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**Smart integration Of local energy sources and innovative storage
for flexible, secure and cost-efficient eEnergy Supply ON
industrialized islands**

D 3.2 – Simulation tool of the entire ROBINSON system

Lead partner: UNIVERSITA DI GENOVA



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Executive summary

Deliverable 3.2 of the ROBINSON project corresponds to Task 3.2 that is entitled “Components modelling and simulation”. This document regards the model development activities and the related simulations considering all the three test cases: Eigenrøy, Western Isles, and Crete. Starting from the data collected on the WP1 and WP2 and properly integrated in T3.1, this report shows the details of each component model, such as the CHP, the renewable sources, the electrolyzer, etc. Special attention is focused on the industrial symbiosis and the related impact on the energy generation (e.g. the gasifier in Eigenrøy). For the developed component models specific validation activity has been performed on the basis of experimental or literature data (depending on the related availability). This document was developed under the leadership of UNIGE, considering that this includes preparatory activity and results for the development of the Energy Management System (EMS) (by UNIGE in T3.3). All the other partners have been involved as support, including discussions in meetings. The simulation results reported in this deliverables and transferred to T3.3 for the integration with the EMS, are the mean of verification of MS5.

In details, the report presents the following topics:

- Presentation of the simulation approach (environment, modelling approach, etc.).
- Details of the main components (CHP, electrolyzer, boiler, etc.) and related validation.
- Details of component models for Eigenrøy.
- Simulation results for the components of Eigenrøy.
- Model details and simulation results for the other islands: Western Isles, and Crete.
- Utilization of these models for the EMS development.

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List of abbreviations

A	Surface area
AD	Anaerobic digestion
BES	Bioelectrochemical system

CHP	Combined heat and power
EMS	Energy management system
HIL	Hardware in the loop
L%	Load percentage
LHV	Low heating value
MIL	Model in the loop
p	Pressure
P_{el}	Electrical power
P_{th}	Thermal power
R	Gas constant
S_{UV}	Solar radiation
TES	Thermal energy storage
Vol, X	Volume concentration
WP	Work package
η	Efficiency
η_{nom}	Nominal efficiency

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) in a real-time mode. Since the EMS will be developed starting from simulations and, then, with the demonstration, it is important to develop apt component models for the simulations planned in T3.3. This will be an essential approach to provide the necessary simulations for the development of this tool.

This report is organized as in these chapters:

- Chapter 2 presents the general modelling approach.
- Chapter 3 reports the details of the component models with special attention on the Eigenrøy case.
- Chapter 4 reports the model validation.
- Chapter 5 reports some simulation results for the Eigenrøy case.
- Chapter 6 regards the replication section for the modelling activities and the simulation results related to the other islands.
- Chapter 7 summarizes the deliverable content.

2. Modelling approach

Since the target of WP3 is the development and the validation of the EMS, no detailed modelling approach is necessary for the components. So, a black box approach has been chosen: each model needs to calculate the global performance (generated or consumed power, efficiency, fuel consumption, generated fuel mass flow, etc.) in dynamic mode. However, no details related to the internal properties (e.g. the compressor outlet temperature in the CHP or the gasifier bed temperatures) are necessary. Most of the model will not include process parameters, but they consider just main inputs and outputs.

All the models have been developed in Matlab-Simulink environment because, with this approach, it has been possible to exploit existing subfunctions related to previous dynamic modelling activities or, in the case of the gasifier, an already existing component model. In details, the State Space approach has been considered for a large part of the components. This takes into account the component off-design performance (on the basis of interpolation maps related to the performance outputs, such as the efficiency and the fuel consumption) and the dynamic response. In details, the dynamic aspects modelled here includes all the time-dependent characteristics including the internal control system performance. For instance, the electrical dynamic response of the CHP is due to the machine control system behaviour in the load changes. However, for other properties, the thermal response effect is highlight priority. The dynamic response of the components impacts the control set-up of each of them, considering static and dynamic constraints.

The data-driven & state-space approach present low computation cost, making cyber-physical test feasible using a basic PC. The model in cyber-physical operation should run in real-time mode having simulation time per wall clock second equal to 1.

Starting from the prime movers in Eigerøy demo site, the UNIGE created a Matlab-Simulink “ROBINSON library”, including all components that are scaled up/down to simulate the ROBINSON concept in the all three case studies. Besides, the UNIGE modified and updated some components (volume tank, gas mixer, and gasifier) starting from the in-house TRANSEO tool [1].

3. Modelling details

The details related to the modelling activities are reported in this section for the case of the Eigerøy island. However, the structure of the component models presented here is valid also for the other cases for replication issues. All the simulation models developed in T3.2 are presented here, including the related calculated results. In general, all the components have been modelled with dynamic approach except for the AD-BES. This choice is due to the purpose of developing the EMS planned in T3.3. So, since the fuel mass flow rate produced by the AD-BES is negligible (the AD-BES produces a fuel flow lower than 3 order of magnitudes of the other fuel flows), the impact on the EMS operations is negligible. However, for the replication issues, the EMS will include the possible integration with the AD-BES technology considering the related dynamic issues (due to the low dynamic response the related produced gas will be a system input without any modelling and control on the AD-BES side).

This section presents in detail each single prime mover model, considering the Eigerøy scale.

3.1. CHP

The Aurelia A400 CHP model integrates part-load curves correlation (D1.3) and dynamic manufacturer characterization to emulate transients and off-design behavior. The model (Figure 1) computes and monitors the main global performance operating parameters, not considering the thermodynamic internal process (e.g. pressures and temperatures between the components shown in Figure 2). The CHP exhaust mass flow (thermal power) heats the air at steam boiler inlet, decreasing the steam boiler fuel consumption.

The CHP input model parameters are:

- Electrical power set-point
- Temperature of the water at intercooler inlet
- Ambient temperature
- LHV
- Nominal efficiency
- Nominal electrical Power

The CHP output model parameters are:

- Electrical power
- Thermal power
- Fuel mass flow
- Electrical efficiency
- CHP efficiency

Figure 1 presents the CHP Matlab-Simulink model, highlighting inputs on the right and outputs on the left, while Figure 2 shows the A400 optimized layout that allows to achieve 40% efficiency.

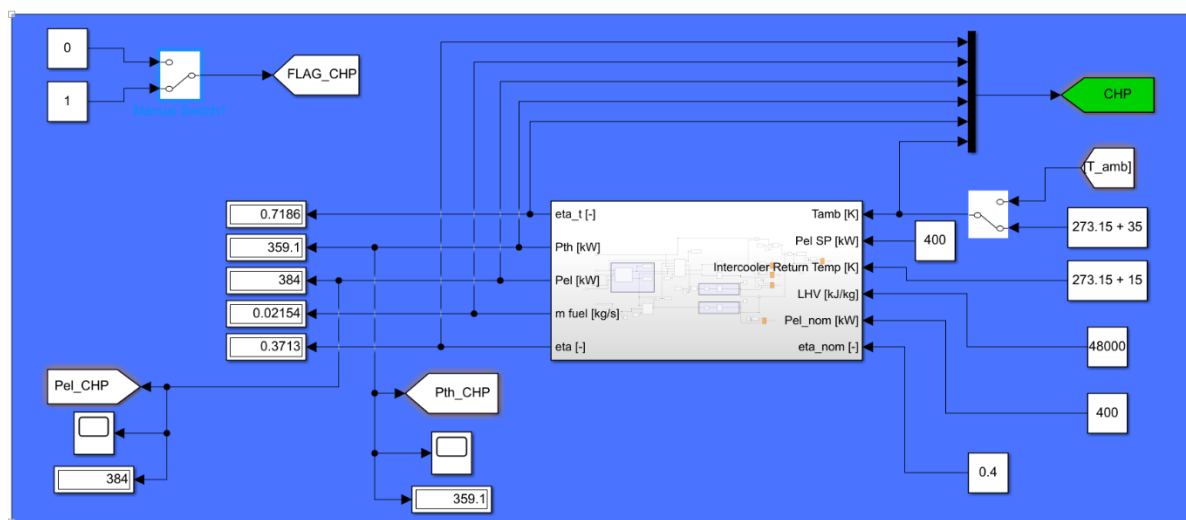


Figure 1 – A400 CHP model

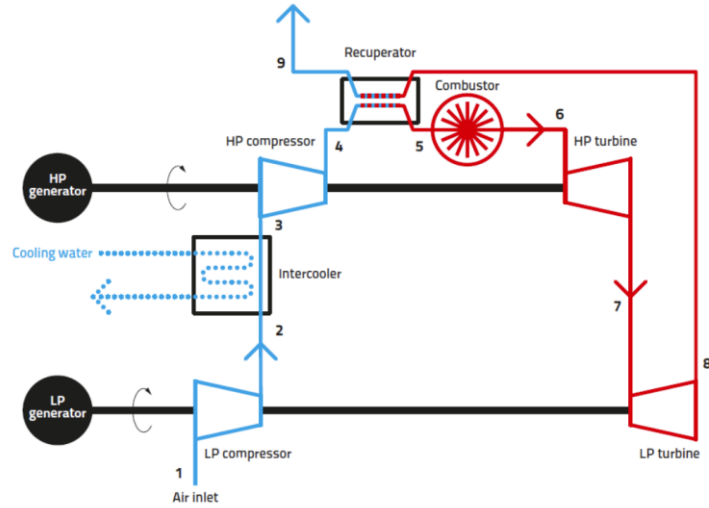


Figure 2 – Intercooled and recuperated, generator on both shafts, process layout

3.2. Steam boiler

The steam boiler model emulates both transients and part-load operations using Prima Protein data and literature off-design characteristic curves. The equation below defines the efficiency at part-load operations according to UNIGE in-house tool [2] (Eq.1).

$$\eta = \eta_{nom} * \sqrt{(1 + l_{\%})/2} \quad (1)$$

Starting from efficiency and LHV the model computes the fuel mass flow. Figure 3 presents the steam boiler model in Matlab-Simulink environment.

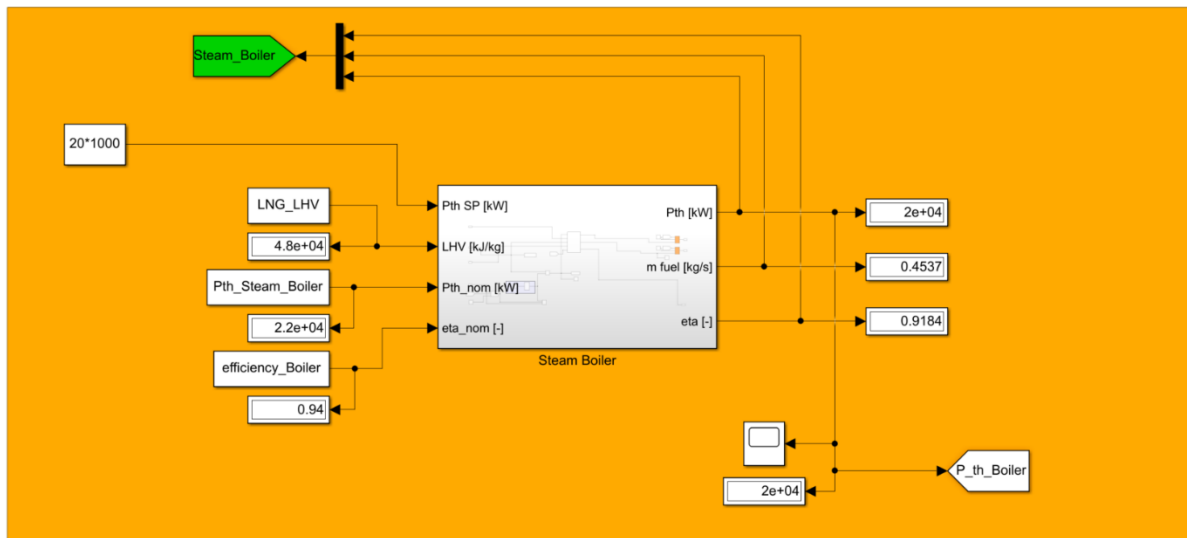


Figure 3 – Steam boiler model

The transients data (e.g., start-up, shutdown) from D1.3 provided time characterization that has been modelled using first order delay.

The CHP input model parameters are:

- Thermal power set-point
- LHV
- Nominal efficiency
- Nominal thermal Power

The CHP output model parameters are:

- Thermal power
- Fuel mass flow
- Efficiency

The steam boiler is regulated on the basis of the steam pressure. Considering a desired pressure set-point (normally 8.0-8.5 bar), the burner operates the start-up as soon as the pressure gets below that set point (some hysteresis of course is present).

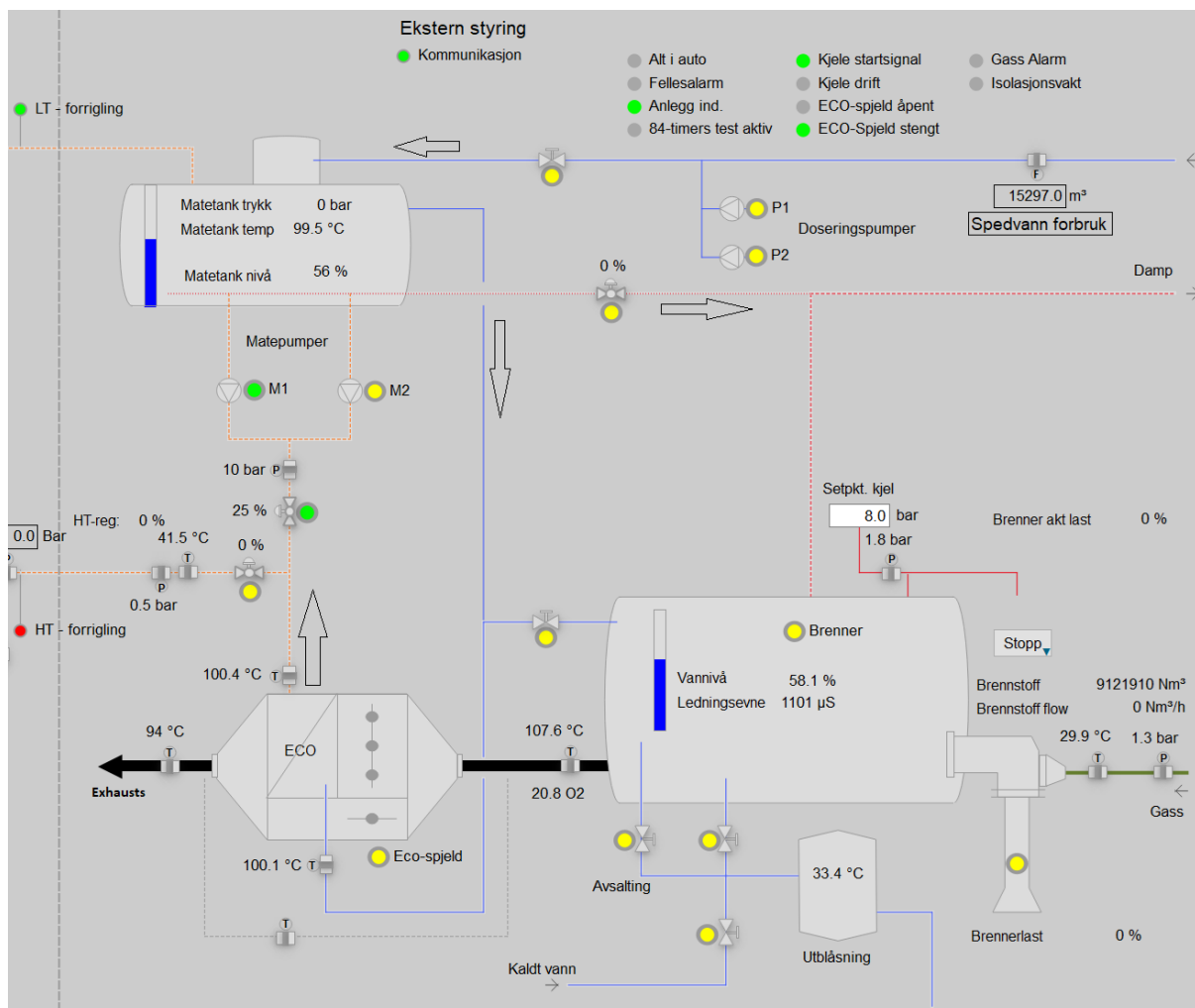


Figure 4 – Screen shot of the steam boiler from PC, in control room

The high level modelling approach presented does not include technical process details (Figure 4), but allows to simulate the global system (main inputs/outputs) for EMS set-up and test (MIL, HIL).

3.3. Wind turbine

The wind turbine model computes the power generation using the manufacturer performance curve. The model input is the wind speed [m/s], while the output is the generated electrical power.

The overall model couples the characteristic curve (look-up-table from D1.3) with a first order delay transfer function, emulating both part-load operation and transient rotating inertia.

The picture below (Figure 5) shows the estimated power generation, considering a typical wind speed profile in Eigerøy.

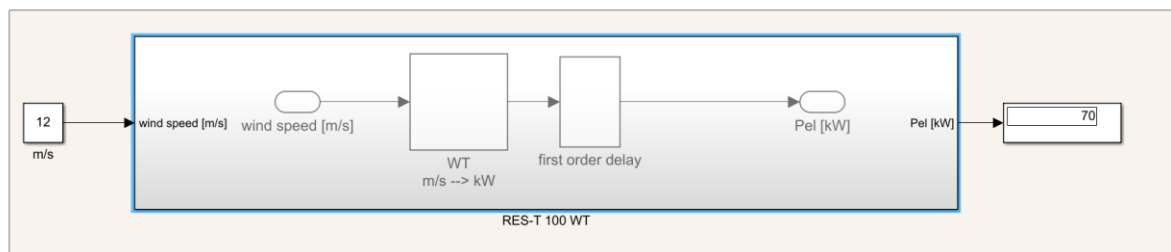


Figure 5 – Wind turbine model

3.4. Gasifier

The gasifier is meant to provide syngas to the CHP. The modelling work by UNIGE was the innovation and the update of the gasifier model present in the TRANSEO library (TPG UNIGE tool) [3].

To achieve the gasifier model a generic “Thermal Network Library” based in MATLAB-Simulink was developed, and relying mainly on embedded MATLAB functions originally developed for this purpose. Such a library is composed of the following three main components:

- 1) Solid domain, simulating a 2D solid matrix with internal conductive heat transfer.
- 2) Fluid domain, simulating a quasi 2D reacting flow of solid/liquid/gas.
- 3) Heat linker, defining the heat exchange relationships between the boundaries of solid and fluid domains.

Such components use a finite-difference formulation of the thermal problem, which is resolved with an implicit time integration scheme. Figure 6 presents the generic reaction scheme.

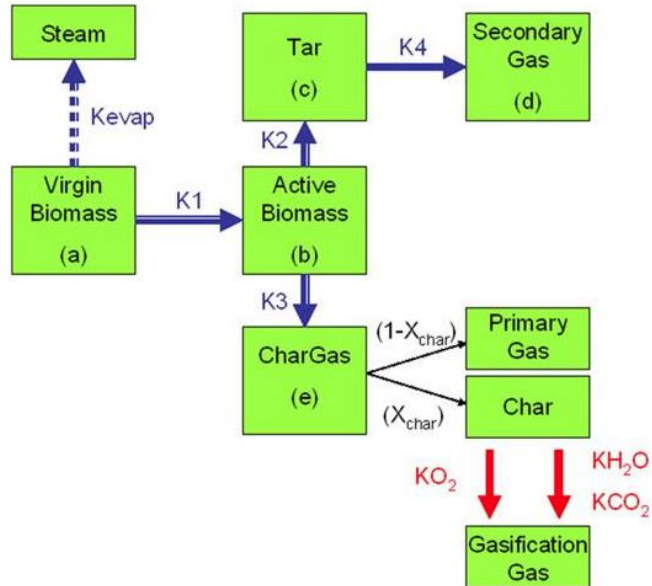


Figure 6 – Generic reaction scheme used to model cellulose, hemicellulose, and lignin pyrolysis (blue and black arrows). Red arrows regard char gasification.

The real-time application of the model constrained the developers to avoid the inclusion of some real effects that may occur in a gasifier. The main phenomena not represented at the moment are:

- Mass accumulation; the level of solid is predefined, as well as the surface available for the vapor phase. Thus, start-up phenomena cannot be captured.
- Tar condensation; tar is considered to be always in the vapor phase, together with the incondensable gases and steam.
- Diffusion and heat resistance; diffusion and heat resistance within the solid particles is not considered (intrinsic apparent kinetics should be used), thus particle size has no influence on results.

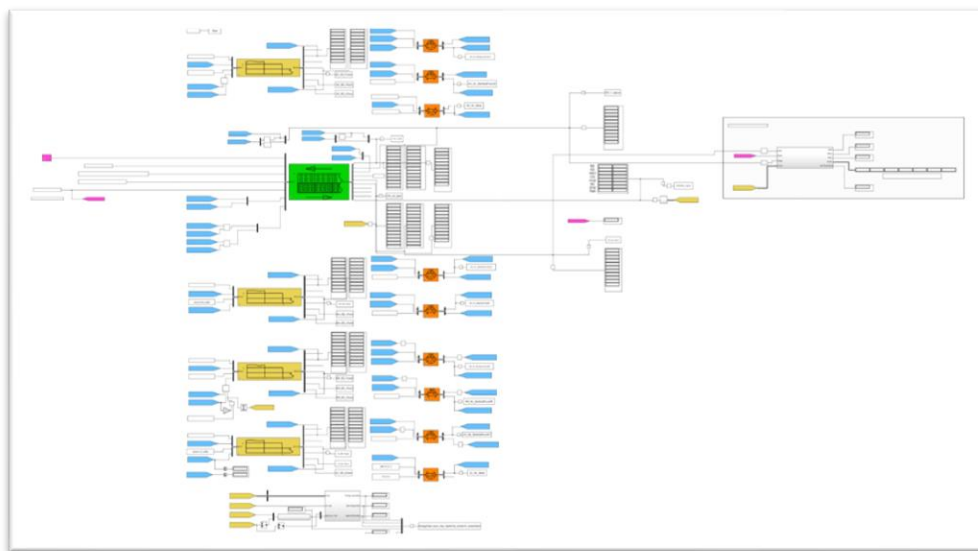


Figure 7 – Gasifier model screenshot

Despite the 2D approach, the present low computational cost makes it (Figure 7) real-time runnable for cyber-physical tests. Further clarification on the gasifier model could be available in paper by Alberto Traverso et al [3], in collaboration with the National Energy Technology Laboratory (US Department of Energy, Morgantown West Virginia).

The gasifier prime mover selection is still on-going (WP2), and the specification features of the biomass composition are still missing (model inputs). So, Figure 8 presents a first guess of it. When these data would be available the gasifier model inputs will be updated for the new validation on experimental data.

Biomass Input (mask)	
Used for interface with dSapce	
Parameters	
Biomass Total Mass Flow [kg/s]	0.11
Temperature [K]	288.15
Biomass Humidity - mass fraction	0.10
Dry Biomass composition - mass fraction (Cellulose)	0.49
Dry Biomass composition - mass fraction (Hemicellulose)	0.27
Dry Biomass composition - mass fraction (Lignin)	0.22
Dry Biomass composition - mass fraction (Ash)	0.02
LHV [kJ/kg]	18000

Figure 8 – Biomass composition guess, gasifier model inputs from its mask

3.5. Electrolyzer

The alkaline electrolyzer model computes the hydrogen and oxygen mass flow, while the input is the total power to the electrolyzer system (compression power included). The model uses the following manufacturer parameters to compute the outlet mass flows:

- Ratio between the compression energy and the stack electrolyzer energy
- Minimum input power percentage
- Nominal power electrolyzer stack
- Nominal efficiency (normalized efficiency curve)

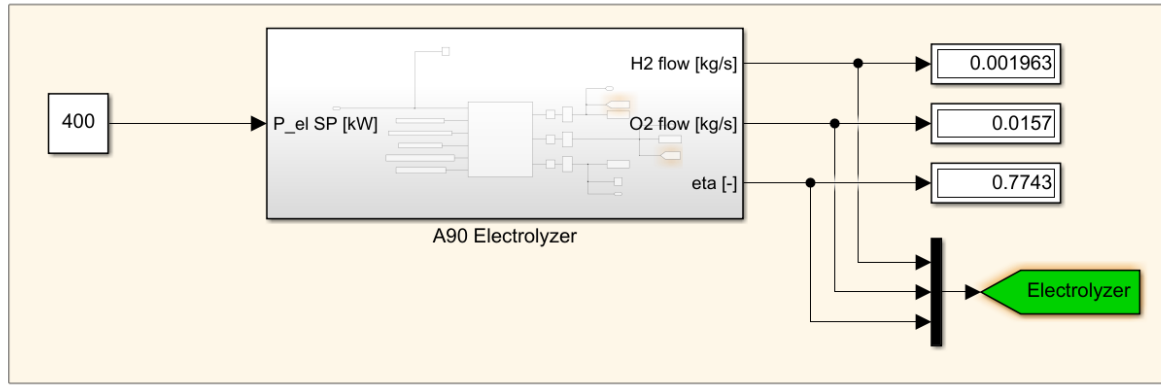


Figure 9 – Electrolyzer model

If the electrical power input (Figure 9) would be lower than the minimum input power, the model considers the electrolyzer in hot stand-by operation.

The model includes part-load performance curves and dynamic behaviour literature data [4], integrating the characteristics curves and the dynamic feature to emulate the transients and the steady state operations. The electrolyzer dynamic response could be modelled as a first order delay, as presented in [4] and confirmed by the A90 manufacturer.

3.6. H₂ storage

The UNIGE developed the H₂ storage tank starting from the TRANSEO plenum model [1], and integrating the real gas properties by REFPROP library [5].

The plenum is assimilated to a rigid volume, which changes its pressure and temperatures with the upstream and downstream components according to the mass and enthalpy exchanges. The user selects the volume and the fluid and the number of input/output stream flows. The plenum receives the incoming and exiting gaseous mass flows as known input. So, it just needs to explicitly integrate the continuity and energy equation, to provide the components themselves with the boundary conditions for the next time step. In the plenum, the total temperature is maintained (unless there is thermal exchange with the environment) while the total pressure is assumed to be equal to the static pressure (Figure 10). This means that a plenum carries out an adiabatic transformation where the flow kinetic energy is dissipated: as a consequence, plena should be inserted where velocity is negligible, while the real kinetic-pressure transfers should be managed within each component (however, this is not mandatory: the user only needs to be aware that the kinetic energy is dissipated into the plenum).

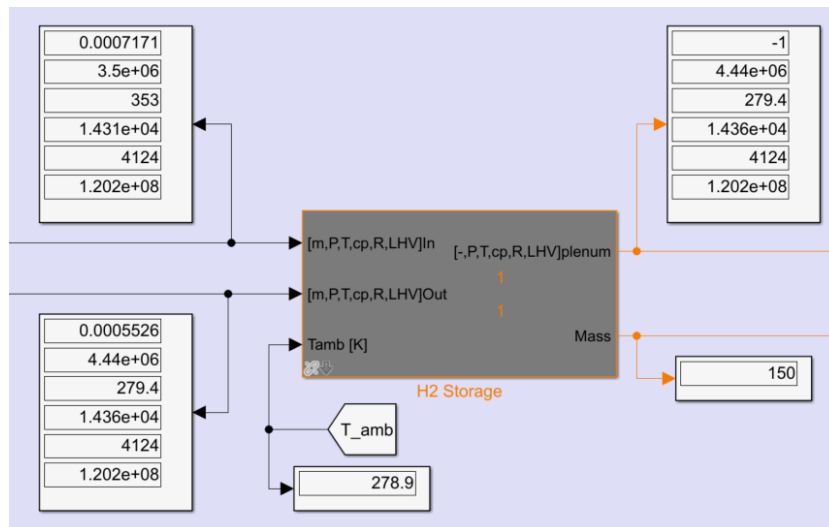


Figure 10 – H₂ Storage model screenshot

The plenum model computes the property of the flow inside it, but not the mass flow at the outlet, then the UNIGE group decided to use the value “-1” for highlighting it.

3.7. Gas mixer

The gas mixer model represents an innovation of the basic plenum component, integrating the volumetric composition computation in the gas volume component. It calculates the outlet composition (of the fuel gas mixture) as well as physical (pressure & temperature) and chemical properties (heating value). The user can set-up in the mixer mask the heat exchange coefficient with external ambient temperature. So, it can be in thermal balance with the surrounding environment or not, depending on the physical situation (including possible thermal insulation).

Starting from inlet flow condition of the individual fuel gas sources (LPG, bio-methane, syngas) at the current time [k] and outlet flow at the previous instant [k-1], the gas mixer model computes the fuel gas mixture properties at the mixing tank outlet (Figure 11):

- pressure
- temperature
- specific heat
- R
- LHV
- composition

As there are currently still limits set for the H₂ content (max. 30%vol. of H₂) of the fuel gas mixture delivered to the CHP unit, optional addition of hydrogen from a separate H₂ source (water electrolyzer) is subsequently determined by the EMS.

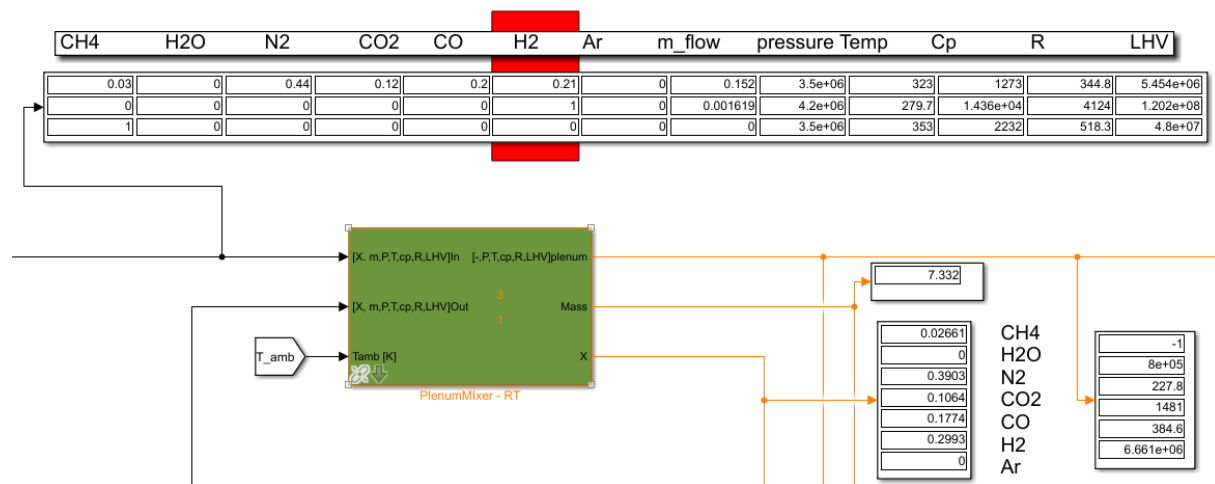


Figure 11 – Mixer model screenshot

4. Single component model validation

UNIGE gained wide experience in the dynamic modelling, simulation and validation of different energy systems since 2003 [6]. In ROBINSON, each model has been validated according to the available data, and considering their structure approach. Table 1 sums up the data source and the references for the validation each component models in steady-state and transient operations. The validation could be achieved using:

- manufacturer data
- in-house data
- previous work validation data
- literature data

Table 1 – Details related to the model validation activity.

MODEL	VALIDATION DATA AND REFERENCE
CHP	Manufacturer data and in-house data
Steam boiler	Manufacturer data and in-house data
Wind Turbine	Manufacturer data

Gasifier	Traverso A., Tucker D., Haynes C., 2012, Preliminary Experimental Results of Integrated Gasification Fuel Cell Operation Using Hardware Simulation, Journal of Engineering for Gas Turbines and Power, Vol. 134, pp. 071701/1-10.
Electrolyzers	Manufacturer data and literature [4]
H₂ storage	Traverso A., 2005, TRANSEO Code for the Dynamic Performance Simulation of Micro Gas Turbine Cycles, ASME Paper GT2005-68101, ASME Turbo Expo 2025.
Mixer	Traverso A., 2005, TRANSEO Code for the Dynamic Performance Simulation of Micro Gas Turbine Cycles, ASME Paper GT2005-68101, ASME Turbo Expo 2025.

4.1. CHP

The data-driven approach (manufacturer data in D1.3 and D3.1) makes the CHP model validated in steady-state operations. The A400 transient and dynamic data are not available yet since the CHP is still in the development and design process, they will be accessible when the CHP will be tested in the Aurelia facility or when it will be installed in the Prima Protein micro-grid. Then, UNIGE considered the in-house transient behaviour data of the AE T100 for preliminary validation; when the Aurelia A400 step response will be available the time constant will be re-calibrated according to the new data. The picture below (Figure 12) shows T100 model validation that provided the time constant for preliminary characterization of the A400 dynamic behaviour, as first guess. Following a load demand step (from 20 kW to 60 kW) performed at time zero, the model is able to match with good accuracy the experimental results.

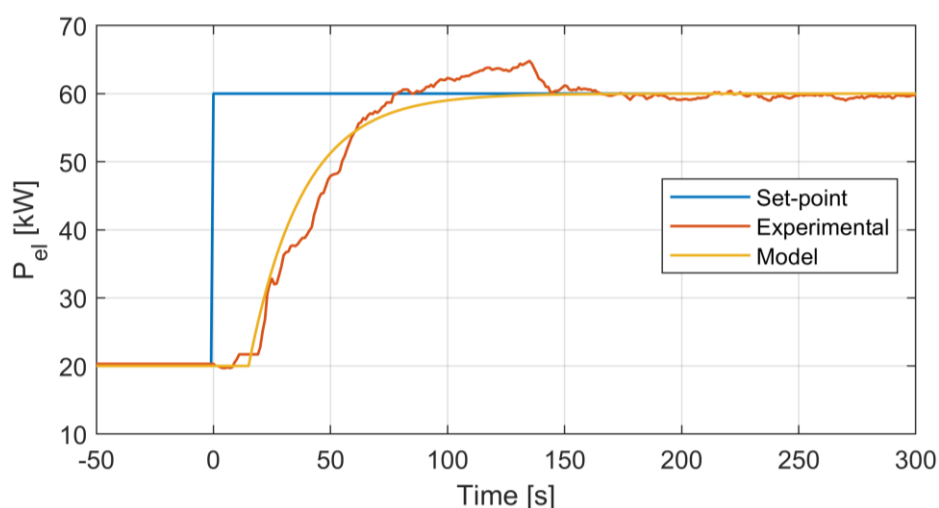


Figure 12 – T100 model validation with in-house experimental data

4.2. Steam Boiler

The steady part-load performance curve has been estimated using the proper correlation [2], coming from the validated in-house tool W-ECOMP for steady-state off-design analysis in polygeneration micro-grid. The dynamic behaviour of the steam boiler model has been validated on the experimental data presenting the transient from stand-by to production (D1.3). In details, Figure 14 shows a good agreement between the model results and the experimental data related to a step response.

4.3. Wind Turbine

The data-driven approach (manufacturer data in D1.3 and D3.1) makes the wind turbine model validated in steady-state operations. The rotor speed variation allows the WT to maximize the efficiency according to wind speed presenting a transient dynamic behaviour, as during start-up and shut-down. These data will be available when the turbine will run in Prima Protein demo-site. UNIGE has already included in the model a first guess time constant that will be updated according to the experimental data.

4.4. Gasifier

The gasifier system choice is still on-going (D3.1). So, the model validation refers to a previous work [3] waiting for the related update when new data will be available.

4.5. Electrolyzer

The steady part-load performance curve has been estimated using the manufacturer data (D3.1), for computing H_2 and O_2 mass flows. The electrolyzer dynamic response is very fast (few seconds), and is extremely difficult getting reliable data. By now, UNIGE validated the model on the experimental data available in the paper “Proton exchange membrane water electrolysis: modelling for hydrogen flow rate control” by Rebah Maamouri et al [4]. The new calibration and validation will be performed when the R&D unit of the manufacturer will provide the transient data.

4.6. H_2 storage and Mixer

The H_2 storage and mixer models belong to the TRANSEO in-house library [1], and they have already been validated in previous works [1][6][7].

5. Simulation results: step responses

The current section presents the simulation results of each component model, considering the dynamic characteristics and proposing transient behaviours.

5.1. CHP

Figure 13 presents a first order system step response for the A400 model. For emulating the transient operation, UNIGE assumed the same time characterization of the AE T100, as in Figure 12. The model presents a time constant equal to 23 s (this value will be update for A400 when the experimental data will be available). The maximum power rate is 2 kW/s.

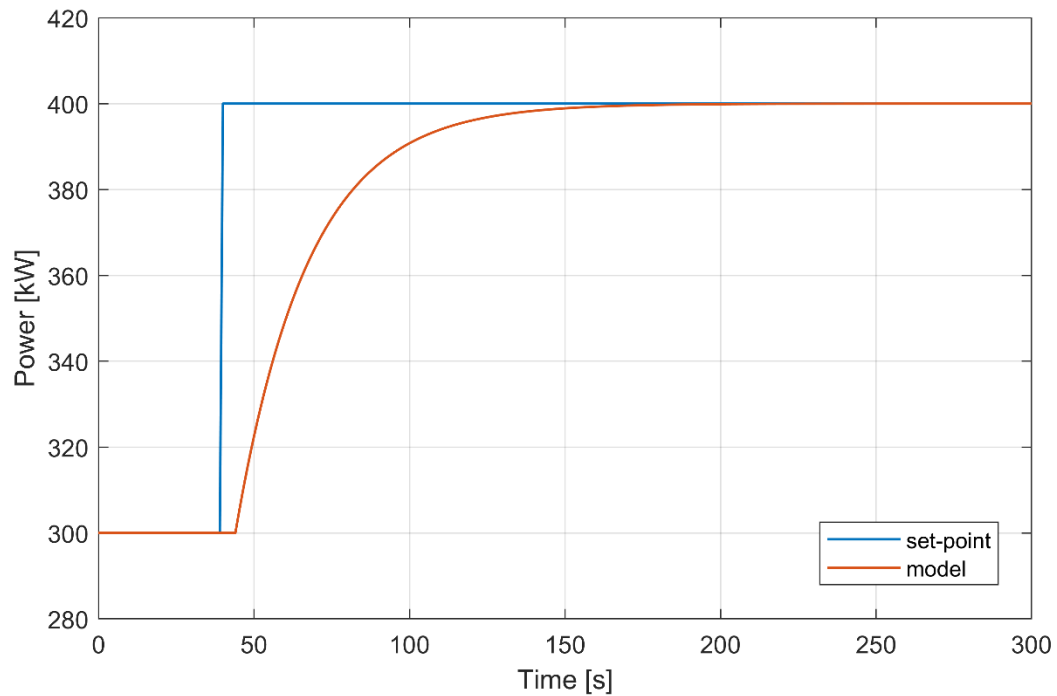


Figure 13 –Step response of the A400 model

5.2. Steam Boiler

The Figure 14 shows the comparison between the steam boiler experimental data by Prima Protein and the results by the UNIGE model. It presents the typical first order system step response behaviour. The estimated time constant is equal to 9000 s. The steam boiler takes almost ten hours to switch from standby condition to production.

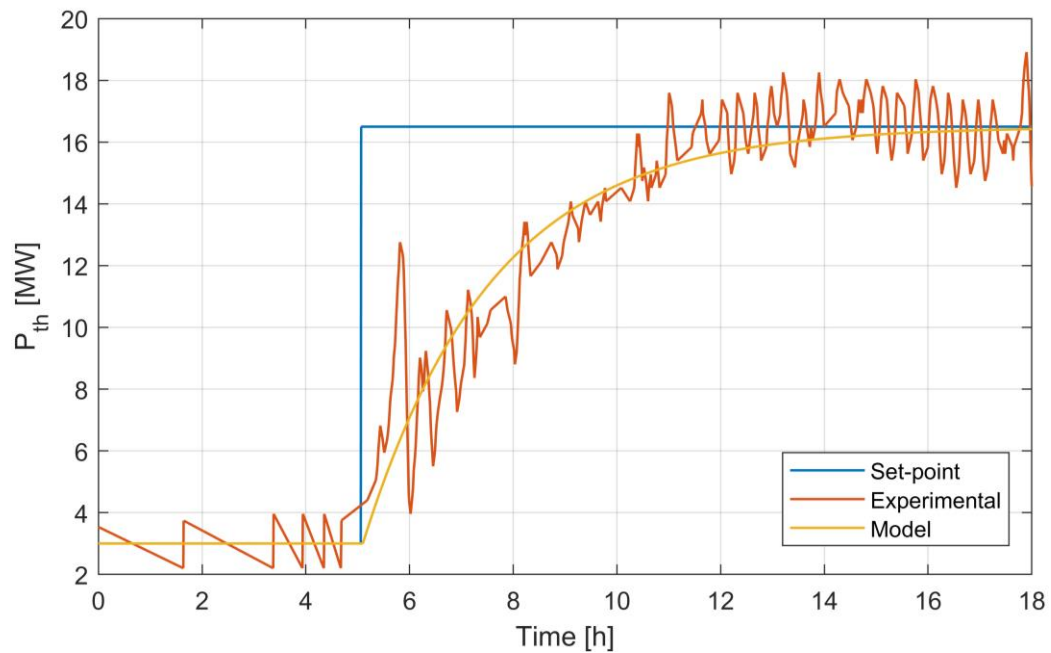


Figure 14 – Steam boiler step response and model validation

5.3. Wind Turbine

The RES-T V 100 WT presents cut-in speed equal to 2.5 m/s, while the cut-off speed is 20 m/s. Figure 15 show the model results for the WT operation during a typical operation day in Prima Protein (in Eigerøy).

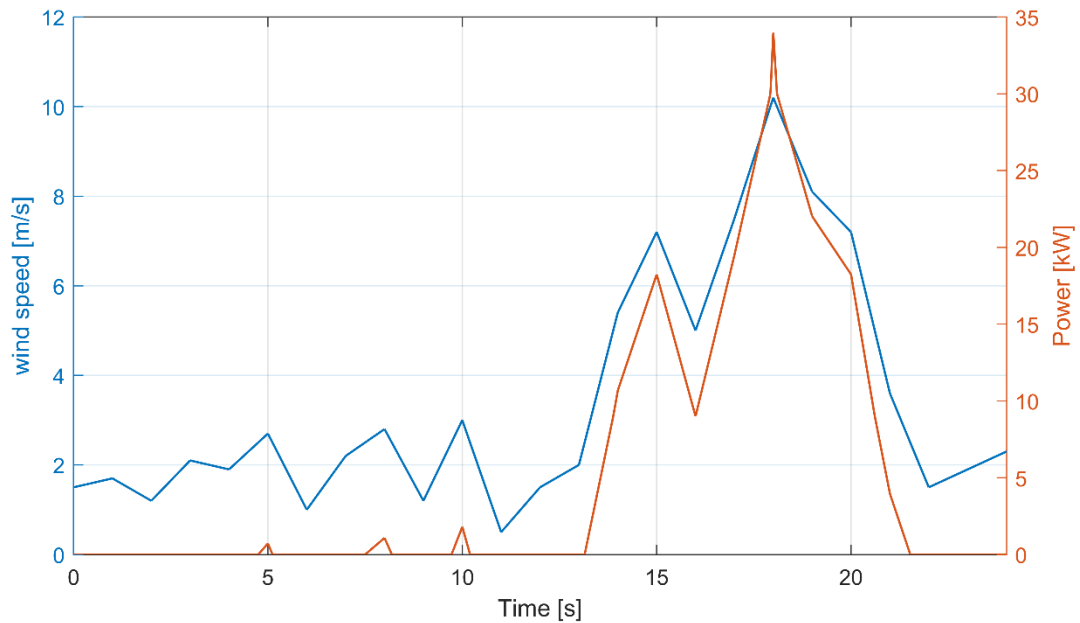


Figure 15 – RES-T V 100 WT daily simulation

5.4. Gasifier

Figure 16 and Figure 17 present the gasifier mass flow and composition dynamic response for the biomass preliminary composition (Figure 8). These results regard the dynamic effect of a step in the biomass inlet.

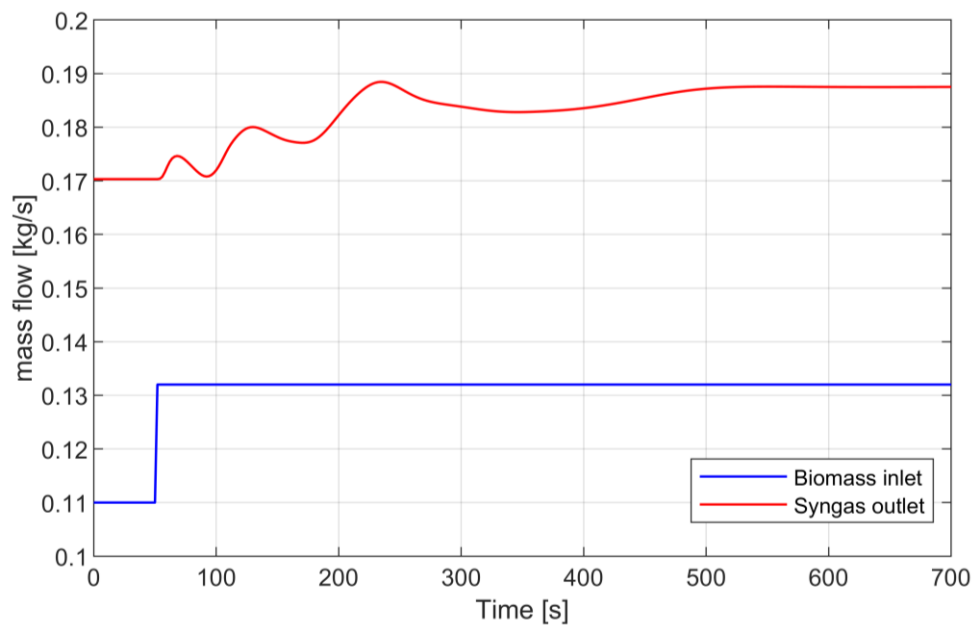


Figure 16 – Gasifier model step response, mass flow

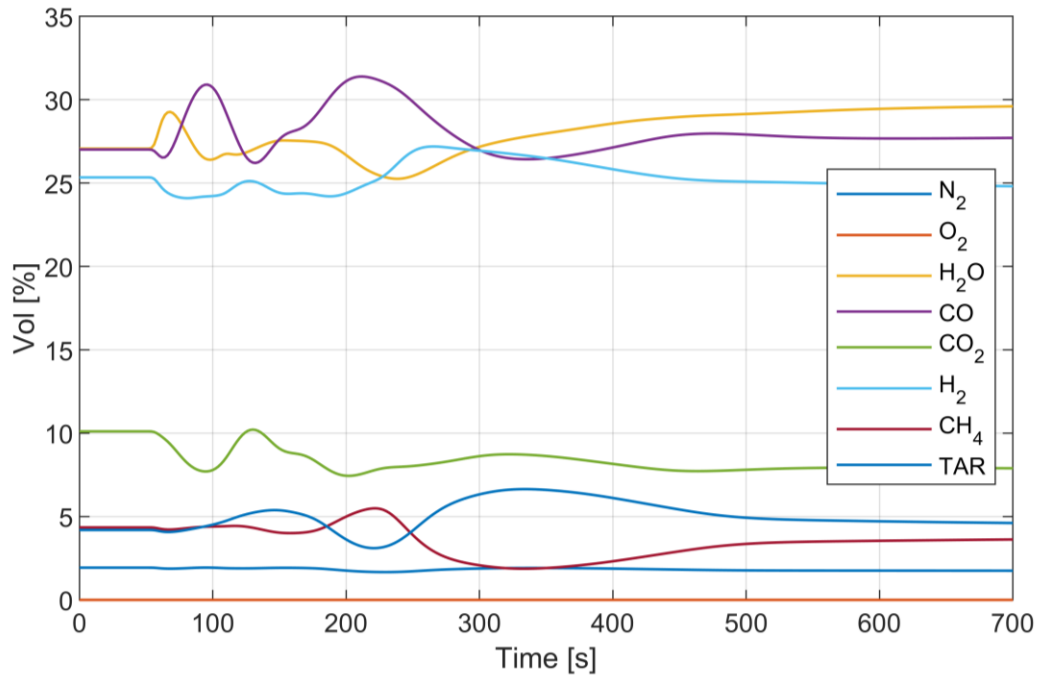


Figure 17 – Gasifier model step response, composition

5.5. Electrolyzer

The Figure 18 shows the part-load and transient behaviour of the A90 Green Hydrogen System electrolyzer, highlighting the fast electrochemical dynamic reaction of it. The first order time constant is equal to 2 s, as it has been preliminary calibrated according to Rebah Maamouri et al paper [4]. This value will be updated according to new data from the R&D section of Green Hydrogen System.

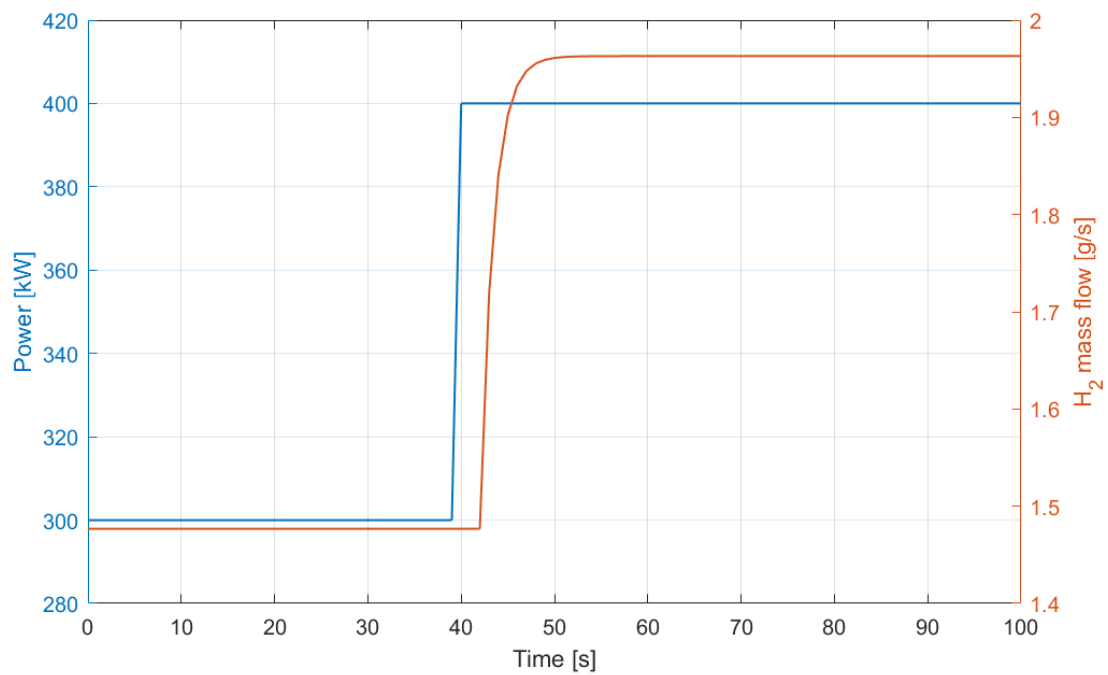


Figure 18 – Step response of the A90 electrolyzer model

The electrolyzer transient time scale from hot standby to operation is approximated 5 s, while from cold standby to operation approximated 7 min (according to the manufacturer).

5.6. H₂ storage

The Figure 19 show hydrogen storage pressure response to the inlet and outlet mass flow steps. When the mass flow at the inlet is equal to the mass flow at the outlet, the pressure is constant; decreasing the inlet mass flow, the storage pressure decreases until such time as the outlet mass flow decreases.

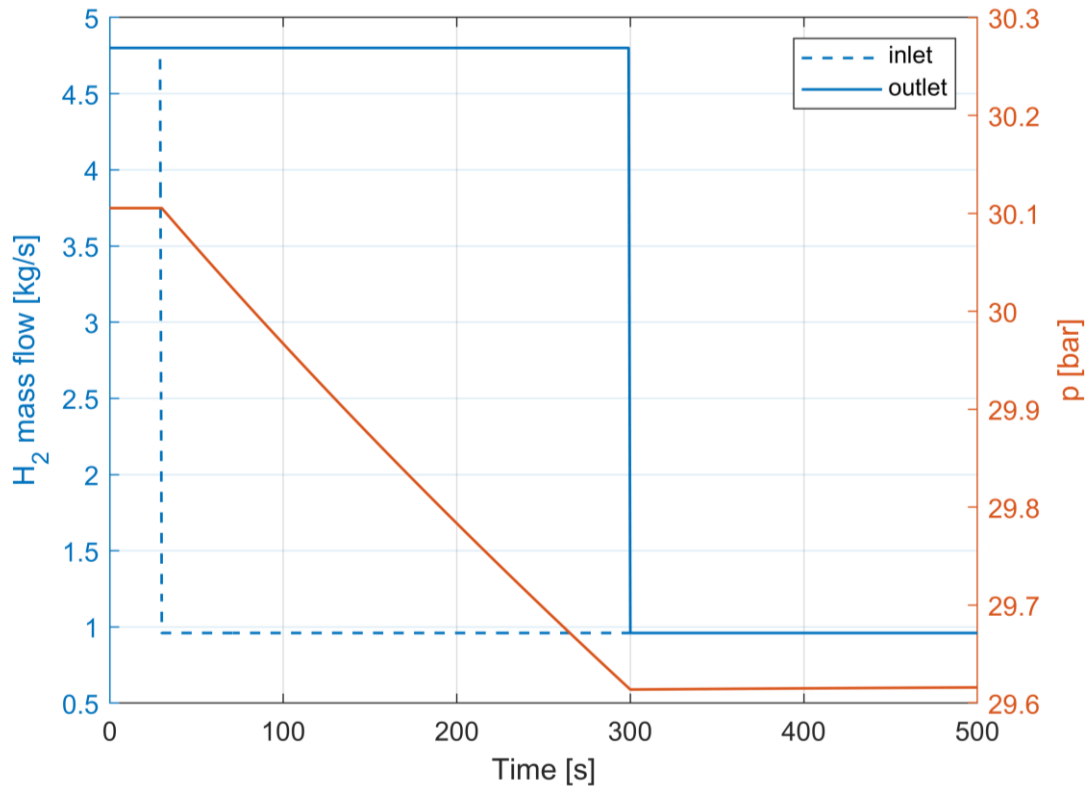


Figure 19 – Double step response of the H₂ storage model

5.7. Mixer

The Figure 20 shows the step response transient analysis for the mixer. The H₂ mass flow step down effects on the fuel outlet composition, decreasing H₂ % volume from 30% to 28% and increasing the other gases % (in particular N₂).

The CHP fuel mass flow control loop will define the gas mixer outlet that would be an input of the plenum mixer model.

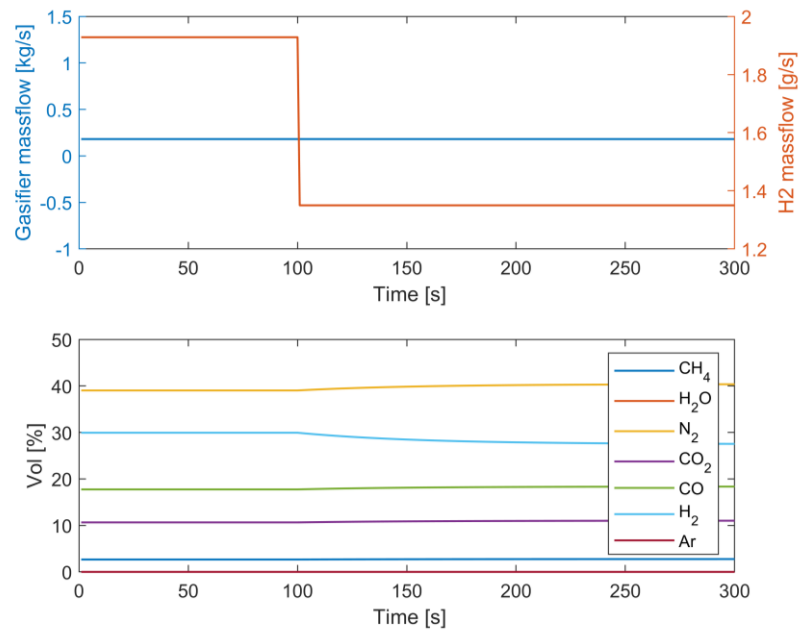


Figure 20 – H₂ mass flow step response for the mixer model

6. Replication section

This section is included in the deliverables to highlight the replication activities related to the model development and the related simulations for the Western Isles, and Crete.

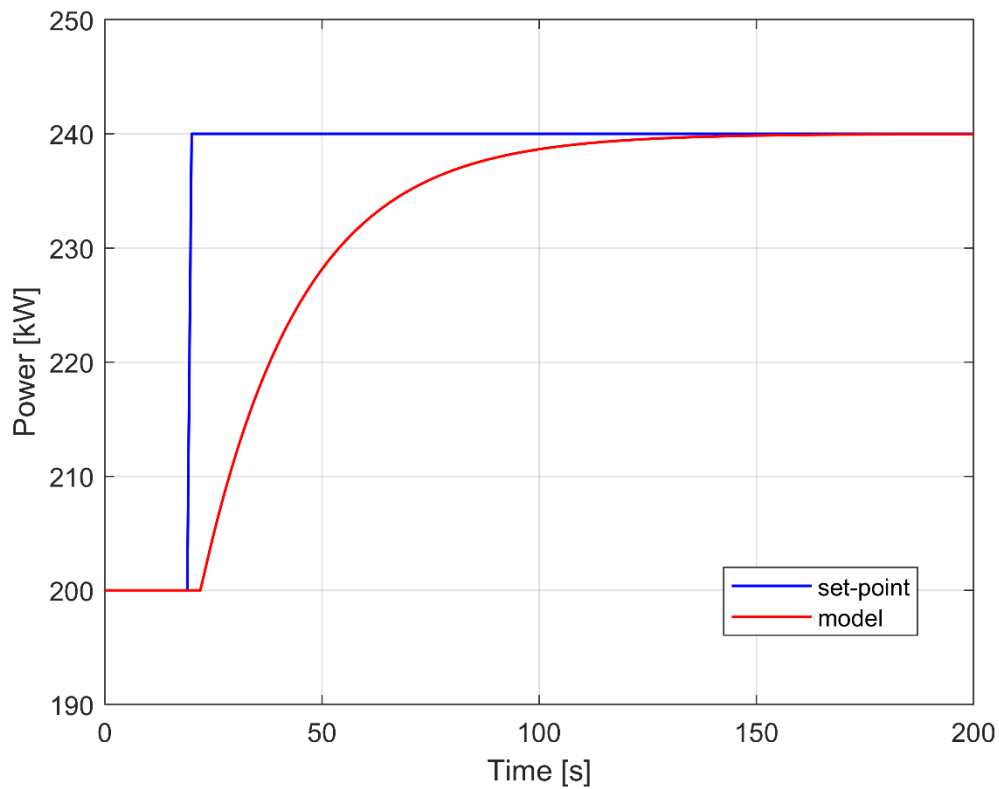


Figure 21 – Step response of the Western Isles CHP

Using the ROBINSON library, every model has been scaled according to the case study size, besides UNIGE updated the specific performance characteristic curves, when available.

For instance, Figure 21 presents the step response of the CHP model scaled to the Western Isles size. Besides, this case study includes a water TES (Thermal Energy Storage) for decoupling the heat generated by the thermal grid and the users demand. It has been emulated through the UNIGE 1-D dynamic model that is scalable according to the tank geometry. This component has been validated in previous UNIGE works [7], in the Innovative Energy System laboratory in the Savona campus (Italy). The Figure 22 shows the TES charge process highlighting temperature distribution along the length, through hot water mass flow (80°C). Comparing the average temperature along the length to the reference temperature, the model computes the state of charge of the TES.

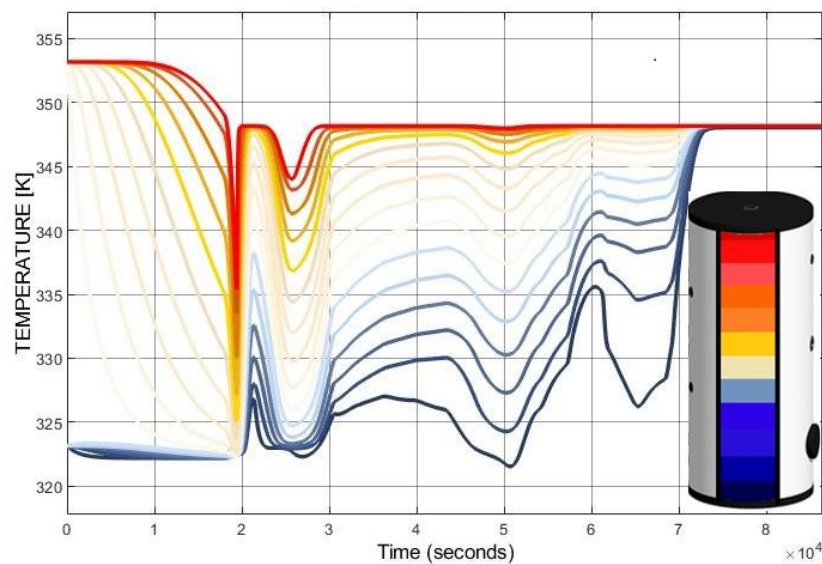


Figure 22 – Temperature profile in 1-D TES model during charging

Finally, for emulating PV plants in the Crete case study or in other replication cases, UNIGE based the model on the following relation that presents the electrical power generated as a function of solar radiation (S_{UV} [W/m²]), efficiency (η), and surface area (A) (Eq.2).

$$P_{el} = S_{UV} * A * \eta \quad (2)$$

In this case, internal dynamic behaviours and transients of the system are neglected since the technology response to the solar radiation variation is extremely fast (lower than 1 second).

7. Summary

This deliverable regards model development and the related simulations with the purpose of obtaining tools for the EMS development (an ongoing activity in T3.3). Following a preliminary description of the general modelling approach, attention is focused on the Eigenrøy island. The models have been developed considering the data (system nominal conditions, off-design and dynamic performance, control system aspects, constraints, etc.) obtained in both WP1 and WP2 and integrated in T3.1. The simulation results presented in this document are significant for both steady-state and dynamic performance of the necessary components of the system. Special attention has been focused on the validation activity carried out on the basis of data provided by the partners or obtained from

literature data. Moreover, modelling and simulation activities have also been performed for the replication target, considering the Western Isles and Crete. As discussed before, the simulation results reported in this document (essential for the T3.3 activities) show that the MS5 has been successfully reached by UNIGE (thanks to the support of all the partners of the ROBINSON project).

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