electrolyzers, and a 40 m^3 pressurized hydrogen storage vessel.

The input data related to a representative 24-hour test were implemented thanks to devoted bilateral meetings with TUC. In details, Figure 12 shows the electricity cost for purchasing from the grid and the flag values for the electrolyzer management that is performed as reported in section 3. This is the same management approach (implemented for the hydrogen generation/storage system) considered and fully described in D3.4. Further input data are: 43.19 €/MWh LNG cost, 55 €/MWh syngas cost, 0.3 sell/buy ratio for the electricity and the demands (for electricity, heat and hydrogen) shown in the related result plots. 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), as in D3.4. For the transport, the charging of a truck tank (up to 32 kg of H_2) was considered.

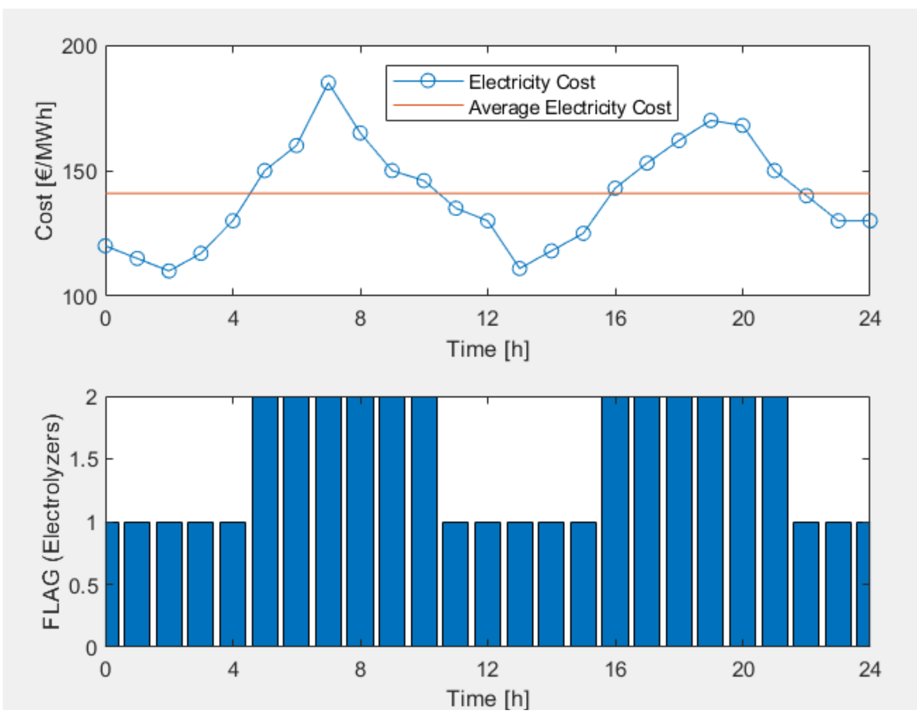

Figure 12 - Electrical costs and electrolyzer flags (Crete case).

The Energy Management System (EMS) is based on the same approach as described in D3.3 for the Eigerøy site and for the WI cases. It includes the optimizer in the decision maker block and an MPC module. Both components are based on the implementing details as described in D3.3 including the optimization approach, a minimization of a variable cost function and including also the operating and maintenance costs. For the subcases related to the different thermal maximum power of the involved prime movers, here a similar approach is implemented depending on the component sizes.

Starting from the EMS defined and used to obtain the simulation results reported in D3.3, the tool was equipped with the UDP communication block for the data exchange with the hardware and the mentioned conversion system. After the T100 start-up and stabilization of the electrical load to the initial set-point, the 24-hour test was started without further modifications on the EMS side. Although D3.3 shows a stable behaviour for the EMS as no oscillations are present in the set-points and in generation, also in this case the experimental tests showed instability problems. As visible in Figure 13 even though starting from a stable condition of the T100 (electricity generation) the EMS produced oscillations with an increasing trend of the amplitude indicating a divergent behaviour. Since this is not acceptable, the test was terminated after 600 s and the MPC response was slowed down before repeating the test. This result again justifies the importance of the experimental tests (although in cyber-physical mode) to develop and implement measures for further stabilization. This problem would not be noticeable with full software simulations only.

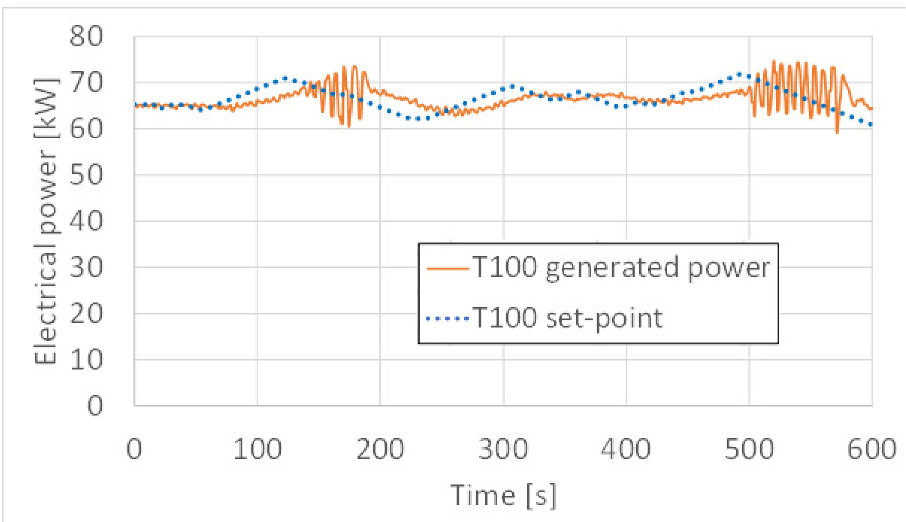

Figure 13 - Preliminary results for the Crete case (T100 microturbine side).

6. 24-hour test for the EMS validation (Crete case)

The laboratory preparation activities (performed in the IES laboratory in Savona) included meetings with the involved partners for the Crete site with discussions on decisions about the technology installed or to be installed. On the laboratory side, it was necessary to carefully plan the tests due to the long duration (24-hour duration has been chosen to represent one typical day). For this reason, also in this case, the support of SIT has been essential to maintain the minimum amount of personnel units. The communication check system presented in D3.4 has been used also for these tests. Finally, it is important to highlight that these tests for the Crete case (both preliminary and 24-h tests) resulted in a high consumption of natural gas (573.36 m^3) for 28.6 hours of operation (in total) and 3 T100 start-up phases.

As shown in D3.4 for the Eigerøy site, for the Crete case Figure 14 shows that the CHP load changed due to the electricity cost change: the cost decrease produced an optimal solution with the CHP at low load. The increase of the electricity cost changed the optimal solution calculated by the EMS and the CHP load was increased. Since the T100 microturbine had some instability problems at about 70 kW electrical load (that corresponds to about 180 kW for the CHP in the Crete site) as shown for the WI case, some oscillations are visible for the CHP generation and the power sold to the local electrical grid. As for the WI case, these results validate again the EMS robustness, important aspects for reaching both KPI 1.1 and 1.2. Differently from the previous cases, this analysis included a large amount of RES (up to values close to 140 kW during the central hours of the day) due to the generation by the PV panels and the wind turbine. Figure 14 includes also the comparison with a reference "No EMS" case that is performed operating the CHP to simply satisfy the electrical demand. During hours with RES-based generation higher than the demand, the CHP (the dotted red line in Figure 14) in the "No EMS" case for more than 5 hours at its minimum load.

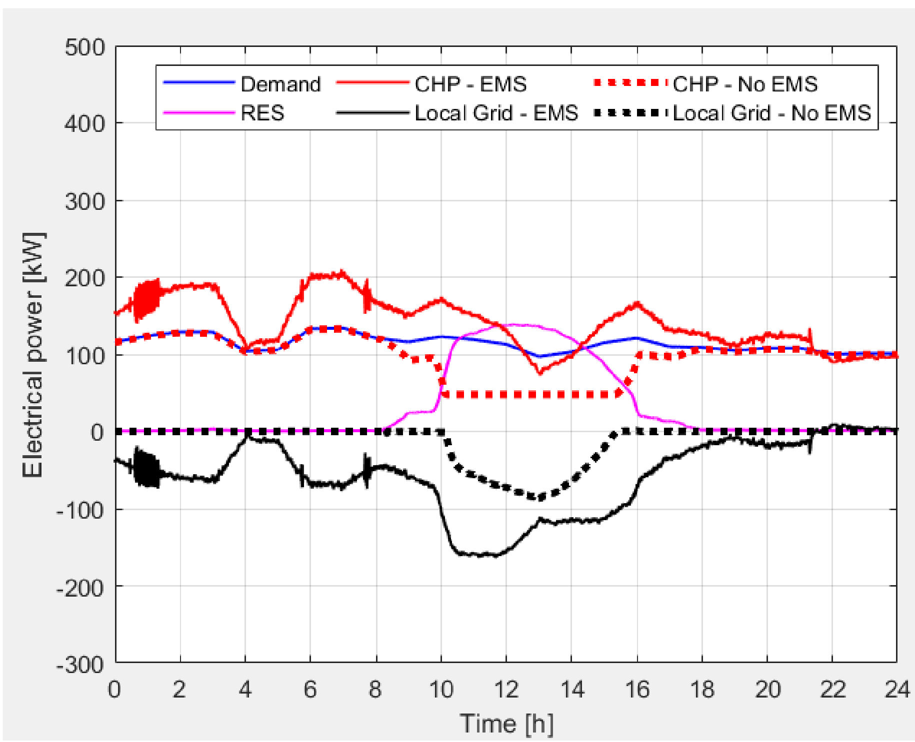

Figure 14 – 24-hour test for the Crete case: electrical power.

To better highlight the EMS robustness, Figure 15 shows the electrical power produced by the T100 microturbine (that is converted to the Crete CHP power) and the related set-point produced by the EMS and converted to the T100 size for the initial 2 hours (7200 s in Figure 14). It is visible that while the T100 turbine produced a significant oscillation (in the ±5 kW range), the EMS remained stable without risks related to the system management. It is therefore proven that the EMS, with the typical oscillations of a real plant, was able to successfully manage the system (hardware + software devices) without faults or unstable operations.

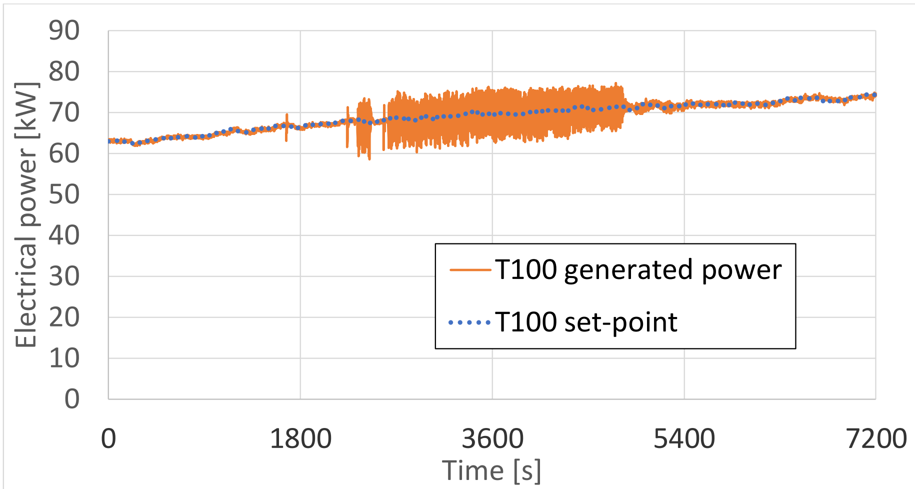

Figure 15 – Detail for the T100 microturbine (Crete case).

The results obtained in the 24-hour test for the thermal side are reported in Figure 16. Since the thermal demand is always higher than the CHP generation, the boiler was always used. Also in this case the comparison with the "No EMS" case is included. The EMS, thanks to the CHP management, allowed to reduce to the boiler utilization with an important benefit for both cost and emissions.

As already described in D3.3 and D3.4, the hydrogen generation/storage/utilization is managed considering the flag values in Figure 12. Moreover, the hydrogen outlet mass flow rate (from the storage vessel) is related to the utilization for transportation: the charging of a truck tank. Figure 17 shows that during the truck charging operations (the first charging event was at 5 a.m. while the second one at 11:15 a.m. – both for a duration of 2400 s) the hydrogen pressure in the storage tank significantly decreases, while the recharging is mainly obtained during the periods with electricity cost lower than the average value (when the flag in Figure 12 was equal to 1). The reference case for the standard management ("No EMS" in Figure 17) was obtained maintaining the electrolyzers at the minimum generation during the entire test. This is not enough to compensate the hydrogen consumption, producing a general decreasing pressure trend in the storage tank.

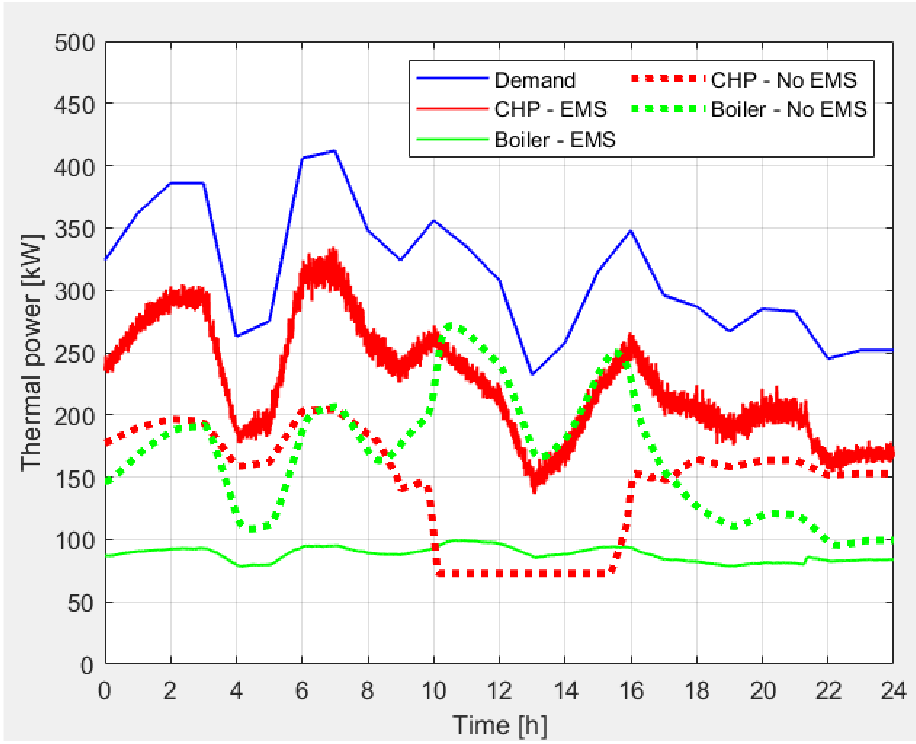

Figure 16 - 24-hour test for the Crete case: thermal power.

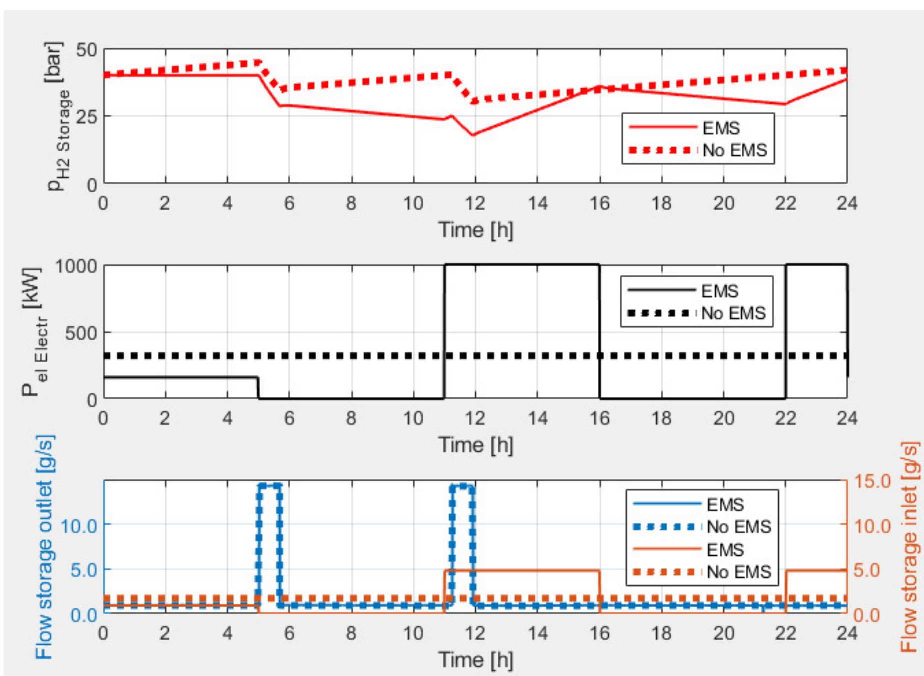

Figure 17 - 24-hour test for the Crete case: hydrogen generation and storage.

6.1. Global results

To finalize these tests for the Crete case, this section reports the comparison of the global main parameters for these 24 hours. Starting from the variable cost comparison (the objective of the optimization tool), Figure 18 shows that the EMS application generated about 5.4% decrease of these variable costs. However, the EMS application generated also positive results for other parameters. Figure 19 shows that the CO_2 emissions decreased by about 1.7% (not high decrease in comparison with the WI case due to the necessity of consuming LNG with the boiler also for the EMS case). Probably with a lower thermal demand (in the 200-300 kW range) the CO_2 emission decease would be even more significant.

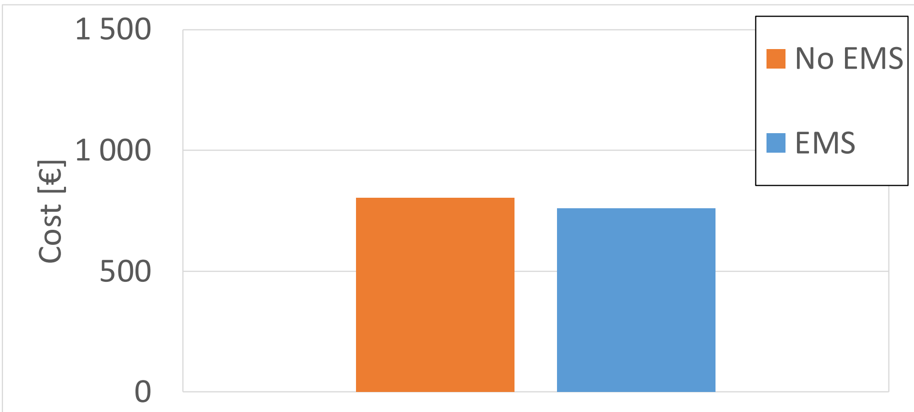

Figure 18 - 24-hour test for the Crete case: global performance comparison (cost).

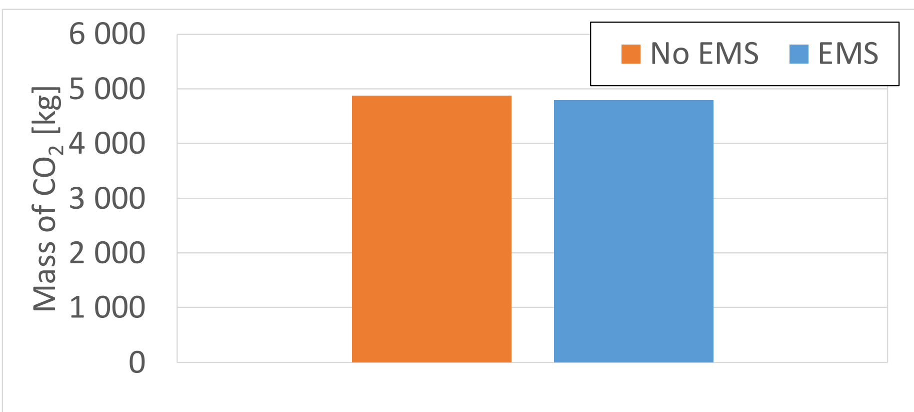

Figure 19 - 24-hour test for the Crete case: global performance comparison (CO_2 emissions).

7. Cybersecurity management system for the EMS

From the cybersecurity point of view and as stated in the ROBINSON objectives, the Blockchain and its API referenced in the architecture, presented in the periodic technical report 2, should be replicable to all sites to provide integrity and availability to the EMS system as mentioned in earlier deliverables. From the point of view of cybersecurity requirements in this deliverable (OB 4 and to some extent OB 8), the API requires minimal or no changes to adapt it to the actual replication sites employed in the three islands, independently of their input configurations or variables. This is because the API can save a file input with any content in the Blockchain (assuming a standard input for each island) so for each of the islands, it already complies with the traceability requirements set at the start of the project. Additionally, the API could be integrated in later WPs with the anomaly detection module developed in cyber-physical mode (OB 1).

The Blockchain and its API is running on FUNDITEC premises in the web address provided to the consortium. To publicise such an address in a secure manner would require a clear roadmap to productivize the EMS, and naturally we would need to add more features as security and authentication to it before the system enters production. That would be beyond the prototype status of our contribution in this deliverable.

7.1. Registering log files at replication sites

We provide several evidences to showcase the use of the Blockchain and its API in ROBINSON. To register a log file, users set the ACTION field to TRUE as usual and provide the log file name and hash. The API interacts with the validator node of the blockchain to add the log file's information to the blockchain. Once the transaction is validated and added to the blockchain, the API returns a "1" as the output (Figure 20).

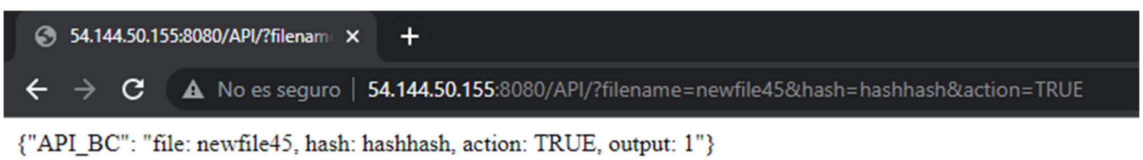

Figure 20 - Register log file process.

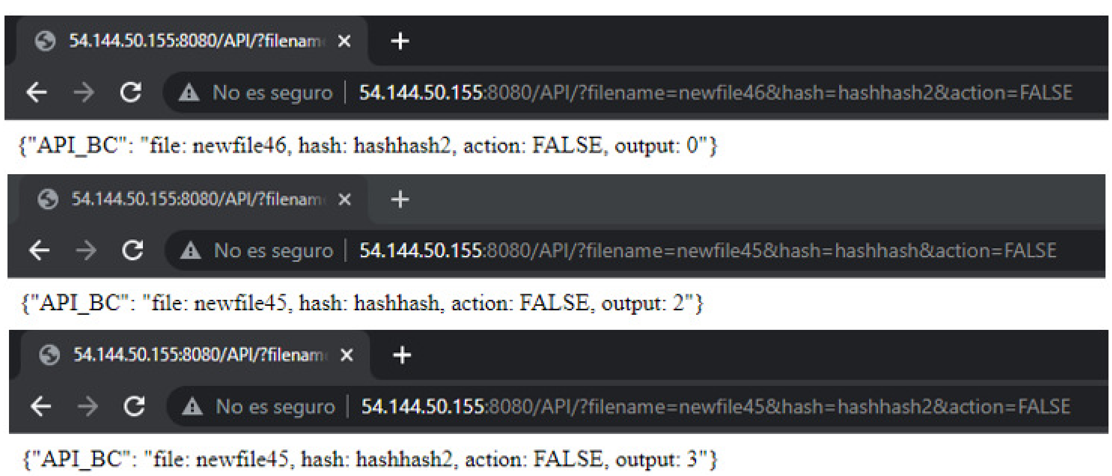

Figure 21 - Verify log file process.

7.2. Verifying log files at replication sites

To verify a log file integrity, users set the ACTION field to FALSE and provide the log file name and hash. The API checks the blockchain for the log file registered information. If the log file is not found on the blockchain, the API returns a "0". If the log file is found and its hash matches the stored hash, the API returns a "2", indicating that the log file integrity is intact. If the log file is found but its hash does not match the stored hash, the API returns a "3", signifying that the log file has been modified as usual (Figure 21).

The blockchain and API code is available at https://github.com/funditec-cyber/robinson-ems-scripts

We are also adding a layer of vulnerabilities assessment to the components of this system as well as the components in cyber-physical mode or real ones used in the plant at PRIMA once installed and finalized. For that, we continue to extend the capabilities to our "pen-testing" software called robinson-crawler: https://github.com/funditec-cyber/robinson-netcrawler, nevertheless to be integrated in later activities.

8. Summary

This report (D3.5 of the ROBINSON project) presents the experimental tests performed in cyber-physical mode in the IES laboratory of the UNIGE partner for the use cases of the two follower islands WI and Crete. However, this activity is the final result of an intense collaboration between the partners involved in T3.4 and in the entire WP3. An important collaboration activity regarded SIT, the UNIGE third party, who provided support especially during the long laboratory tests (24 hours for each test plus the start-up/shutdown time and the rig preparation). Considering the experimental activities presented here for both sites the main results are reported in the following points.

- A cyber-physical approach was successfully implemented for the EMS validation tests in the two replication cases (The Creed and the Manna districts for the WI and Crete sites respectively).
- Two 24-hour tests were performed considering two different cases.
- In both cases the EMS correctly managed the system (including the hardware) without instability problems (this result was obtained after the MPC stabilization because the preliminary results showed instabilities in both cases).
- 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 (WI case: +23.2% overall electrical efficiency, -40.8% cost and -97.5% CO_2 emissions; Crete case: -5.4% cost and -1.7% CO_2 emissions).

Considering these 24-hour tests, the obtained +23.2% overall electrical efficiency for the WI case (efficiency ">20% compared to standard energy management approach") and the confirmed software stability, this document (D3.5) shows the confirmation of the achievement of KPI 1.1 and KPI 1.2 of the ROBINSON project. Moreover, the experimental results (for tests in cyber-physical mode) reported in this deliverable are the mean of verification of MS11 (“The EMS is validated for the follower islands”).

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