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 3.3 – Preliminary performance of integrated system operating with the management tool

Lead partner: UNIVERSITA DI GENOVA

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	D3.3		
Title	Preliminary performance of integrated system operating with the management tool		
Work Package	3		
Dissemination level	Public		
Due date (M)	29	**Submission date (M)**	24.02.2023
Deliverable responsible	Mario L. Ferrari		
Contributing Author(s)	Mario L. Ferrari		
Reviewer(s)	Peter Breuhaus		
Final review and quality approval			

Document History

Version	Date	Name	Comments[1]
1.0	10.02.2023	D.332_Robinson_Draft 0.docx	Document for review
1.1	22.02.2023	D.332_Robinson_Draft 1.docx	Document after review
1.2	24.02.2023	D.332_Robinson_Final.docx	Document sent for hearing
1.3	24.02.2023	D.332_Robinson_Final.pdf	To be submitted to European Commision

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

Executive summary

Deliverable 3.3 of the ROBINSON project corresponds to Task 3.3 that is entitled "Integration of all components in the EMS incl. local management systems". This document regards the Energy Management System (EMS) development, its integration in the system and the analysis to evaluate preliminary performance. In details, for the Eigerøy case, attention is focused on simulation results and on preliminary tests operated in the Innovative Energy Systems (IES) laboratory in cyber-physical mode. Moreover, in the replication section simulations are presented for the Western Isles and Crete. Starting from the modelling activities performed in T3.2, this report shows the results obtained with the EMS ranging from pure software simulations to preliminary laboratory experimental results. Moreover, special attention was devoted to data traceability and cybersecurity. The results reported in this deliverable will be transferred to T3.4 for the EMS validation activities in the IES laboratory.
In details, the report presents the following topics:

- Development and description of the Energy Management System (EMS).
- EMS integration with the component models.
- Simulations with the EMS considering component models for Eigerøy.
- Laboratory preparation for the tests in cyber-physical mode.
- Preliminary tests showing the EMS performance in cyber-physical mode.
- Laboratory tests for data integrity and cybersecurity.
- EMS details and simulation results for the other islands: Western Isles, and Crete.

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List of abbreviations

AD	Anaerobic digestion
BES	Bioelectrochemical system
CHP	Combined heat and power

EL	Electrical
EMS	Energy management system
IES	Innovative Energy Systems laboratory
KPI	Key Performance Indicator
LNG	Liquefied Natural Gas
max	Maximum
min	Minimum
MPC	Model Predictive Control
P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
PV	Photovoltaic
RES	Renewable Energy Source
TH	Thermal
TRL	Technology Readiness Level
UDP	User Datagram Protocol
WP	Work package

<u>Variables</u>

A, B, C	General matrixes for the MPC
c	cost
E	Energy
LHV	Low Heating Value
J_{cost}	Total operational cost
k	Generic variable for the MPC presentation
m	Mass flow rate
M	Mass
N	Number
P	Power
r	Set-points by the Decision maker
T	Temperature
u	Set-points or input variables for the system
x	State variables

y	Output variables for the system
η	Efficiency
Subscripts	
amb	Ambient
CHP	Combine heat and Power
el	Electrical
O&M	Operation and Maintenance
st	Startup
th	Thermal

1. Introduction

The ROBINSON project "Smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands" aims at developing an integrated system for island application, managed by a software (the Energy Management System, EMS) in a real-time mode. The development of a real-time software for the optimization of a smart grid [1] is essential for the ongoing energy transition process. This tool needs to be based on an optimization algorithm able to operate with non-linear systems and to work in real-time mode. The software concept can range from very simple models (e.g. some if/else cases coupled with a prime mover ranking [2]) to very complex approaches using optimizers [3] or agent-based calculations [4]. In this work, considering the positive results obtained in previous activities including experimental tests [5], the EMS is based on the coupling of a market function block (with a minimization algorithm and if/else cases) with a Model Predictive Control (MPC) tool. This MPC takes into account the generator dynamics avoiding a rigid connection between the optimizer and the physical systems [6]. Since this approach was already tested at Technology Readiness Level (TRL) equal to 5 [4], in the ROBINSON project the demonstration in the Eigerøy island (Norway) is expected to reach TRL 7 [6].

Considering the needs of the ROBINSON project, the activity has been started with simulations in Matlab-Simulink including the models (software) of the necessary generators. The project activities continue with experiments in the Innovative Energy Systems (IES) laboratory [7] at the University of Genoa before implementation at the demo site in Norway. Both simulation and experimental results reported in this deliverable will be transferred to T3.4 for the EMS laboratory validation for all the three cases (Eigerøy, Western Isles, and Crete)

This report is organized as in these chapters:

- Chapter 2 presents the general EMS development.
- Chapter 3 reports the EMS integration with the component models (at software level).
- Chapter 4 reports the simulation results with the Eigerøy case.
- Chapter 5 presents details of laboratory preparation activities for tests in cyber-physical mode.

- Chapter 6 reports the results of preliminary tests in cyber-physical mode.
- Chapter 7 is a section devoted to the activities on data integrity and cybersecurity performed at the UNIGE laboratory.
- Chapter 8 is the replication section devoted to simulation results for the Western Isles, and Crete cases.
- Chapter 9 summarizes the deliverable content.

2. Development and description of the Energy Management System (EMS).

The Energy Management System (EMS) developed for the ROBINSON project needs to control and optimize the operation of the polygeneration grid in a robust way, integrating the inputs from other sources around it. The target is the minimization of costs, considering also the management of the hydrogen storage vessel. The general approach presented here is the basis for all cases. Starting from the Prima Protein district in the Eigerøy island, the same general EMS concept is used for the Western Isles, and Crete cases (minor modifications have been implemented in these cases, as described in the replication section). The EMS is basically constituted by a decision maker module (the block called "Decision maker - Market function" in Figure 1) and an MPC module. The necessary inputs are the power demands (in real-time mode), the cost curves for the electricity market and the fuel costs.

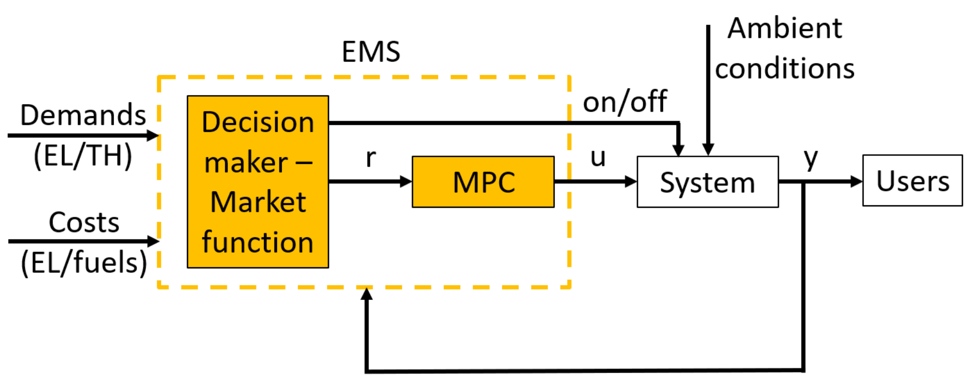


Figure 1 – EMS layout

Basing on the demand curves, the Decision maker calculates the best strategy with a 15 minutes time step (optimization performed every 900 s), defining the set points (r, in Figure 1) for the system in order to minimize the operational cost. The 15-minute optimization time step was chosen due to the component slow dynamics, the electrical grid connection, and the necessity to reduce the computational effort to obtain real-time performance. This is done using an optimizer, described in section 2.1. The set point signals computed by the Decision maker are the MPC inputs for the calculation of the actuator signals (u, in Figure 1). The system output (the generation for the users – y, in Figure 1) is the feedback for the EMS. These three vectors (r, u, and y) include the following power set-points or measurements: the CHP electrical power, the boiler thermal power, and the electrical power of the electrolyzers. An additional value (the storage vessel pressure) is necessary for the hydrogen system, as described in section 2.3. Figure 2 shows the details of the interactions between the EMS and the components with a simplified system P&ID.

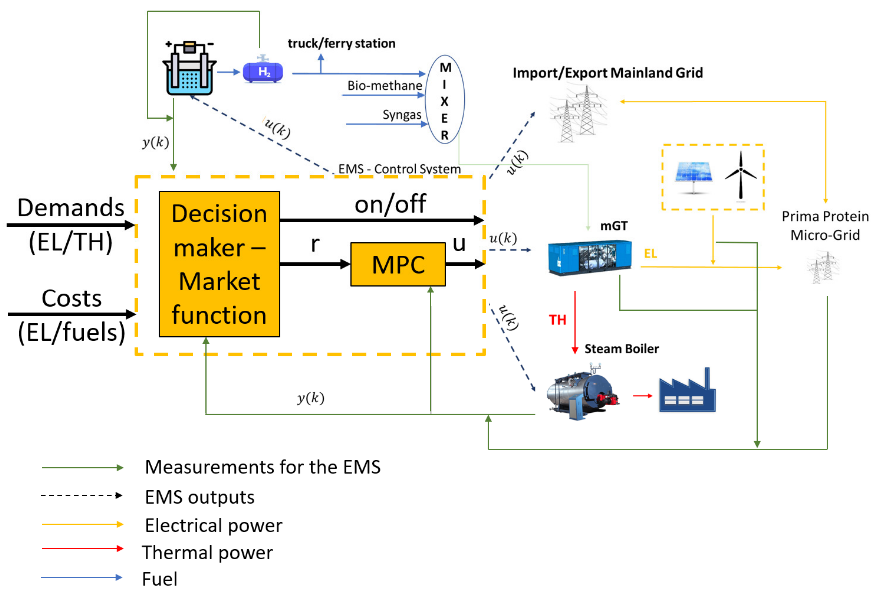


Figure 2 - Simplified system P&ID

In the final application, the controlled system (in Figure 1) will be the real energy generators of the ROBINSON demo. However, in order to set up the controller, it is fundamental to study it in a simulation environment, and this requires a model as accurate as possible. This is made through the development of data-driven models of each component of the system, as presented in D3.2. These models are used to set up and test the EMS in the simulation environment, and then followed by an implementation in cyber-physical mode (in the IES laboratory, as described in section 6 from the preliminary experimental results).

The controller is an MPC tool, which itself is split in the actual discrete-time MPC and an observer, that provides information on the system. A predictive control software needs a model of the system itself in order to accurately predict the response of the real system and calculate the best set point signals (also taking into account the different dynamic response of each component). So, it is necessary to know the actual state of the system. However, considering that it is not possible to know every system parameters, an observer is used to estimate the state of the real system, using the measured outputs of it (y, in Figure 1). The MPC runs using the global tool sample time that is 1 s because it produces the signals for the component models (or plants in the demo site) taking into account their dynamic responses. However, the MPC set-points (r in Figure 2) are updated every 15 minutes by the Decision maker – Market function (rate transition blocks are included in Simulink). This is an effective approach considering that demand/generation mismatches on the electrical side can be compensated by the grid and that the time response on the thermal side is very long.

2.1. Decision maker

The decision maker implements an optimizer in order to calculate the best set-point values, given the state of the system, the demands and the variable costs. As previously introduced, the decision maker aims to minimize the total operational cost (J_{cost}) to satisfy the electrical and thermal demands, updating the set point values every 15 minutes. The optimizer receives the electrical and thermal demands, the renewable energy production, the electricity and fuel costs, together with the characteristics of the boiler and the CHP. The optimization variables are the electrical power exchanged with the grid ($P_{el_{grid}}$) and the electrical power produced by the CHP ($P_{el_{CHP}}$). The objective function is fully presented by Eqs.1, 2 and 3 to show how the calculation of different parts.

The fuel mass flow for the CHP is computed, starting from the rated values, using the related consumption curves. If power is purchased from the grid, the cost is based on the purchasing price, otherwise if the power is sold to the grid, the electrical power is multiplied by the selling price value (purchasing price per the selling-buying ratio). So, with this approach, it is possible to use a selling price lower than the buying one (as it happens in some electricity contracts). Moreover, the optimization includes the constrains reported in Table 1. The tool also receives the constraint related to the electrical power balance: the electrical power bought (or sold) from the grid is the difference between the electrical demand and the electrical production by the CHP. If the sign is positive the system is buying from the electrical grid, while in case of negative values, the system is selling to the grid (obtaining an economic income that is taken into account). The Operation & Maintenance costs and the start-up operation impact are included in Eq.1. Finally, no thermal energy cost is included in Eq.1 because it is considered as an internal production and consumption, not generating any cost.

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

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

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

The result of the optimization is thus the 15-minutes interval scheduling, resulting in a Boolean indication whether it is convenient to produce electricity with the CHP and sell it to the grid (if the optimal power of the CHP is higher than its minimum value, or if it is convenient to buy the electricity from the grid, in case the optimal power of the CHP is lower than its minimum value). This is applied in a logic to satisfy the thermal demand of the system, as shown in Figure 3. There are three possible CHP behaviours: thermal power demand lower than the minimum provided by the CHP, thermal power demand between the minimum and maximum that can be provided by the CHP, and when an integration with a boiler is necessary (to satisfy the thermal load).

Table 1 – System constraints used by the EMS for Eigerøy.

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

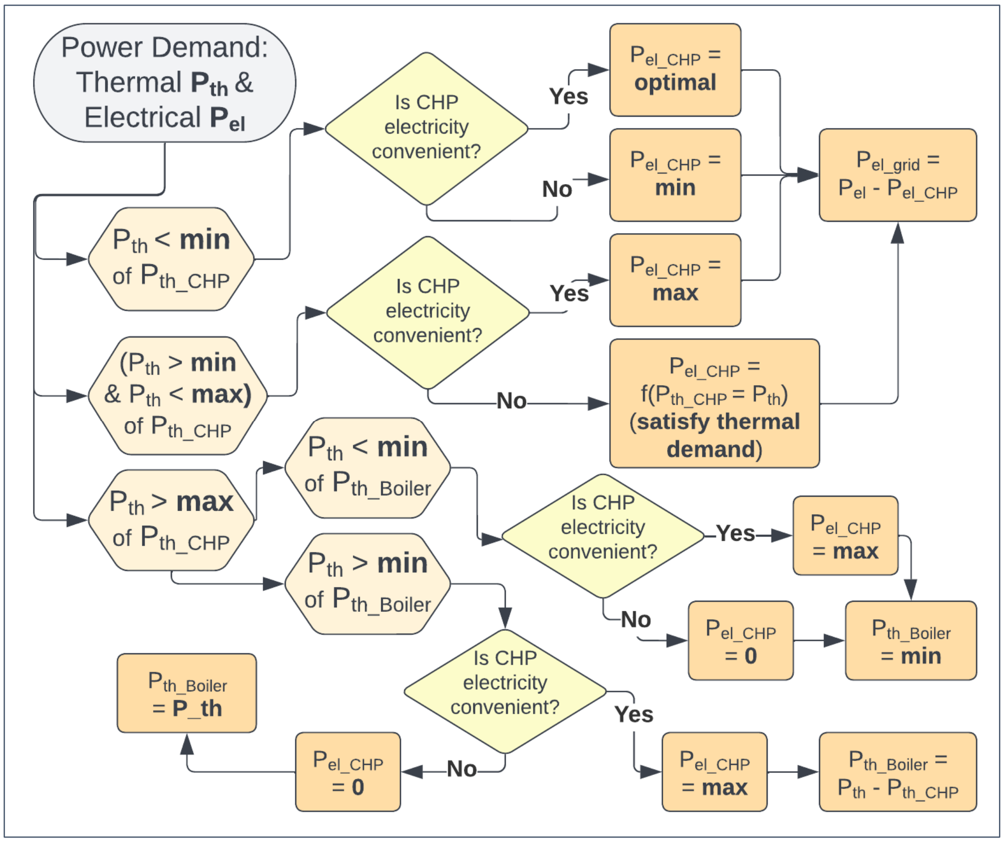


Figure 3 – EMS flowchart logic

2.2. Model Predictive Control

The model predictive control (MPC) system was developed following the procedure suggested in the book by Wang [24]. This controller is a constrained multi-input multi-output MPC, constituted by the actual discrete-time MPC and the integrated observer, used to estimate the state of the system. Its role regards the system control, by computing the values of the actuator variables, given the information on the setpoints from the decision maker, and the system state (feedback of measured values).

The initialization consists in the definition of the time windows for the prediction horizon (N_P = 40 steps) and for the receding control horizon (N_C = 1 step), together with the definition of the sample time of the discrete system (Ts = 1 s). Although the MPC receives updated setpoints (target values) every 15 minutes, this controller operates faster (timestep of 1 s) to calculate in real-time mode the actual setpoint values taking into account the dynamic of the components. Then, the information on the controlled plant, constituted by the CHP turbine and the steam boiler, is needed. A linearized state-space representation of the plant is then used, and passed to the observer; then, it is transformed into an augmented state-space model (matrices A, B, C): it can be based on the differences of the state variables (Δx) and of the input variables (Δu), as shown in the Eq.4. After that, the knowledge of the augmented state-space system, as described, is reordered to be parametrically passed to the actual MPC, together with the constraints on the variables.

$$\begin{cases} \begin{bmatrix} \Delta x(k+1) \\ y(k+1) \end{bmatrix} = A \begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix} + B\Delta u(k) \\ y(k) = C \begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix} \end{cases} \tag{4}$$

When running the code, the controller receives the set points from the decision maker, and the measured values ($y(k)$) from the plant, giving the control signal as an output. Inside the controller, the observer receives the control output from the actual MPC, the estimated state of the system, and the measured values from the plant (through a Kalman filter). From this information and the knowledge of the state-space representation of the system, the observer computes a new estimation of the system state. This is received by the actual MPC (computes a new value for the control variables), which are then passed to the plant and sent in feedback to the MPC and the observer too, for the next step.

2.3. Hydrogen management

The hydrogen production depends mainly on the electricity price; thus the main schedule of the production is made off-line. This results in a daily scheduling with a 1-hour time span, with two possible behaviours, as form Figure 4. If the electricity price is lower than the average one, the electrolyzers will run at design point (flag 1), otherwise the electrolyzers will run in part-load condition on the basis of the implemented maps (flag 2). In details, Figure 4 reports the electricity cost variation for a day in the month of November 2021 for the Eigerøy island. Given this scheduling based on price, the hydrogen (H_2) management follows the storage pressure, using an on-line scheduler and a dedicated MPC. In details, the target pressure for the hydrogen storage can be 40 bar (in case of low electricity price) or 22 bar (in case of high electricity price), while the maximum and minimum values are 42 bar and 10 bar. These values were set on the basis of the technology constraints form the manufacturer and to ensure a good energy safety margin.

The control of the electrolyzers is structured with this approach: an on-line scheduler receives the off-line daily scheduling and the target pressure of the H_2 storage and calculates the set points of the absorbed electrical power. In case of flag 1 (low electricity price), if the pressure of the storage is lower than 90% of the maximum value, the electrolyzers work at design point; instead, if the pressure is between 90% and 96% of the maximum value, the power of the electrolyzers is controlled by the dedicated MPC. Finally, if the pressure is higher than 96% of the maximum value, the electrolyzers are switched off. Instead, in case of flag 2 (high electricity price), the pressure target is 22 bar. In case the storage pressure is higher than this value, the electrolyzers are switched off. Otherwise, the power of the electrolyzers is controlled by the devoted MPC.

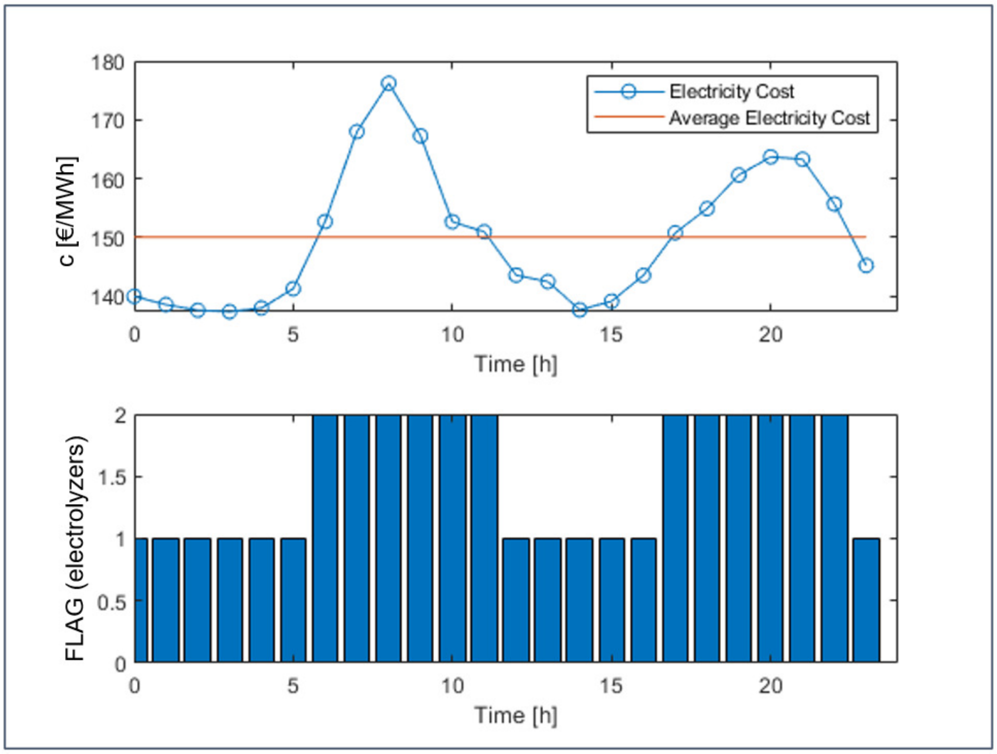


Figure 4 – Electricity cost and flags for the hydrogen system

The models of the electrolyzers, two identical working in parallel (see D3.2 for details), receive an electrical power set point and calculate the efficiency, and the related production (H_2 and O_2), with a dynamic first-order delay. The mass flow rates are then used by the hydrogen storage model (more details in D3.2), to evaluate the storage pressure (40 m^3). The outlet mass flow rates from the storage are calculated by the utilization for transportation and by the need of the gas mixer to satisfy the desired percentage of hydrogen in the CHP fuel. On the transportation side, trucks/trailers storing H_2 to be used as fuel in transport sector are charged at precise moments, and the tank of each truck/trailer can hold up to 32 kg of H_2; a further constraint is that the charging process must not lead to a pressure in the storage lower than the minimum allowable. Thus, the outlet mass flow rates of hydrogen are computed and the MPC tool takes them into account to control the absorbed power of the electrolyzers (to achieve the storage target pressures).

3. EMS integration with the component models

The EMS integration with the components was performed considering the data from WP1 and T3.1. In details, the EMS was connected to input blocks that include the component sizes and main constraints (e.g., minimum and maximum power values). Moreover, the EMS receives other parameters to properly calculate the cost function (in this case this is linked with the A400 efficiency off-design curve) and to set-up the decision boundary values as in Figure 3 (e.g., the coefficients to calculate the maximum and the minimum thermal power values produced by the A400). As shown in Figure 2, the EMS receives in input (in real-time mode) also the demands, the power generation by the renewable sources, the costs (for fuels and electricity). The integration with the component models was developed as presented in the following points:

- the set-point values and the on/off commands for the component models are the EMS outputs and the input of each power generator;
- the real generated power (or storage vessel pressure for the hydrogen generation) by the components is collected in real-time mode provided as input to the EMS.

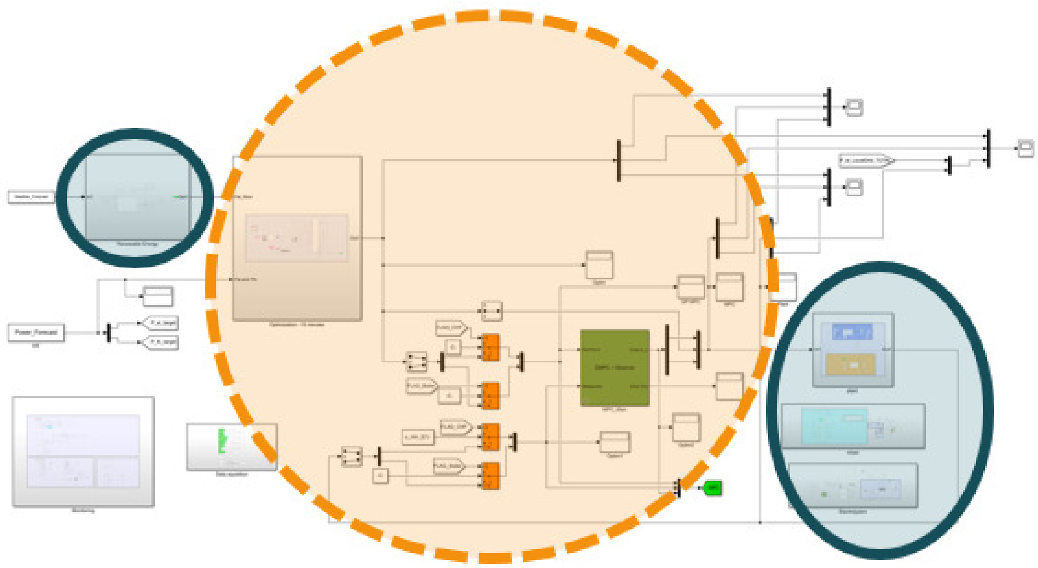


Figure 5 – EMS integration with the component models

Although this is a general integration approach for all the cases, Figure 5 shows the simulation tool for the Eigerøy case. The EMS (with the decision maker and the MPC) is in the dotted ellipse, while the other two ellipses highlight the component models (the PV and the turbine models on the left side – the CHP, the boiler, the fuel mixer, the electrolyzers and the grid connection on the bottom right side).

No models and no direct integration were considered for the AD-BES and the gasifier because they are very slow response devices. So, they are supposed to be controlled to maintain constant the pressure in their gas outlet buffers (devices installed to compensate the system slow dynamic response and to be able to deliver to the mixer all the gas needed for the CHP). So, at the moment, these systems are not managed by the EMS because the mentioned controllers are supposed to be installed in the PLCs of the gasifier and the AD-BES.

4. Simulations with the EMS considering component models for Eigerøy

The simulation results included in this section were obtained with the component models presented and validated in D3.2 and interacting, as in Figure 5, with the EMS. The analysis was performed for the data (electricity costs, weather conditions and demands) related to a day of November 2021 for the Eigerøy island (Prima Protein grid including the connection to the distribution grid). The electricity cost trend was already presented in Figure 4 (the sell/buy ratio was set to 1), while for the syngas a cost 5 €/MWh was considered (it is mainly related to the wood cost). For the LNG (the fuel for the boiler) a cost of 150 €/MWh was implemented in the tool. For the hydrogen flow used for filling H_2-truk/trailer storage, N.2 13.3 g/s demand periods were included for a duration of 2400 s each. The first charging event is implemented at 5 a.m. while the second one at 11:15 a.m. (to simulate a possible future real situation). Another assumption regards the hydrogen percentage in the CHP fuel. Although different compositions are possible, this was fixed to 30% in volume for all the simulations. So, depending on the CHP load (and its fuel consumption calculated by the model) this fixed percentage allows to calculate the amount of hydrogen for the CHP to be taken from the storage vessel.

4.1. EMS performance against a standard management (KPI 1.1)

An initial result regards the comparison of the system management: operation with the EMS against an operation with a standard management approach. This reference approach (named "No EMS" in the following figures) means that the system is managed in the following way: (i) the CHP is operated to satisfy the electrical demand, (ii) the boiler is used when the thermal demand is higher than the CHP maximum thermal generation (since the boiler is a low response device with 2.2 MW of minimum load, the set-point signal is calculated with a PI controller), (iii) the two electrolyzers are maintained at minimum load for the entire simulation.

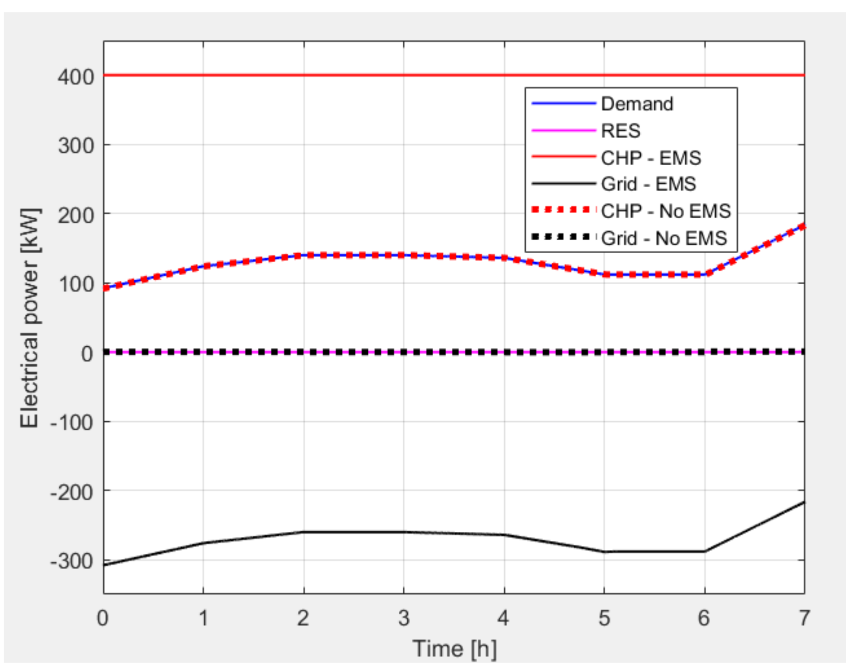


Figure 6 – EMS vs No EMS: electrical power

Due to the system sizes (a 400 kW CHP with a 22 MW boiler), instead of simulating an entire day (performance mainly driven by the boiler) attention was devoted on the initial 7 hours (from midnight to 7:00 a.m.). This is the factory (Prima Protein) start-up period including an important simulation part with the electrical demand lower than the CHP maximum and the boiler ignition. Due to the chosen hours, no PV generation was present. Moreover, due to low wind condition (data from D1.3), also the wind turbine contribution was null (as shown in Figure 6). Since the syngas cost is very low (in comparison with the electricity one), the EMS maintained the CHP at its maximum for all the 7-hours. This was a good solution for obtaining profit from the electrical energy (not consumed and so sold to the grid). Moreover, Figure *6* shows that in the no EMS case, the CHP simply matched the electrical demand.

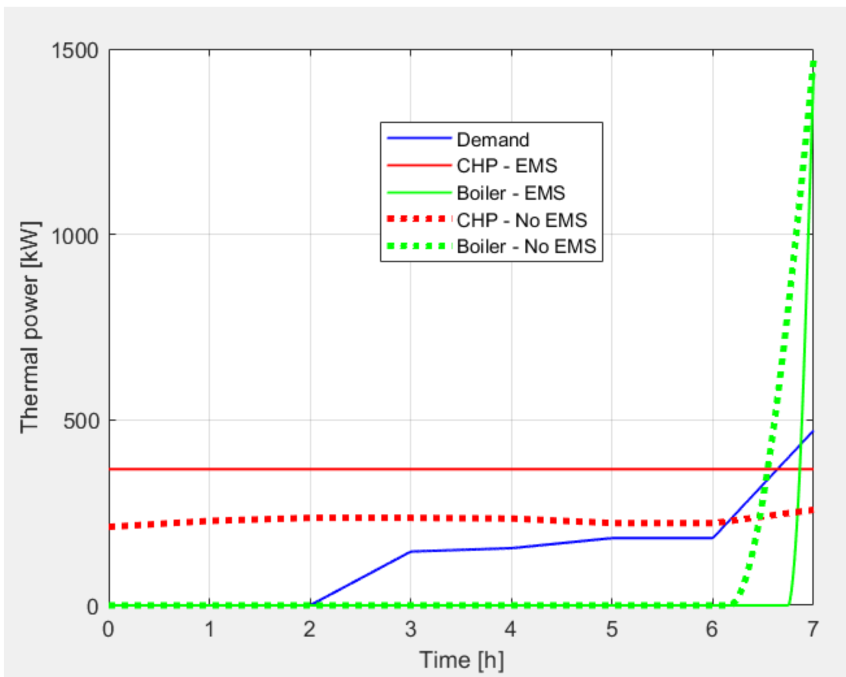


Figure 7 – EMS vs No EMS: thermal power

On the thermal side (Figure *7*), the CHP produced the necessary power for more than 6 hours (since, at the moment, the system does not include a thermal storage, the generation excess was dissipated). The excess of thermal power was more significant in the EMS case because the CHP is at maximum load condition. Finally, when the CHP was not able to satisfy the thermal demand, the boiler was activated: due to the MPC tool the optimized case was more effective because the boiler switch on was delayed of about 30 minutes (with significant fuel saving) and presented a faster increase trend (in comparison with the no EMS simulation).

For the hydrogen side (Figure *8*), in both cases the pressure decreased during these 7 hours due to the charging of the trucks/trailers (as presented before). While the EMS increased the set-point of the electrolyzers (because the electricity cost was lower than the average value), the no EMS case did not exploit this cost benefit. On the other hand, since the no EMS case was not able to switch off the electrolyzers, the pressure vessel showed a slow recharging trend (started at the end of the truck charging). In both cases, the hydrogen pressure vessel remained in the 22-40 bar range maintaining a good energy security margin (no risk of empty condition).

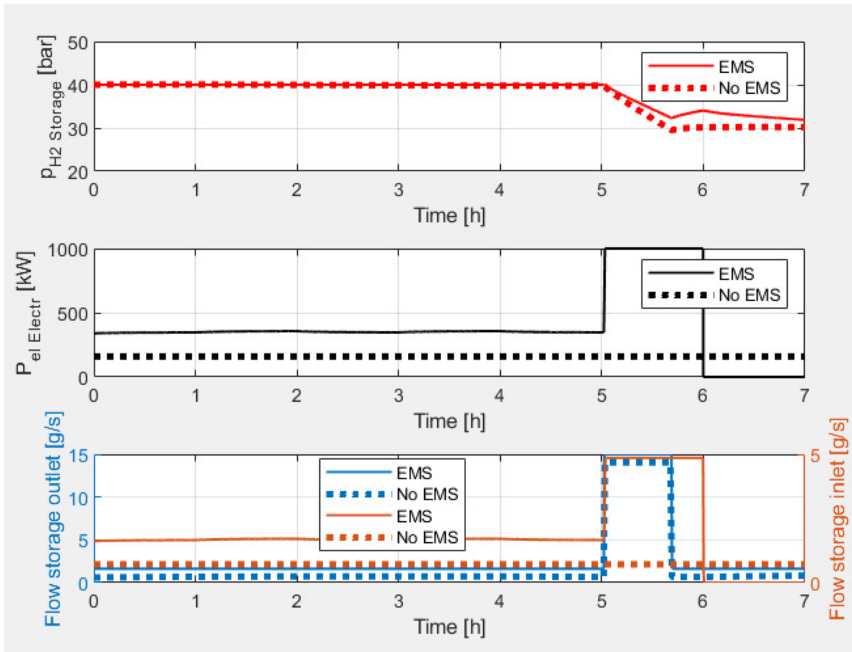


Figure 8 - EMS vs No EMS: H_2 generation, storage and utilization

After the details about electrical, thermal power and hydrogen system, a global comparison was performed for different parameters. Since cost minimization is the EMS objective, Figure 9 shows the variable cost comparison related to this 7-hour simulation. Due to no available specific data for the component O&M costs, literature values were implemented: 0.015 €/kWh for the CHP [11], 1.5% of the capital costs for the electrolyzers [12]. It shows a cost decrease (-30.1%) obtained with the EMS application. This comes from the EMS choice to operate the CHP at its maximum load (cost saving from selling some electrical energy). Moreover, the delayed boiler activation produced a significant fuel saving.

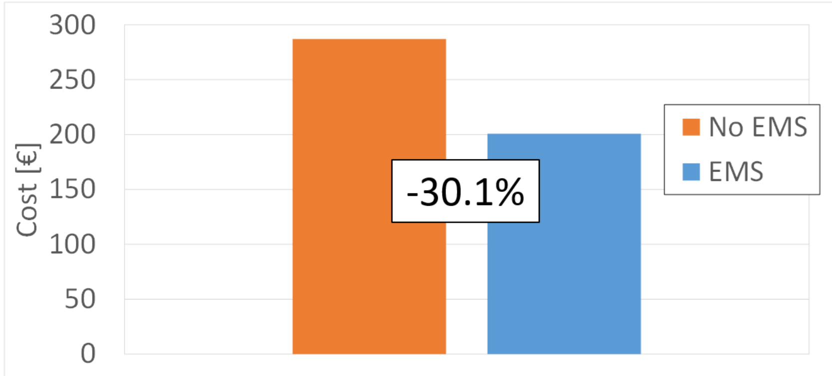


Figure 9 - EMS vs No EMS: variable cost comparison

Although the optimization objective is the cost minimization, this global analysis shows positive effects on other parameters, such as the efficiency values (Figure 10). Attention is focused on the electrical side because on the thermal efficiency is driven by the boiler one because this device is 1-2 orders of magnitude larger than the other components. So, the first-principle total efficiency remains close to the boiler thermal one when this device is used (variation lower than 1.5% in this case). So, two types of electrical efficiencies are compared here (in Eqs.5 and 6). They are expressed in terms of the energy values (produced, consumed or stored) in these 7-hours. The fuel energy (at the denominator in both equations) is calculated doing the sum (for every simulation second) of the products of the fuel mass flow rate per the mixture lower heating value (at the mixer outlet). Eq.6 shows that this system electrical efficiency includes also the consumed hydrogen for the truck/trailer charging ("users" subscript) and the related storage balance (in case of pressure decrease in the hydrogen vessel, this term would be negative to take into account that the consumed hydrogen needs to be produced in the following hours or days).

$$\eta_{el_{CHP}} = \frac{E_{el_{CHP}}}{E_{fuel_{CHP}}} \qquad (5)$$

$$\eta_{el_{system}} = \frac{E_{el_{CHP}} + E_{H2_{users}} + \Delta E_{H2_{storage}}}{E_{fuel_{CHP}} + E_{el_{grid}}} \qquad (6)$$

The electrical efficiency comparison is shown in Figure 10. Due to the EMS utilization (it operated the CHP at the nominal condition), the microturbine worked at higher electrical efficiency, with an increase of 35.3%. Moreover, Figure 10 shows a system electrical efficiency increase of 41.6%.

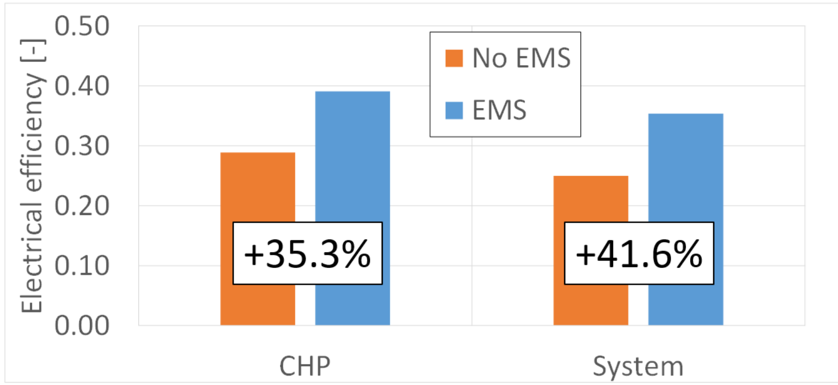


Figure 10 - EMS vs No EMS: electrical efficiency comparison

Considering the environmental issues, it is important to highlight that the EMS has an important impact on the CO_2 emission side (for this 7-hour calculation). These emissions are based on (Eq.7) the sum of the mass of CO_2 produced by: boiler combustion, electrolyzer operations, energy generation bought from the grid (in case of energy purchase), change in the state of charge of the hydrogen pressure vessel. The CO_2 emitted from the syngas/biogas combustion is considered null. This is a typical approach considering that it was produced from a renewable source (in case of missing utilization it would produce the same amount of CO_2 as in a rubbish dump). Moreover, since the grid electricity from fossil fuel is just the 2% of the entire amount (as in D1.1), the CO_2 generation is mainly driven by the boiler that is operated using LNG as fuel.

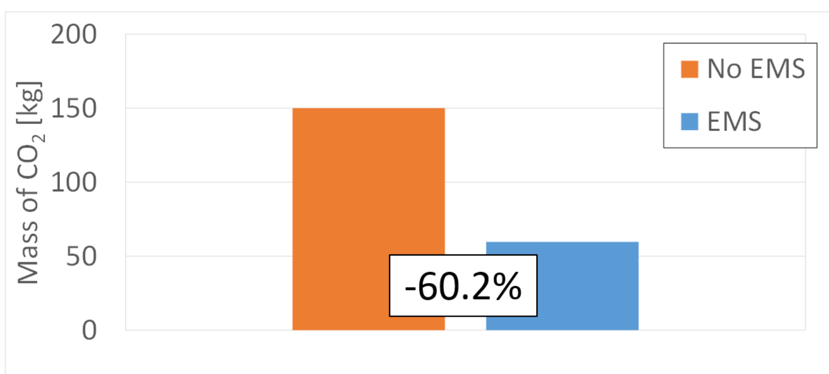


Figure 11 - EMS vs No EMS: CO_2 emission comparison

$$M_{CO2_{system}} = M_{CO2_{boiler}} + M_{CO2_{electrolyzers}} + M_{CO2_{grid}} + \Delta M_{CO2_{H2\ storage}} \quad (7)$$

Figure 11 shows the comparison for the emitted CO_2 during this simulation. The EMS produced a positive effect also in this case, obtaining a CO_2 emission decrease (-60.2% for these 7-hours).

These results demonstrate the reaching of the initial part of KPI 1.1 (efficiency increase >20% for all the system).

4.2. EMS robustness simulations (KPIs 1.1 & 1.2)

Considering the same inputs and boundary conditions, simulations were performed to demonstrate the EMS robustness. So, errors in the input data were implemented starting from the measurements related to the electrical power generated by the turbine (Figure *12*), the CHP thermal power (Figure *13*) and the generation by the boiler (Figure *14*). Since no data are available on measurement errors, the simulations implemented the worst cases. In these preliminary simulations 9-hours were considered and the impact on the management of the other properties was null or negligible. Moreover, no instabilities in the EMS or in the system were generated.

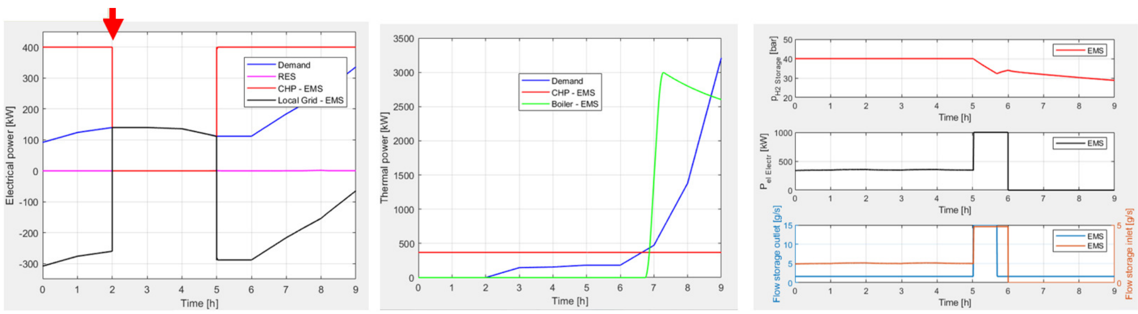


Figure 12 – Error in the CHP electrical power measurement (-50 kW – limited to 0 kW - instead of 400 kW, for 3 hours)

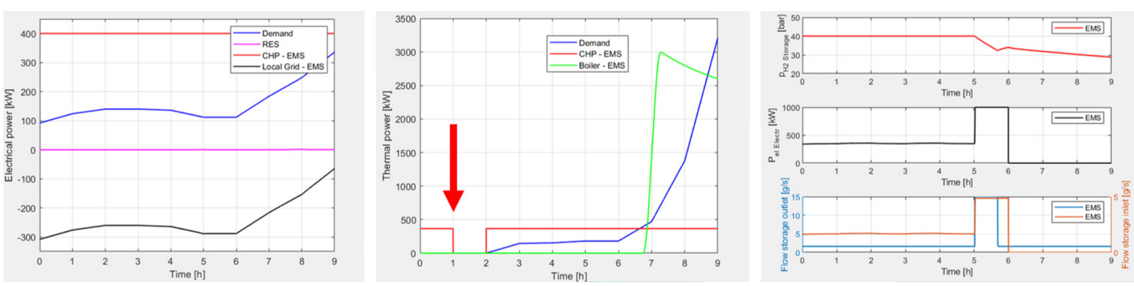


Figure 13 - Error in the CHP thermal power measurement (-50 kW – limited to 0 kW - instead of 365 kW, for 1 hour)

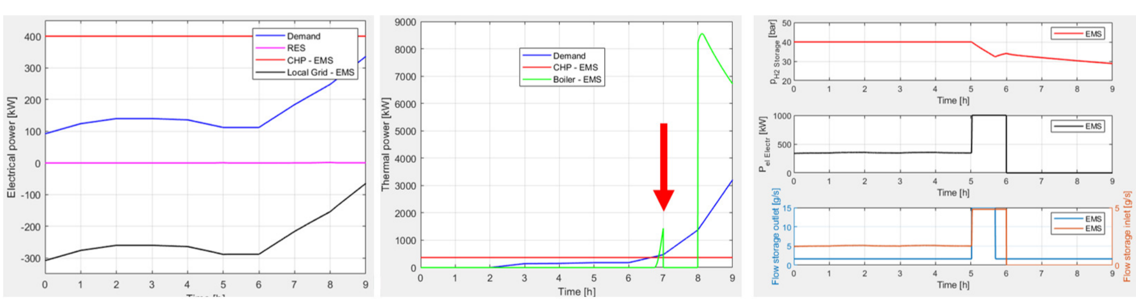


Figure 14 - Error in the boiler thermal power measurement (-1000 kW – limited to 0 kW, for 1 hour)

A further simulation was a calculation for 24 h, using the entire data of Figure *4*. This was another calculation to assess the EMS robustness. As example of wrong measurements (due to probe errors or cyberattacks) the following events were simulated: (i) measured CHP thermal power of -50 kW for 1 h (event started at 4:00), (ii) measured boiler thermal power of -1.0 MW for 1 h (event started at 9:00), and (iii) measured pressure in the hydrogen vessel of -1 bar for 1 h (event started at 16:00). Saturation blocks were also included for an initial data check and to exclude not-physical values. So, the measurements of both CHP and boiler thermal power values were limited to 0 kW and the hydrogen vessel pressure to 1 bar (absolute).

The EMS operated the CHP at the maximum load (400 kW) for the all the 24-hours (Figure *15*). So, the EMS was able to calculate the solution (already described for the initial 7 hours) for all the 24 h. During the afternoon the system obtained some electrical power from the renewable sources (the wind turbine), up to 33.6 kW. This reduced the electrical energy needs (bought from the grid). Moreover, Figure *15* shows that the mentioned measurement errors had no influence for the CHP management and this assess the related tool robustness.

The measurement errors (or cyberattack effects) are visible also for the the thermal side (Figure *16*). Although these problems produce errors in global parameters, no problems were reported in the system management. The only impact regards the boiler: it was moved to a very high power generation following the measurement error due to the set-point (it was increased too much to try to compensate the missing thermal generation). However, in about 1 hour the EMS reduced the produced power to values in good agreement with the demand (Figure *16* after 12:00).

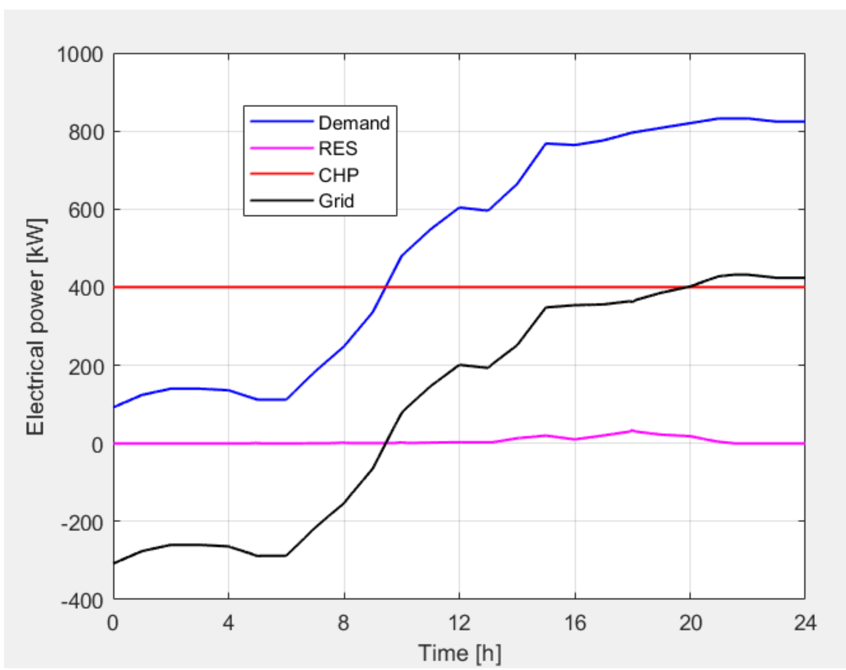


Figure 15 – EMS robustness evaluation (electrical power)

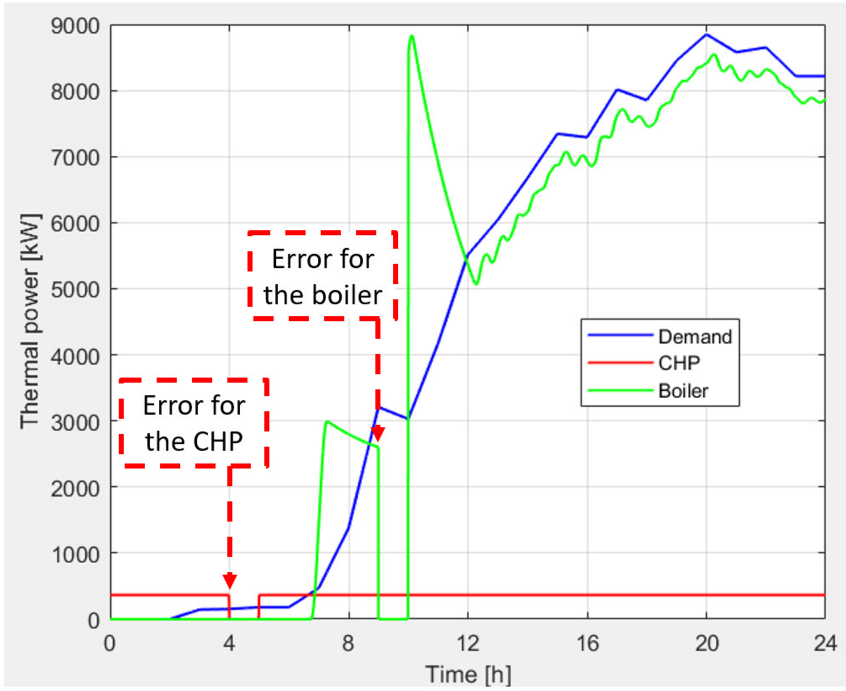


Figure 16 – EMS robustness evaluation (thermal power)

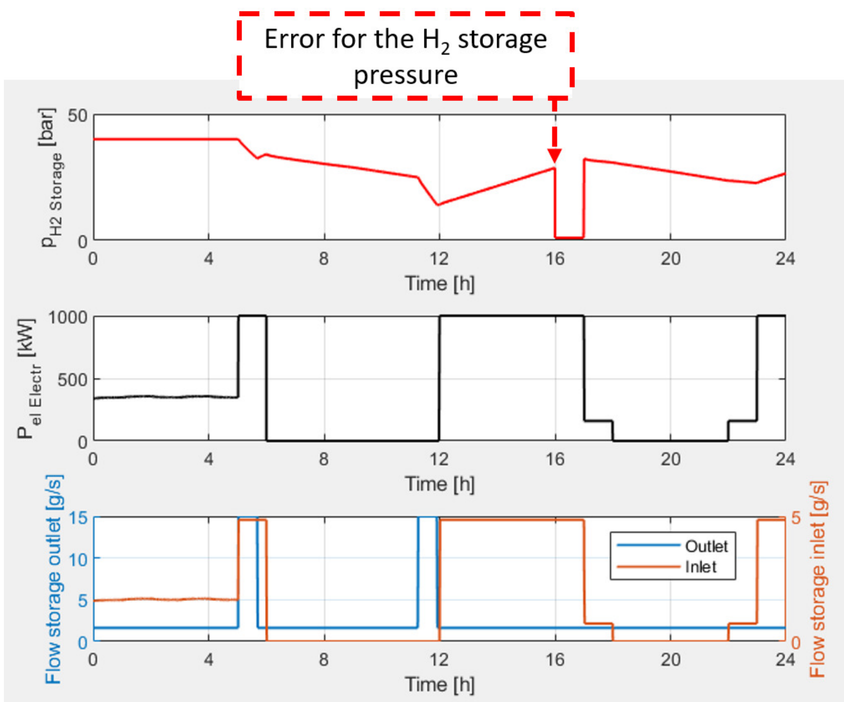


Figure 17 – EMS robustness evaluation (hydrogen system)

Figure *17* shows the tool robustness also on the hydrogen system side. While these errors on measurements on the thermal side had no effects on the results, also large errors in pressure measurements for the hydrogen storage vessel did not produced problems. While before the error the vessel pressure was low (about 23.4 bar), the electorlyzers continued to be operated at the maximum (2 X 500 kW) without any discontinuity.

The results of this sub-section demonstrate the reaching of a second part of KPI 1.1 (software stability with wrong input data >5). Moreover, they are able also to demonstrate the reaching of KPI 1.2 (anomaly detection in the input data of the EMS < 10% - as in the GA).

5. Laboratory preparation for the tests in cyber-physical mode

An important part of WP3 consists in laboratory tests to assess the EMS performance and proceed to software improvement activities (if necessary) before transferring the tool to the demo site on Eigerøy (Prima Protein site). Since the laboratory is not equipped with all the grid components, the tests are proposed to be performed in cyber-physical mode. As demonstrated in previous works [8], this is an effective approach at half-way between model results and demonstration activities with a complete plant. This intermediate approach is important to introduce experimental aspects and problems in the activities, without the critical aspects, costs and risks of a complete prototype. In this case, the cyber-physical approach allows having experimental tests for improving the EMS before moving to the demonstrator, to reduce time, costs and problems.

In this part of the WP3, a test bench available at the UNIGE laboratory, located in Savona, and developed in previous activities [9,10] was prepared for the tests of the ROBINSON EMS. This bench is a local grid (with both electrical and thermal components) including: a T100 microturbine working in CHP mode, a 20 kW heat pump, thermal solar panels, 1.1 kWp PV panels, a 102 kW absorption chiller, two 5000 l thermal energy storage tanks (for hot water), a local thermal grid based on two distribution pipes and equipped with fan coolers for local load generation, a local electrical grid and the connection of both grids to the University campus systems. In this work, since some components are not included in the ROBINSON project, the planned tests are organized to involve the following components: (i) the CHP microturbine, (ii) the PV panels, (iii) the electrical local grid, (iv) the thermal local grid with the related thermal components (the fan coolers).

5.1. Laboratory preparation activities by UNIGE

Although the activities started from an existing facility, it was necessary to perform some laboratory preparation before doing the tests. As planned in the GA, UNIGE performed some maintenance activities that were essential to operate the tests on safe mode for both the operators and the components. These activities included simple ordinary component maintenance of the device manufacturers or the substitution/installation of additional devices, such as new probes. This is the list of the main laboratory preparation activities by UNIGE:

- Fire sensor maintenance
- Air compressor maintenance

- Piping modifications
- New mass flow probe
- New temperature probes and substitution of damaged components
- New ethernet communication device
- New control valve
- Flanges for pipes
- New air dryer
- Accelerometers and microphone for vibration acquisition (T100 safety)
- Re-calibration of some mass flow probes
- Substitution and maintenance of other components

5.2. Laboratory preparation activities by SIT

Due to the complexity of the planned tests (EMS + software models + real components) the laboratory experience in energy harvesting technologies by SIT was exploited in T3.3, as planned in the GA. In details, the following activities were performed: (i) development of the UDP communication between the hardware (controlled by LabView – see Figure *18*) and the software in Matlab-Simulink, (ii) activation of the data acquisition from the PV panels, (iii) software development in LabView for the integration of the PV panels and (iv) general support during the preliminary tests (e.g., presence in the laboratory for operators' alternation during long tests).

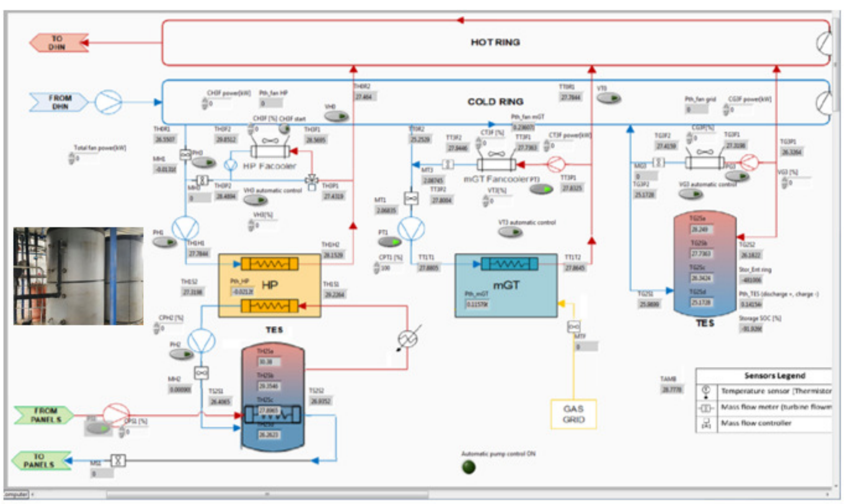
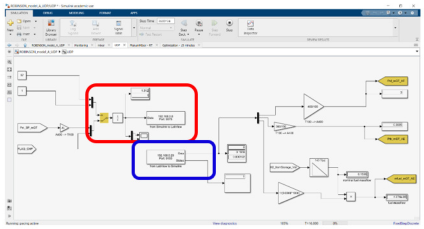
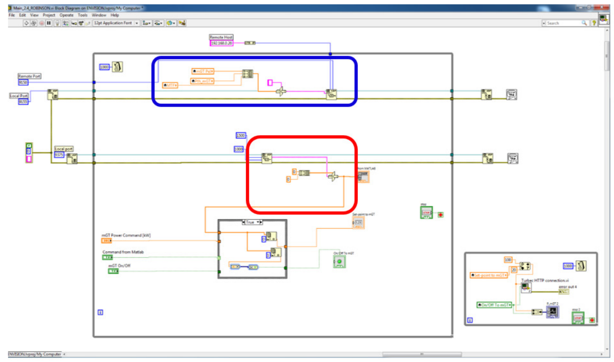


Figure 18 – Main part of the front panel in LabView for the test rig management and picture of the thermal grid

The communication between the software (in Matlab-Simulink) and the hardware (controlled by LabView) was obtained implementing the blocks in Figure 19. The boxes in red include the components necessary to transfer data from Matlab-Simulink to LabView, while the reverse communication is highlighted with the blue boxes.



UDP communication (Matlab-Simulink side)



UDP communication (LabView side)

From LabVIEW to Matlab-Simulink | **From Matlab-Simulink to LabVIEW**

Figure 19 – UDP communication between Matlab-Simulink and LabView

The final communication result is shown in Figure 20. The software receives four measurement values from the field: CHP produced electrical power, CHP produced thermal power, CHP fuel mass flow rate, and produced power by the PV panels. On the other side, the hardware receives two calculated values from the software: the CHP on-off signal and the related set-point. Moreover, since the hardware includes a 100 kW microturbine while the software performs calculations with a 400 kW machine, a data conversion system was included: lookup tables to scale the signals in both communication senses. For the T100 machine, the operations were constrained in the 30 kW – 90 kW range to avoid problems in case of significant ambient temperature change. Also, for the PV panels a signal re-scaling was included to take into account the different installed panel areas in the laboratory (in comparison with Eigerøy.

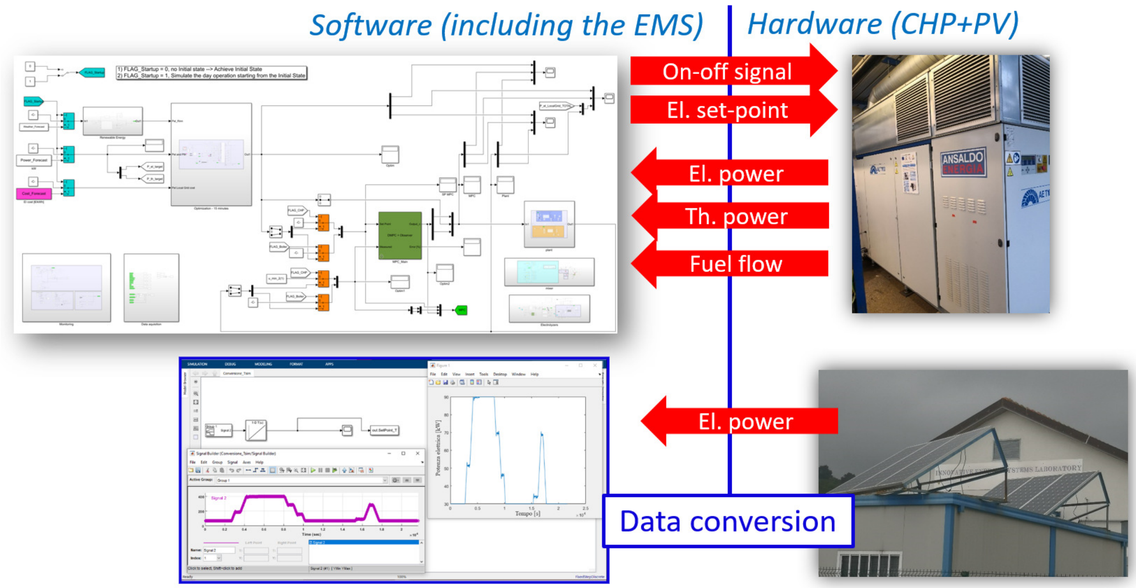


Figure 20 – Details for the software-hardware communication

Finally, SIT supported the UNIGE team in the preliminary experimental activities in cyber-physical mode.

6. Preliminary tests showing the EMS performance in cyber-physical mode

Although the experimental validation is planned in T3.4, in T3.3 preliminary experimental results were performed to check the presented cyber-physical mode.

An initial test was performed without the PV panels. Following the T100 start-up and stabilization at 90 kW, the connection with the software was activated. For this test, the H_2 volume concentration in the A400 fuel was maintained constant at 30%. Moreover, constant fuel costs were considered: 150 €/MWh for the LNG and 5 €/MWh for the syngas produced by the gasifier. Since the biogas from the AD-BES was negligible in terms of mass flow in the pilot installation, no cost details are necessary. Since the syngas cost was very low in comparison with the electricity cost (139 €/MWh, as at time zero of Figure 4), the EMS maintained the T100 machine at 90 kW after the connection. Since the EMS would maintain the CHP at maximum load due to the low-cost condition of the syngas, an electricity decrease step was performed (from 139 €/MWh to 1,39 €/MWh). The electrical and thermal demands are the same of the initial part of Figure 15 and Figure 16. This generated a too expensive CHP operation (in comparison with the utilization of the energy from the grid) and, as a consequence, the machine switched off, as in Figure 21 (the CHP set-point was decreased to the minimum to be ready for an increase operation). Figure 21 also shows the effect of the data conversions reporting the power produced by the T100 and the related CHP power values accounted in the software.

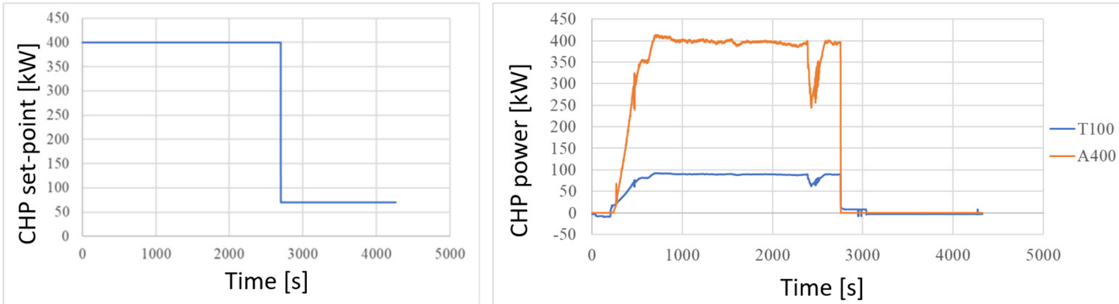


Figure 21 – CHP set-point and electrical generation during the electricity cost step

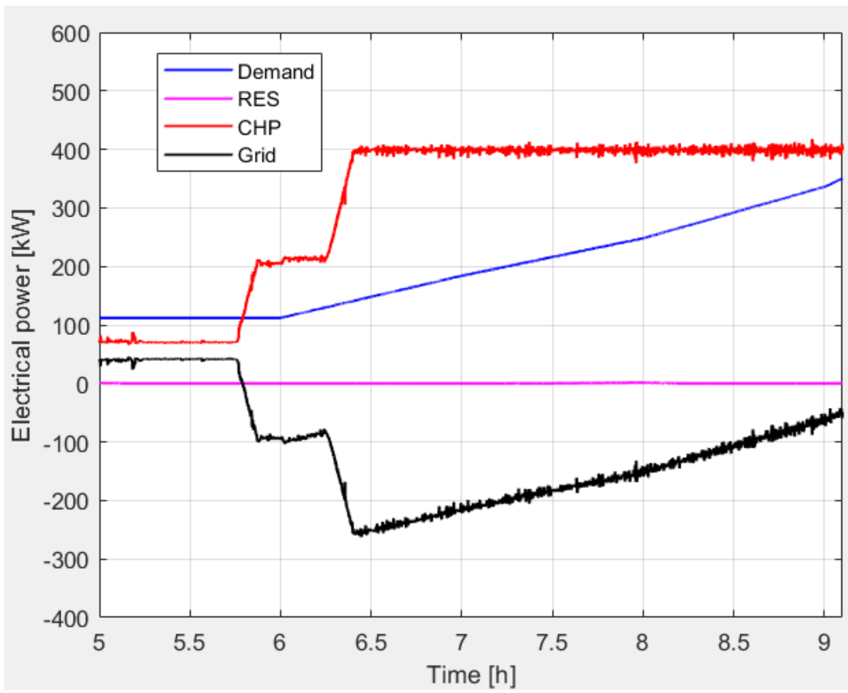


Figure 22 – Electrical power (Demand, RES, CHP and Grid) for a test with 95 €/MWh syngas cost

A second test was performed for 4.1 h starting from the T100 at the minimum electrical load of 30 kW. This situation was obtained with the usual demands starting from the hour number 5 of Figure 4, Figure 15 and Figure 16. For obtaining a machine load variation due to the electricity cost increase, a syngas higher cost was considered (it was 95 €/MWh for this test in cyber-physical mode). In this case PV panels were included. However, the related power production impact in the Prima Protein grid was in the 200 W range due to a cloudy condition. Figure 22 shows that close to the hour number 6 (when the electricity cost had an important increase) the EMS calculated more profitable to sell electrical energy to the grid. So, the CHP load was increased to the maximum (following an intermediate load period). This test was performed including the boiler activation and the hydrogen storage management. However, these results are discussed in the next section, due to an important cybersecurity test that was performed on the thermal generation side.

7. Data traceability and cybersecurity

As planned in T3.3, UNIGE performed data traceability and cybersecurity tests at laboratory level considering the application target in the Eigerøy demo site.

For the data traceability point of view a script in Python (Figure 23) on data traceability and cybersecurity was integrated. In details, a result file of the laboratory tests (including second-by-second the main exchanged data) was registered in a blockchain. Following this registration operation, different cases were tested putting “FALSE” in one of the last parameter of the script. This was checked (i) without doing modifications in the registered file or (ii) after minimal changes. The script was able to return different values when (i) the file was identical to the registered one or (ii) it was modified. Several tests with different files were performed obtaining the same positive results. So, the script was considered ready for application in the demo site.

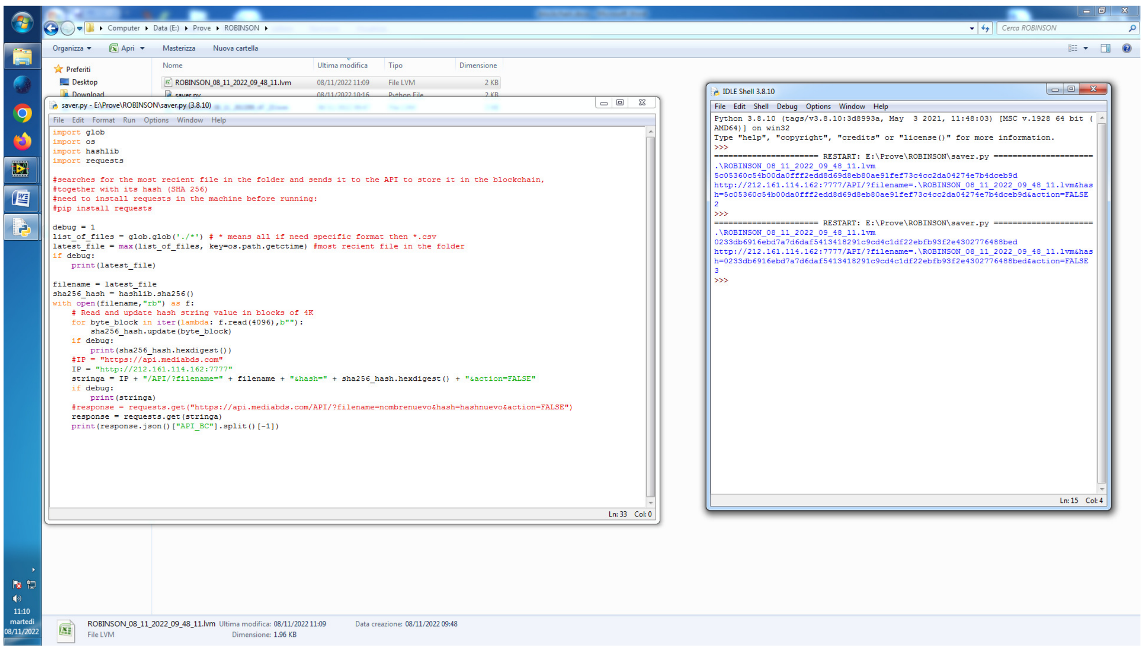


Figure 23 – Python script by FUNDITEC and data traceability tests on the laboratory result file

For the cybersecurity point of view, a test considering the impact of a wrong thermal power measurement was done, as for the effect of a cyberattack. In details, the test already presented in Figure 22 was performed including a wrong measurement for the CHP thermal power at hour number 8 (this value was set to -50 kW – limited to 0 kW – in correspondence of the red arrow) for one hour. As shown by Figure 24 and Figure 25 this wrong measurement did not produce significant impacts on the system management: it was able to maintain the necessary stability and no large effects were transferred to the electrical side (Figure 22) and the hydrogen system (Figure 25).

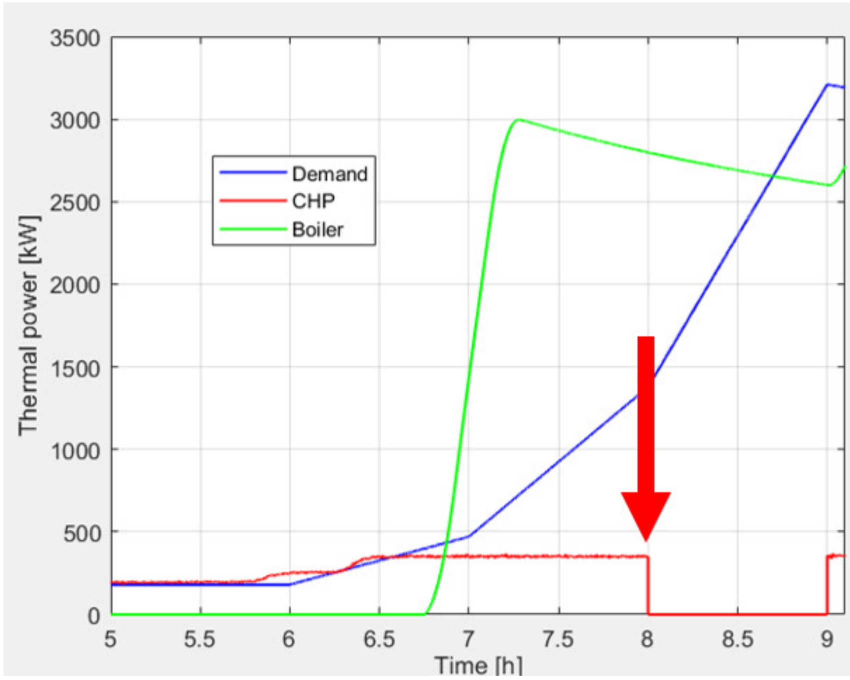


Figure 24 - Thermal power (Demand, CHP and Boiler) for a test with 95 €/MWh syngas cost

For the hydrogen point of view, Figure 25 shows a good management of the storage vessel, as described before. Following the truck/trailer charging operation, the elctrolyzers were maintained at maximum for about an additional half hour. This generated a visible pressure re-increase in the vessel. However, in the following hours, the electrolyzers were switched off due to the high electricity costs. So, the consumption by the CHP produced a further slight pressure decrease. However, the pressure value remained significantly high guaranteeing a good energy security margin.

These results can be considered as a further confirmation of the reaching the second part of KPI 1.1 and KPI 1.2 (as previously discussed for the simulations).

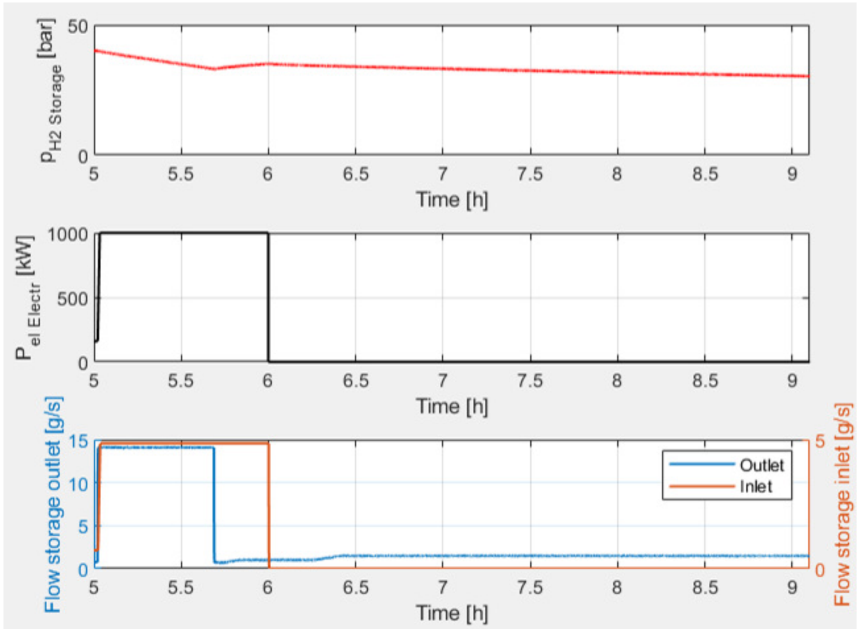


Figure 25 – Hydrogen system (pressure, electrolyzer power and inlet/outlet flows) for a test with 95 €/MWh syngas cost

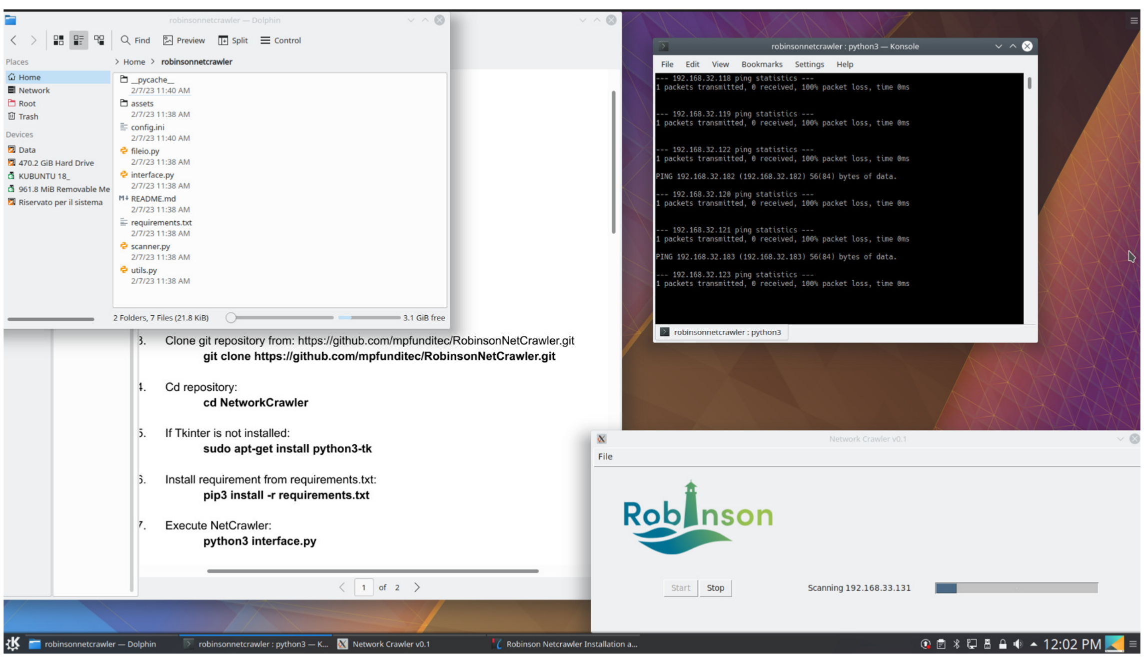


Figure 26 - NetCrawler running for cybersecurity applications

To complete the discussion on cybersecurity aspects, Figure *26* shows a network scan) using another Python script. It is the NetCrawler software that is proposed for the demo site in Eigerøy.

8. Replication section

An important part of T3.3 regards the concept replication for further applications. These analyses were performed at simulation level adapting the EMS tool for two other different cases: the Western Isles (WI) (Creed site) and Creta (“The Manna” district). So, the EMS and the component models were adapted considering the data reported in the previous project deliverables (mainly D1.3 and D3.1) and further input data collected from the involved partners. Although in both WI and Crete cases there are important basic aspects similar to Eigerøy (e.g., the presence of a CHP microturbine, the integration with renewable sources, a hydrogen generation/storage/utilization system, etc.), the presence of some differences requires the analysis differentiation in the following two different sub-sections.

8.1. Western Isles

An example of the WI system management with the EMS is reported in Figure 27. Except the initial 30 minutes when the software performed the necessary iterations to be aligned with the system initial conditions, the EMS was able to manage the system to satisfy the load demands. The initial oscillation, although different from the previous cases where the simulation started from a stable condition, demonstrated the EMS robustness and the possible easy connection with the system. In comparison with the previous results for the Eigerøy case, here the contribution of renewable sources is very important. Moreover, the system includes also a thermal storage that was managed to uncouple the electrical generation (the CHP was operated to minimize the costs) with the thermal demand matching. On the hydrogen side, the simulation included a truck/trailer recharging operation (as described for the Eigerøy case) that generated the vessel pressure decrease. This is due to an important amount of hydrogen discharged from the pressure vessel (as in Figure 2 for the truck/trailer recharging). This was followed by the 40 bar restoring thanks to the operation of the electrolyzer.

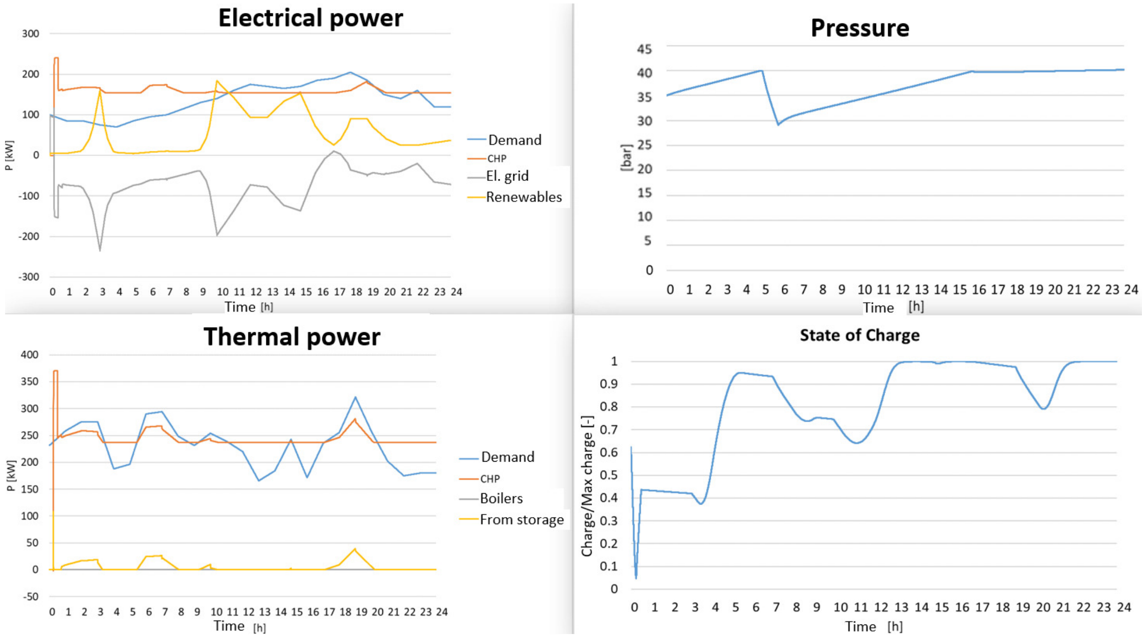


Figure 27 - EMS system management in the WI case (simulation results)

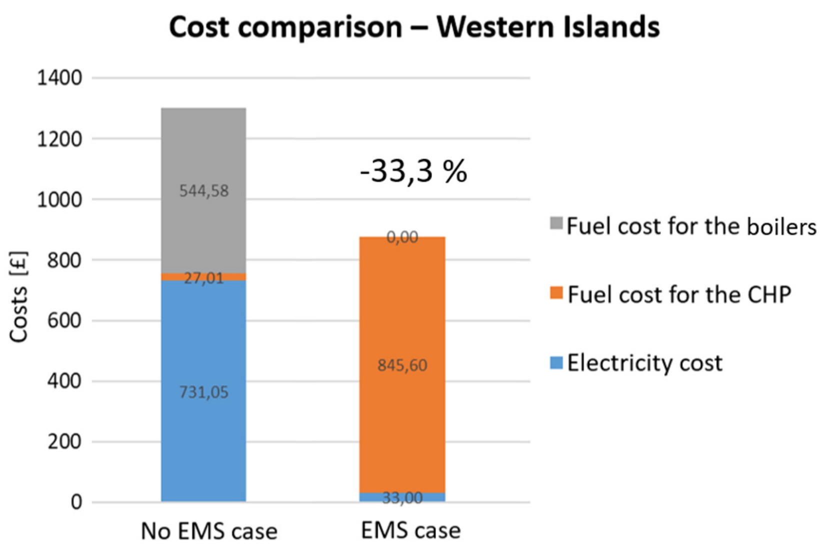


Figure 28 - Generation cost comparison for the WI case

As performed for Eigerøy, the results obtained with the EMS were compared with the no EMS simulations in terms of global variable costs. Also in this case the cost saving is significant (-33.3% as shown in Figure 28) thanks to a CHP utilization increase that allowed to avoid the switch on of the boilers.

8.2. Crete

For the Crete case, the daily demands were selected considering a typical working day for the 2021 year. As shown in Figure 29, in this case the electricity production from the renewable sources is very important. Although the wind turbine includes some production also overnight, the main contribution regards the PV panels that in the central part of the day increased the generation from renewables to values higher than 200 kW. The CHP is managed by the EMS to satisfy the thermal load when this operation is cost effective. When the CHP operations were not producing the optimal profit, some part of the thermal demand was covered by the boiler or the CHP was switched off. This event happened during this highest production from the renewables. For the electrolyzers point of view, Figure *29* shows an important increase in the storage vessel pressure during the initial day hours, due to the electricity cost being lower than the average value. Then, due to the truck charging (at 5:00) the pressure significantly decreased. After an almost balanced period, at 10:30 the electricity cost decreased to values lower than the average one producing a further important pressure increase in the H_2 storage vessel. Following this condition, the pressure decreased again for the second truck charging event. Then, the economic conditions changed and the EMS completed the vessel charging. The operations continued with this management: in the 16:00-22:00 the vessel was discharged due to the CHP operations and high energy cost condition, in the period of 22:00-24:00 it was recharged due to low energy costs.

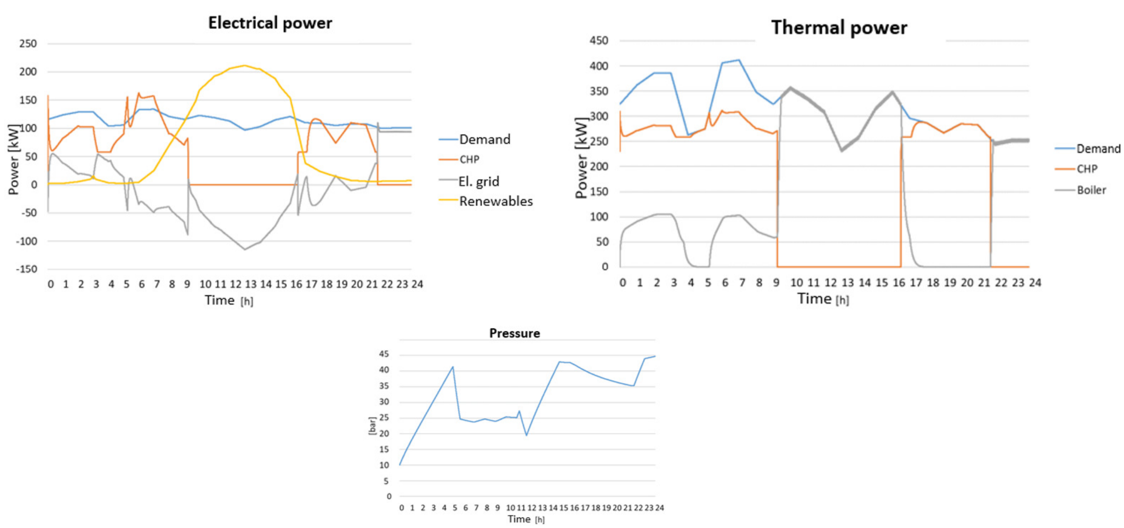


Figure 29 - EMS system management in the Crete case (simulation results)

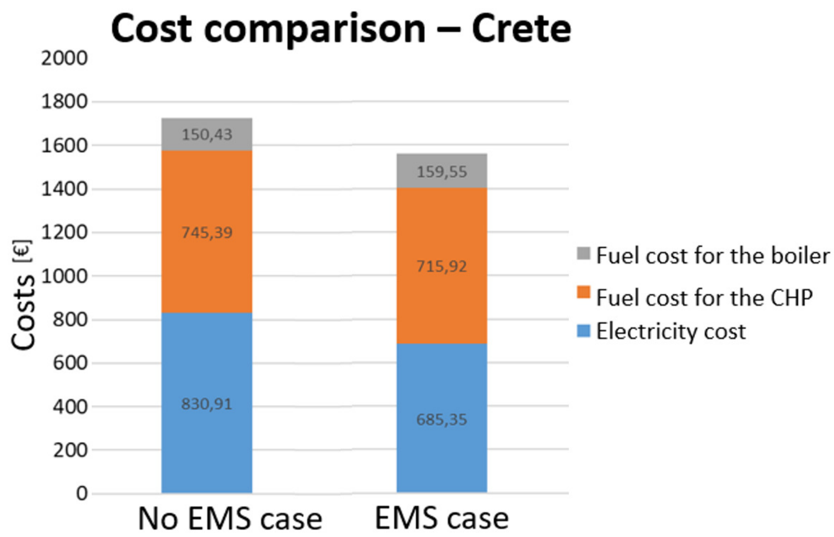


Figure 30 - Generation cost comparison for the Crete case

As performed before, the results obtained with the EMS were compared with the no EMS simulations in terms of global variable costs. Also, in this case the cost saving is significant (-9.4% as shown in Figure 30).

9. Summary

This deliverable regards the EMS development, the related simulations with the component models described in D3.2 and the preliminary experimental tests for the EMS validation. In details, following the EMS description and the related integration with the component models, attention is focused on simulations performed for the Eigerøy case. The results were able to show a system electrical efficiency increase higher than 20% thanks to the EMS application (+41.6% considering the factory start-up conditions simulated in this project). Moreover, the simulations performed with input errors (considering possible measurement errors in field applications) showed a good model stability and no significant problems or impacts on the results following the error removals. So, these results demonstrated, with simulations, that several parts of KPI 1.1 are met (overall efficiency >20% and software stability with wrong input data >5). Moreover, they were able also to demonstrate the reaching of KPI 1.2 (anomaly detection in the input data of the EMS < 10%).

Due to the planned experimental validation in T3.4, this deliverable also reports the laboratory preparation activities, and the related preliminary experimental tests in cyber-physical mode (as a further confirmation on the reaching of the second part of KPI 1.1 and KPI 1.2). In details, these activities included also data traceability and cybersecurity tests.

Finally, the replication section reports simulation results for the Western Isles and Crete cases during typical working days (on the basis of the data collected in D1.3 and integrated in D3.1). The EMS application on the Western Isles (Creed district) produced a 33.3% variable cost decrease. For the Crete case (“The Manna” district) it was possible to obtain a good integration with a high renewable-source generation obtaining variable cost decrease of 9.4% with the EMS utilization (in comparison with standard management operations).

As discussed before, the simulation and experimental results reported in this document will be essential for the WP3 continuation in T3.4.

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