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SOFC CHP operation at the integrated pilot plant

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EXECUTIVE SUMMARY

The deliverable D6.2 "SOFC CHP operation at the integrated pilot plant" refers to Task 6.2 System operation algorithms based on selected production strategy and to Task 6.3: Pilot plant SOFC tests with real syngas. The indicators of success are firstly the definition of a system operation algorithm that will allow to operate the plant at improved performance (e.g. 20% of more cogeneration efficiency or more annual equivalent operating hours or more demand satisfied) with respect to the absence of the operation algorithm; secondly the reaching via the real tests of the plant performance (e.g. cold start-up and hot stand-by time less than 12 hours and 20 min rispectively, 1:3 power modulation, elettrical efficiency up to 50% and overall up to 90%).

In Task 6.2, because to a great extent the CHP performance depends on operation algorithms, based on an operating scenario defined in Task 4.1 (the great buildings cogeneration demands), different system operation scenarios have been evaluated, with respect to the selected production strategy (specific heating demands of buildings in particular in electric load tracking, I.e. "run in accordance with the electrical demand"), analysing the behaviour of each scenarios with respect to the energy coupling (heat and electricity) and so the energy and cost saving and as a result the identification of scenarios that maximise the plant performance under given process constraints.

Regarding Task 6.3, gasifier and conditioning system characterisation that quotes the biomass gasification and conditioning results at pilot scale (e.g. dry and wet gas composition, organic and inorganic contaminants load, gas flow rates) have been described in D6.1. The electrical and thermal (in terms of thermal power and temperature) capability of the plant have been evaluated in D4.1, D4.4, D7.1, D8.5. Furthermore owing to the plant scheme change and the more work than foreseen on the realization of the pilot plant, e.g. SOFC control system, the pilot plant, even if realised and all integrated, has not operated with the SOFC. Thus this deliverable quotes instead the syngas compressor not foreseen realised.

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T6.2 SYSTEM OPERATION ALGORITHMS BASED ON SELECTED PRODUCTION STRATEGY

It is generally known that the building industry accounts for about one-third of the overall national energy consumption, contributing to the emission of environmentally harmful greenhouse gases. Most of this consumption is due to buildings that are poorly insulated and that are not designed to take advantage of free heat inputs, and also to outdated systems and generators with very low efficiency values compared with those achievable with more modern equipment. The interventions that can be carried out in the field of existing residential construction can therefore achieve important results for a decisive reduction in overall energy consumption and emission.

For the reduction of energy consumption and emission of climate-altering gases, in recent years increasing attention has been paid to the evaluation of the impact of the use of new technologies to improve the energy situation of the Italian building stock, and in this scenario it becomes very important to be able to quantitatively evaluate the effect of the adoption of the various available technologies in order to maximize their benefits in terms of the search for the best economic and energy efficiency. Most of the Italian housing stock is heated by means of autonomous systems, that is, equipped with a generator and a distribution system for each housing unit. The introduction of optimization procedures applied to the design process of buildings and their systems makes it possible to approach the problem from a new, more rational and rigorous point of view.

The following case studies describe energy efficiency interventions in a building, including systems used for indoor air cooling with the introduction of renewable energy sources. An innovative technology for power and heat generation based on fuel cell micro cogeneration processes that can greatly increase the efficient and rational use of resources is studied. In particular, a TRNSYS model has been developed in order to evaluate different system operation scenarios for specific electricity and heating demands of residential buildings. The achievable energy and operational cost savings through the proposed plant with respect to traditional technologies (i.e., condensing boilers and electricity grid) will be assessed by means of simulation. In particular cost, PES-Primary Energy Saving and electrical and thermal load coverage will be investigated for different climate and latitude in the EU.

1.1. INTRODUCTION

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Energy use in European Union (EU) countries is steadily increasing, and, as internal energy production is unable to cover its needs, dependence outside EU has grown.

However, the European economy has been marked by various breakdowns in recent years, but there has never been detailed decisions on the choice of technologies and energy policies to be pursued in the context of security of supply. Today, the pressures of environmental concerns and the operation of the European energy market make such decision essential.

Among the various documents written by the European Commission, of particular note is the "Green Paper" of 2001, which sought to open a discussion on the security of energy supply, underlining the weaknesses of the system and proposing for consideration the various instruments that can be applied.

The EU energy demand has increased by 1-2% per year since 1986. The stability of consumption by industry, aided in particular by the introduction of the cogeneration concept and the use of more efficient technologies, is contrasted by the increase in consumption by households and the tertiary sector in electricity, transport and heat.

The fundamental point proposed for consideration in the 'Green Paper' is that the of traditional primary energies (crude oil, natural gas, coal and solid fuels) do not allow, with current technology, to provide for an energy autonomy for Europe. Only the combination of renewable resources and technology can limit the trend towards increasing energy dependency. One of the strategies that may prove suitable for the EU's energy requirements, with a view to sustainable development, is the variety of sources of supply and the diversification and improvement of energy production systems.

This work lies precisely within the research aimed at expanding knowledge and enhancing new technologies, which gasification combined with fuel cells can play an important role.

1.2. SOFC Applications

The best application for SOFC systems is stationary and distributed power generation. Depending on the size of the generator, a further distinction can be made between different types of applications:

- Residential: the residential users typically require 3-5 kW of electrical power, so a SOFC system of 1-3 kW is sufficient (considering that the SOFC is used for the base load) for a house, depending on the user's needs. As mentioned, the system can work in cogeneration and thus the home can also be provided with hot water, heating, and cooling as by-products. The supply of fuel is not a major issue as natural gas can be used, which is already widely available for many residential areas today.

- Industrial: SOFC systems are able to power small industrial units or hospitals, which can' t accept power supply cuts. The size typically varies between 100 and 1000 kW of electricity. Again, the heat for cooling and hot water can be provided by cogeneration and the fuel supply can rely on existing pipelines.
- Distributed: a large SOFC system could be used to power a large industrial unit or a small community so as to install a system capable of supplying about 2 to 10 MW of electricity, using natural gas as fuel [1].
- Central: this system resembles the current method of electricity distribution, in which a few high-power generators are distributed throughout the territory to supply consumers, both domestic and industrial. The largest SOFC generation system could be around 100 MW of electricity. The final focus is on producing electricity as efficiently as possible, and indeed this system is expected to produce and distribute electricity with an efficiency of more than 60% [2]. Natural gas and methane can be used as fuels, but the aspect to which most attention is drawn is certainly the type of system to be used: excess heat is of little use as an end use, so a hybrid system with a downstream microturbine is the right way to make the best use of the energy provided by the fuel.

1.3. Coupling of biomass gasification and SOFC

In the ‘80s, gasification and fuel cells were combined to improve advanced coal gasification systems. It wasn’t until the late ‘90s, moreover, that biomass gasification systems and fuel cells were thought of as a potentially interesting technology for generating electricity from biomass-derived production gas. The first to report on a thermodynamic analysis of the combination of a biomass gasifier and SOFCs were Alderucci et al. in 1994, in which a fluidized bed gasifier using steam or CO2 as the gasifying agent was studied, and balance calculations were used to provide the conversion levels in the gasifier. The electrical performance of the SOFC was calculated at different gasifier operating conditions, like the operating temperature [3].
This coupling was also mentioned by Craig and Mann in the 1990s in a study of biomass-based integrated combined cycle gasification, a potential future for efficient cogeneration of biomass production [4]. Barchewitz reported in 2000 an advanced design study of SOFC and gas turbine systems combined with biomass gasification, which calculated the overall system efficiency for

plants with a production capacity of 4-5 MWe. The considered gasifier was an autothermal fluidized bed pressure system, and the SOFC was a planar type. Assuming that all the tar will break down in the gasifier, which is quite unusual for this type of gasifier, a heat recuperator was added to recover the heat output by the gas turbine and the resulting electrical system efficiency was 59%. [5].

A different study was completed by Hutton et al. [6] where two SOFC systems were fuelled with producer gas obtained from biomass. In this work, the effect of hot versus cold gas cleaning on system efficiency and cost was studied. The electrical efficiency of the overall system was around 25% for both cases, but the hot gas cleaning performed better heat treatment and therefore better overall CHP efficiency. The low electrical efficiency was due to the low fuel utilisation in the SOFC and the fact that the SOFC waste gas was fired for further heat production instead of decreasing the auxiliary fuel consumption. The efficiency is significantly lower than that of Barchewitz's work, emphasizing the importance of proper use of SOFC exhaust gas. In Barchewitz's case, this is done in a recycled gas turbine. Furthermore, the study by Omun et al. did not include extraction of sulfur compounds that are harmful for SOFC. Fryda et al., in 2008, worked on a self-thermal (air) biomass gasifier integrated with SOFC and/or a gas microturbine with a biomass throughput of 200 kg/h. The combination of gasifier, SOFC and gas microturbine achieved the highest electrical efficiency of 40.6%. Surprisingly, the gasifier and gas microturbine system outperformed the gasifier and SOFC combination with an electrical efficiency of 26.1% versus 20.0%. An electrical efficiency of less than 20% in the gasifier and SOFC combination seems unrealistically low when sized and operated correctly [7].

Many EU projects from 2000 to 2023 (e.g. BioCellus, Green-Fuel-Cell, Woodgas-SOF, FlexiFuel SOFC, etc) both dealt with the combination of biomass gasification and SOFCs, with a focus on obtaining a clean production gas through appropriate gasifier design and/or hot gas cleaning. Thermal integration between an alothermal biomass gasifier and tubular SOFCs by means of liquid metal heat pipes that transfer excess heat from the SOFCs to the gasifier comprises an innovative coupling for small-scale cogeneration, was also presented in the BioCellus project. Based on a modelling study, Panopoulos et al. reported a total electrical efficiency of 36% and a current density of 250 mA/cm2 to produce 140 kWe [8].

For the physical coupling between the biomass gasifier and the SOFC, either a pressurized feeding system or an intermediate syngas compressor is required to overcome the pressure losses in the system. The design and development of such a novel syngas compressor, carried out by EPFL for the BLAZE pilot plant, is described in Section 2.

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1.4. TRNSYS model

Trnsys is a complete and extensible dynamic systems simulation environment, including multi-zone buildings. It is a software designed for the analysis, with considerable degree of detail, of the transitory performance of energy systems whose behaviour is variable over time. It is used by engineers and researchers all over the world to validate new energy concepts, by simple domestic hot water systems to the design and simulation of buildings and their systems, integrating control strategies, occupant behaviour, alternative energy systems (wind, solar, photovoltaic, systems and hydrogen). One of the key success factors of Trnsys is its open modular structure. The source code and models of the various components are open to the final user, which makes it easy to modify and extend existing models to make them suitable for the user's specific purposes. Its modular nature makes the software very flexible, easy to use and allows the addition of mathematical models that are not present in the standard library. A system defined in Trnsys consists of a series of components, connected in an appropriate way in order to be able to simulate the performance of the specified work. Trnsys contains a series of sub-programmes (subroutines) written in Fortran. Every subroutine contains a component model of the system marked by a number that illustrates its function (Type number); specifying parameters (time-independent values) and input data (time-dependent values); the model can calculate output functions of the time. The outputs so obtained can be used as input for other components (which contain a different mathematical model). The architecture based on files with DLL extension makes it easy to add customised component models, using all the most common programming languages (C, C++, PASCAL, FORTRAN, etc.). In addition, Trnsys can be easily connected with many other applications (for example Excel, Matlab, Comis, etc.).

Typically, a Trnsys project is built by graphically connecting the various components within Simulation Studio, which is the main graphical interface of the software. In fact, from this any new project can be created by simply selecting and dragging the various components from a list to the workspace, connecting them together and setting global simulation parameters. Every Type (component) is described by a mathematical model and has a series of parameters, inputs and outputs.

TRNbuild is the tool used to load building related data. It allows to specify all the details of the structure and everything that is necessary to simulate the thermal behaviour of the building, such as the optical properties of the windows, air conditioning settings, technical devices, etc [9].

The scope is to investigate and discuss the operation of a mCHP based on the gasifier + SOFC system for the different dwellings in Europe, specifically in Rome. Three different cases of the residential building with eight, twenty-four and forty dwellings with 100 m^2 heated area have been considered. Space heating, electricity appliances consumptions and domestic hot water (DHW) demand have been investigated in order to evaluate electrical and thermal coverage.

1.5. Locations

Three different locations in Italy have been considered: Milan, Rome and Palermo. For each city, the daily average high and low air temperature (Figure 1) and the average daily shortwave solar energy reaching the ground per square meter (Figure 2) have been considered.

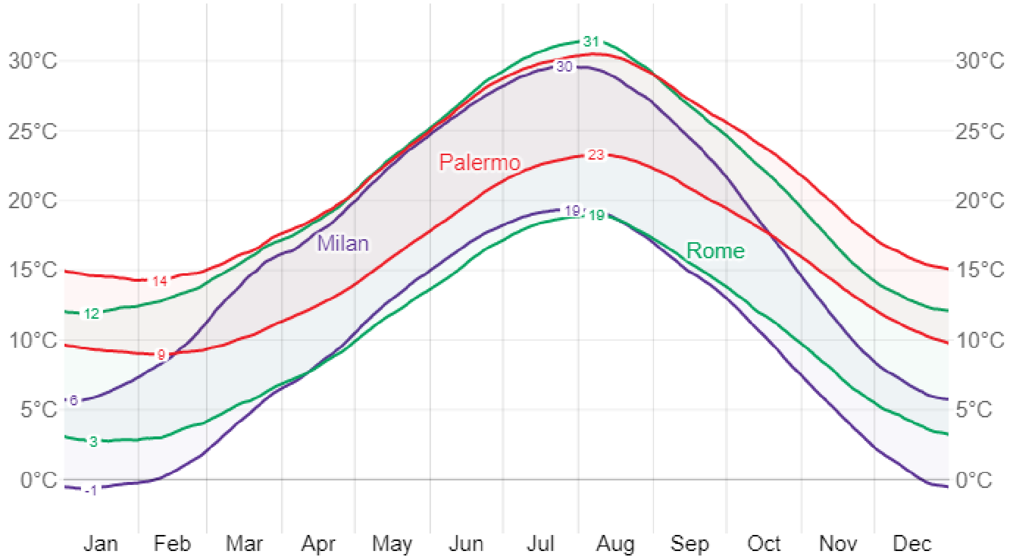

Figure 1.The daily average high and low air temperature

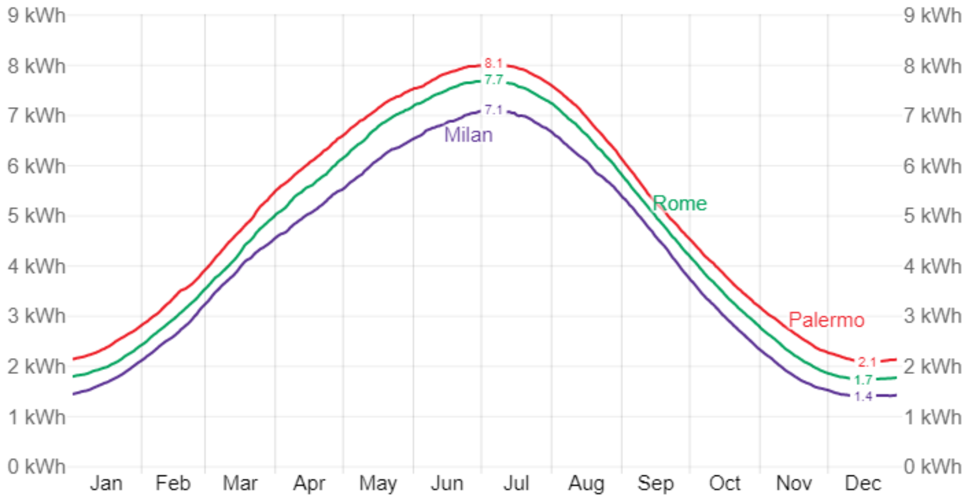

Figure 2. The average daily shortwave solar energy reaching the ground per square meter.

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In Rome, the hot season lasts for 2.8 months, from June 17 to September 10, with an average daily high temperature above 28°C. The hottest month of the year in Rome is August, with an average high of 31°C and low of 18°C. The cool season lasts for 3.9 months, from November 20 to March 17, with an average daily high temperature below 16°C. The coldest month of the year in Rome is January, with an average low of 3°C and high of 12°C. The brighter period of the year lasts for 3.2 months, from May 10 to August 18, with an average daily incident shortwave energy per square meter above 6.5 kWh. The brightest month of the year in Rome is July, with an average of 7.5 kWh. The darker period of the year lasts for 3.5 months, from October 28 to February 15, with an average daily incident shortwave energy per square meter below 2.9 kWh. The darkest month of the year in Rome is December, with an average of 1.8 kWh.

In Milan, the hot season lasts for 3.4 months, from June 1 to September 13, with an average daily high temperature above 25°C. The hottest month of the year in Milan is July, with an average high of 29°C and low of 19°C. The cold season lasts for 3.2 months, from November 19 to February 25, with an average daily high temperature below 10°C. The coldest month of the year in Milan is January, with an average low of -1°C and high of 6°C. The brighter period of the year lasts for 3.2 months, from May 12 to August 18, with an average daily incident shortwave energy per square meter above 6.0 kWh. The brightest month of the year in Milan is July, with an average of 7.0 kWh. The darker period of the year lasts for 3.5 months, from October 26 to February 13, with an average daily incident shortwave energy per square meter below 2.5 kWh. The darkest month of the year in Milan is December, with an average of 1.4 kWh.

In Palermo, the average percentage of overcast clouds exhibits significant seasonal variation throughout the year. The clearer part of the year in Palermo begins around June 12 and lasts for 2.9 months, ending around September 9. The clearest month of the year in Palermo is July, on average 95% clear, mostly clear, or partly cloudy. The cloudy day of the year begins around September 9 and lasts for 9.1 months, ending around June 12. The cloudy month of the year in Palermo is January, and the sky is overcast or mostly cloudy 42% of the time on average. The light season lasted for 3.3 months, from May 7 to August 18, with an average daily incident shortwave energy exceeding 6.9 kWh per square meter. The brightest month of the year in Palermo is July, with an average of 7.9 kWh. The dimmer period of the year lasted 3.5 months, from October 29 to February 13, with average daily incident shortwave energy below 3.3 kWh per square meter. The darkest month of the year in Palermo is December with an average of 2.1 kWh.

1.6. Building model

Each dwelling has a surface of 100 m2 and a window area of at least 10% of the wall surface with north–south orientation. It was assumed about 30 m2 per person providing an internal gain of 120 W each and a 0.5 ACH (air changes per hour) was modelled. The building model for Italy was designed accordingly to the thermal specifications reported in Table 1 [10].

Table 1 Building thermal specifications (U-values in W/m^2K)

Country	External Walls	Roof	Floor	Windows
Spain	0.74	0.46	0.62	3.1
Italy	0.34	0.32	0.30	2.0
France	0.36	0.20	0.22	2.1
Germany	0.28	0.20	0.30	1.3
UK	0.28	0.16	0.22	2.0
Sweden	0.18	0.15	0.15	1.2

The daily DHW tap profile is taken from the European standard UNI EN 15316-3, tap profile number 2, because the most representative of the average DHW use in Europe [11]. A typical size of 300 L was assumed for the DHW tank in each dwelling and a tank with an internal coil was considered in order not to mix the technical water from the plant and the domestic water for the final user. A thermally stratified water storage tank was used to collect the thermal energy produced by the SOFC unit and partially cover DHW consumptions. A back-up boiler was included to cover the thermal energy demand not provided by the SOFC, with a design power able to produce the peak DHW thermal demand (25 kW per dwelling).
Electrical heat pump (air to liquid with a COP equal to 3) was assumed as a distribution system in the dwelling. The electricity profile for the appliances consumption of each apartment was obtained by means of [12].

1.7. SIMULATION MODEL

A dynamic simulation model was developed and a schematic of the Trnsys model is shown in Figure 3.

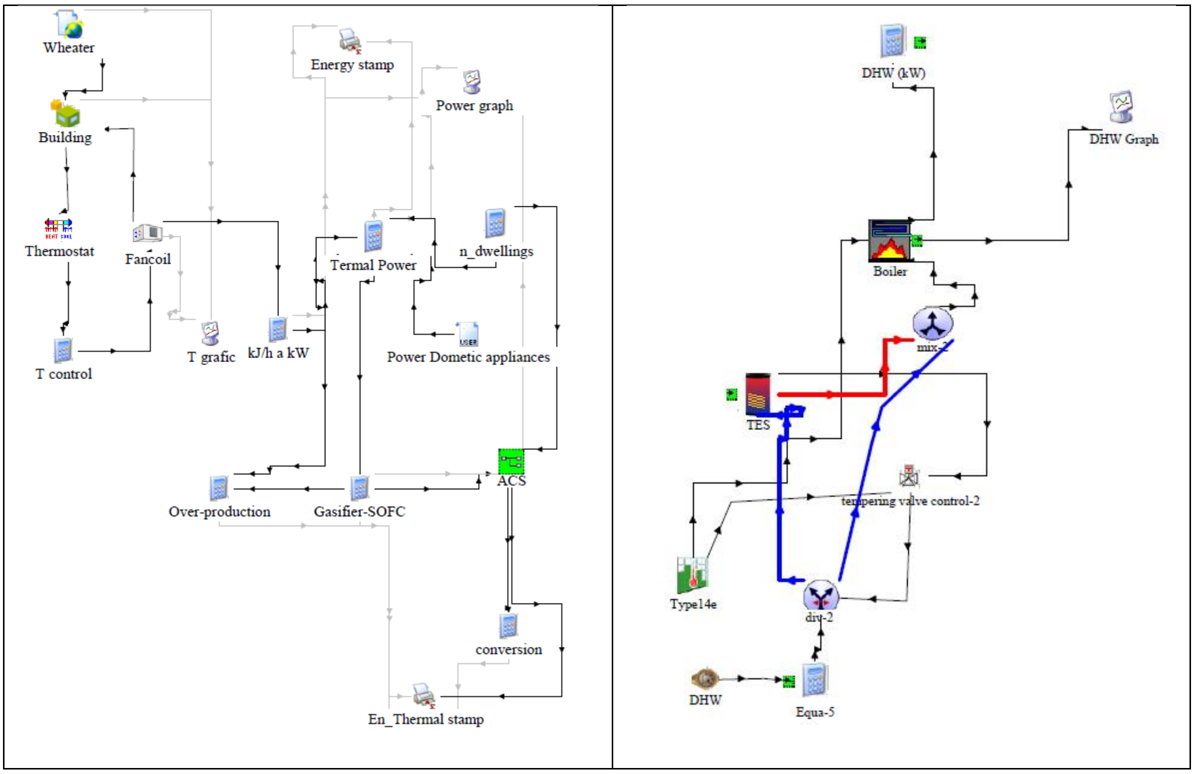

Figure 3 TRNSYS Model layout

The main types used for the outline of the model are the following:

- **Weather data** (Type 109): simulations were run using Meteonorm data for Milan, Rome and Palermo.
- **Gasifier-SOFC**: a calculator evaluates the electric and thermal energy produced by the SOFC according to table 2 (electrical efficiency was calculated considering a biomass with 18.8 MJ/kg lower heating value)

Table 2 Correlation between gasifier biomass input and SOFC power output

Biomass input	% of gasifier	El. Power	El. Efficiency	P thermal	T water out	Water Flowrate
kg/h		[kW]		[kW]	[°C]	[kg/h]
5	50%	14,60	55%	13,1	60	258,1
7,5	75%	20,26	51%	18,2	60	358,1
10	100%	24,82	47%	22,3	60	438,6

- **TES:** This component (Type 156) models a cylindrical tank with a vertical configuration. The fluid in the storage tank interacts with the fluid in the heat exchanger (through heat transfer with the immersed heat exchanger), with the environment (through thermal losses from the top, bottom and edges) and with up to two flow streams that pass into and out of the storage tank. The tank is divided into isothermal temperature nodes, which interact between them for fluid conduction and movement.

- **Building:** (Type 56) This component models the thermal behaviour of a building having multiple thermal zones. The building description is passed to the model by the building description file (*.bui). This file can be generated the pre-processor program called TRNBuild.
- **Boiler:** The model (Type 122) calculates the energy required to elevate the temperature of the liquid from its inlet value to the setpoint value.
- **Fancoil:** (Type 137) This component models a fancoil where the air is cooled as it passes across coils containing hot and cold liquid flow streams. This model relies on user-provided external data files which contain the performance of the coils as a function of the entering air and fluid conditions.
- **DHW:** (Type 14) In transient simulations, it is sometimes convenient to use a time-varying forcing function that exhibits behaviour characterized by repeating patterns. The pattern of the forced function consists of a series of discrete data points representing the value of the function at different times during the loop. Provides linear interpolation to generate continuous constraint functions from discrete data. The loop repeats every N hours, where N is the last specified time value. While the code for Type 14 is completely generic, this version of the component uses kg/h units more suitable for creating water forcing functions.

Three different scenario have been studied considering gasifier power rate at 50, 75 and 100%: the number of dwelling for each scenario is equal to 29, 40 and 50 (approximated to an integer number) respectively, calculated by (1) in order to have a roughly estimation of the minimum number od dwelling which electric consumptions could be covered by SOFC power output.

$$n_{dwel} = \frac{E_{el\ SOFC50,75,100\%}\,(kWh)}{E_{el\ 1dwel\ demand}(kWh)} \qquad (1$$

1.8. Results and discussion

The annual electrical energy balance for Rome is reported in Table 3,4 and 5 for 29, 40 and 50 dwellings respectively.

Table 3 Monthly electrical energy demand of 29 dwelling and electrical energy produced by SOFC

Month	*D_el Heating (kWh)*	*D_el. Coooling (kWh)*	*Del. conditioning*	*D_el. appliances (kWh)*	*E_el. SOFC tot (kWh)*	*D_eltot (kWh)*	*Overproduction (kWh)*	*Electrical coverage*

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			including fan (kWh)					
January	5063,01	0,00	5944,42	5868,44	10862,40	11812,86	950,46	92%
February	3175,26	0,00	3727,95	8203,23	9811,20	11931,18	2119,98	82%
March	991,72	0,00	1164,35	8985,36	10862,40	10149,71	712,69	100%
April	4,35	0,00	5,22	7208,53	10512,00	7213,75	3298,25	100%
May	0,00	950,91	1059,95	7295,53	10862,40	8355,48	2506,92	100%
June	0,00	2126,28	2369,88	8640,55	10512,00	11010,43	498,43	95%
July	0,00	3902,53	4350,00	6311,27	10862,40	10661,27	201,13	100%
August	0,00	3506,10	3908,33	8461,91	10862,40	12370,24	1507,84	88%
September	0,00	851,73	949,46	8345,62	10512,00	9295,08	1216,92	100%
October	0,00	0,00	0,00	7425,16	10862,40	7425,16	3437,24	100%
November	2766,39	0,00	3248,00	7335,26	10512,00	10583,26	71,26	99%
December	5197,85	0,00	6102,76	9027,41	10862,40	15130,17	4267,77	72%
TOT	17198,58	11337,55	32830,32	93108,27	127896,00	125938,59	1957,41	**94%**

Table 4 Monthly electrical energy demand of 40 dwelling and electrical energy produced by SOFC

Month	*D_el Heating (kWh)*	*D_el. Coooling (kWh)*	*Del. conditioning including fan (kWh)*	*D_el. appliances (kWh)*	*E_el. SOFC tot (kWh)*	*D_eltot (kWh)*	*Overproduction (kWh)*	*Electrical coverage*
January	6983,46	0,00	8199,20	8094,40	15073,44	16293,60	1220,16	93%
February	4379,66	0,00	5142,00	11314,80	13614,72	16456,80	2842,08	83%
March	1367,89	0,00	1606,00	12393,60	15073,44	13999,60	1073,84	100%
April	6,00	0,00	7,20	9942,80	14587,20	9950,00	4637,20	100%
May	0,00	1311,60	1462,00	10062,80	15073,44	11524,80	3548,64	100%
June	0,00	2932,80	3268,80	11918,00	14587,20	15186,80	599,60	96%
July	0,00	5382,80	6000,00	8705,20	15073,44	14705,20	368,24	100%
August	0,00	4836,00	5390,80	11671,60	15073,44	17062,40	1988,96	88%
September	0,00	1174,80	1309,60	11511,20	14587,20	12820,80	1766,40	100%
October	0,00	0,00	0,00	10241,60	15073,44	10241,60	4831,84	100%
November	3815,71	0,00	4480,00	10117,60	14587,20	14597,60	10,40	100%
December	7169,45	0,00	8417,60	12451,60	15073,44	20869,20	5795,76	72%
TOT	23722,18	15638,00	45283,20	128425,20	177477,60	173708,40	3769,20	**94%**

Table 5 Monthly electrical energy demand of 50 dwelling and electrical energy produced by SOFC

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Month	*D_el Heating (kWh)*	*D_el. Coooling (kWh)*	*Del. conditioning including fan (kWh)*	*D_el. appliances (kWh)*	*E_el. SOFC tot (kWh)*	*D_eltot (kWh)*	*Overproduction (kWh)*	*Electrical coverage*
January	8729,33	0,00	10249,00	10118,00	18466,08	20367,00	1900,92	91%
February	5474,58	0,00	6427,50	14143,50	16679,04	20571,00	3891,96	81%
March	1709,87	0,00	2007,50	15492,00	18466,08	17499,50	966,58	100%
April	7,50	0,00	9,00	12428,50	17870,40	12437,50	5432,90	100%
May	0,00	1639,50	1827,50	12578,50	18466,08	14406,00	4060,08	100%
June	0,00	3666,00	4086,00	14897,50	17870,40	18983,50	1113,10	94%
July	0,00	6728,50	7500,00	10881,50	18466,08	18381,50	84,58	100%
August	0,00	6045,00	6738,50	14589,50	18466,08	21328,00	2861,92	87%
September	0,00	1468,50	1637,00	14389,00	17870,40	16026,00	1844,40	100%
October	0,00	0,00	0,00	12802,00	18466,08	12802,00	5664,08	100%
November	4769,63	0,00	5600,00	12647,00	17870,40	18247,00	376,60	98%
December	8961,81	0,00	10522,00	15564,50	18466,08	26086,50	7620,42	71%
TOT	29652,72	19547,50	56604,00	160531,50	217423,20	217135,50	287,70	**93%**

It's evident that the system, in all scenarios, does not cover 100 % of the electricity requirements, because there are periods when the total demand is higher than what is produced. For the months in which this gap results, the values are shown in red; the electrical coverage value is less than 100%. For the yearly period, the average over all the months is reported, resulting in around 94% total coverage for all cases. Where positive values of overproduction result, 100% coverage is reached and the surplus is fed into the grid.

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Concerning the domestic hot water, the auxiliary thermal energy required for each scenario (in Rome) is shown in Table 4, 5 and 6 respectively:

Table 6 DHW demand for 29 dwellings

Month	D_ DHW (kWh)	Eth Aux Heater (kWh)
January	4961,30	4286,01
February	4481,17	4240,81
March	4961,30	4695,18
April	4801,26	4543,72
May	4961,30	4695,18
June	4801,26	4543,72
July	4961,30	4695,18
August	4961,30	4695,18
September	4801,26	4543,72
October	4961,30	4695,18
November	4801,26	4543,72
December	4961,30	4695,18
TOT	58415,27	54872,77

Table 7 DHW demand for 40 dwellings

Month	D_ DHW (kWh)	Eth Aux Heater (kWh)
January	6843,20	5896,73
February	6180,93	5839,51
March	6843,17	6465,17
April	6622,42	6256,61
May	6843,17	6465,17
June	6622,42	6256,61
July	6843,17	6465,17
August	6843,17	6465,17
September	6622,42	6256,61
October	6843,17	6465,17
November	6622,42	6256,61
December	6843,17	6465,17
TOT	80572,81	75553,70

Table 8 DHW demand for 50 dwellings

Month	D_ DHW (kWh)	Eth Aux Heater (kWh)
January	8554,00	7351,87
February	7726,16	7284,32
March	8553,96	8064,78
April	8278,03	7804,62
May	8553,96	8064,78
June	8278,03	7804,62
July	8553,96	8064,78
August	8553,96	8064,78
September	8278,03	7804,62
October	8553,96	8064,78
November	8278,03	7804,62
December	8553,96	8064,78
TOT	100716,02	94243,35

It's clear that the SOFC is not able to cover all the DHW demand. As expected, the percentage of yearly thermal coverage is equal to 6% for both scenario calculated as follows:

$$Cov_{th} = \frac{E_{DHW} - E_{therm\ aux\ heater}}{E_{DHW}} \times 100\ (\%)$$

In Tables 9, the comparison of the proposed Gasifier+SOFC system with separate generation by means of traditional technologies is shown. The primary energy use by taking the electricity from the grid and by producing thermal energy with a condensing boiler (110% efficiency) was assessed and compared with the primary energy (PE) use when the Gasifier+SOFC system was introduced (2.5 and 1 were assumed as conversion factors for PE related with electricity and natural gas respectively). Furthermore, the operational costs reduction was also evaluated, by considering national prices for electricity, natural gas and biomass [12, 13].

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Table 9 primary energy (PE) savings and operational cost savings of the BLAZE system concept coupled with dwellings compared to traditional technologies (trad)

Scenario	PE_trad (kWh)	PE_GAS+SOFC (kWh)	Variation_PE %	Cost_trad €	Cost_GAS+SOFC €	Variation_cost €
29 dwellings	367951	49884	86%	38173	31629	83%
40 dwellings	507519	68685	86%	52652	43318	82%
50 dwellings	634398	85675	86%	65815	53833	82%

Finally, in order to understand how the performance of the system varied as the temperature trend changes, two other locations (Palermo in the south and Milan in the north of Italy) for 50 dwellings scenario have been tested. Figure 4.

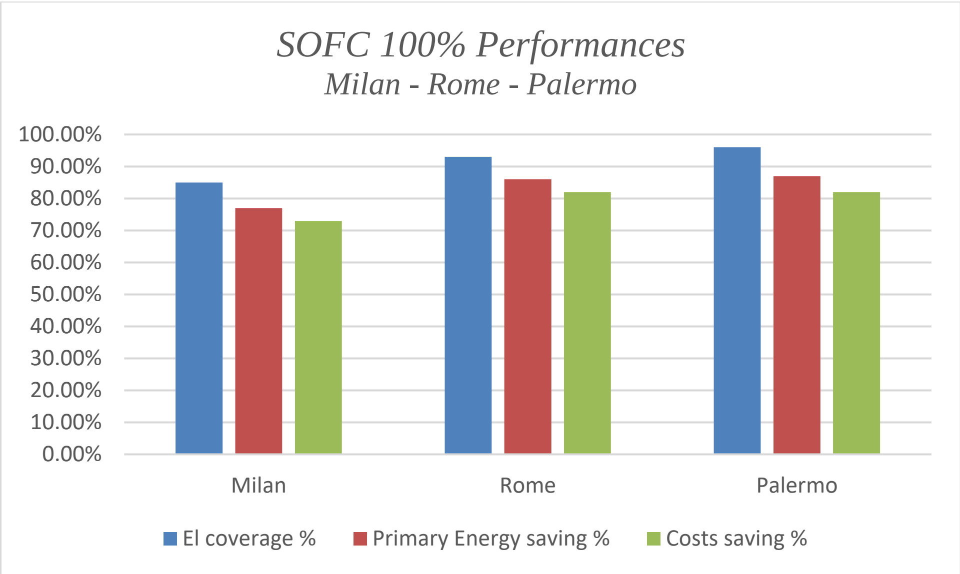

Figure 4 Electrical coverage compared, primary energy and cost savings comparison

Electricity coverage for Palermo is 96%, while for Rome it is 93% and for Milan 85%: this is because the overall energy demand for heating and cooling, both in summer and winter, is lower compared to the last two cities. Consequently, the primary energy and cost savings are greater compared to Rome and Milan. DHW analysis has not been considered because the demand is fixed in all cities.

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1.9. Conclusion

The implementation of a GASIFIER+SOFC system for residential buildings offers advantages in terms of energy consumption and cost savings.

It is an enhanced system of energy production from the use of biomass and is intended to have a sustainable development as it avoids drawing in smaller quantities from non-renewable energy sources.

Different cases were examined as the power of the system and thus the biomass input varied. At 100% maximum gasifier power, it's possible to cover all electric consumption of 50 residential dwellings including appliances demand and the conditioning provided by heat pumps. Considering also the DHW demand the total energy coverage reach 70.3% reducing the primary energy consumption and the related energy costs up to 86% and 82% respectively when compared to traditional technologies.

2. TO TASK 6.3: PILOT PLANT SOFC TESTS

2.1. Syngas compressor development

Since no suitable pressurized feeding system was found for the biomass gasifier, and due to the layout changes following the findings of Pérez-Fortes et al.[1] and the project amendment, a syngas compression device is required to overcome the pressure losses in the system and to physically couple the biomass gasifier with the SOFC. This novel device, consisting of a gas bearing supported thermally-driven compressor-turbine-unit (CTU), as well as the in-house test rig (with required equipment) have been designed, developed, manufactured, assembled and tested at EPFL LAMD in the time period between M40-M51 (June 2022 – May 2023).

2.2. DESIGN PROCEDURE

Experimentally validated 0D to 3D design procedures coupled with SOFC-gasifier system level process modeling as well as gas bearing and rotor optimization using an artificial neural network (ANN) are employed to achieve the final design of the compressor-turbine unit (CTU). The radial compressor impeller consists of 9 backward-curved main and 9 splitter blades, designed for an inlet syngas mass flow of 18.23 kg/h at 350°C and 0.81bara. The full-admission cantilever steam turbine, inspired by the design of Wagner et al.[2], uses steam at a design inlet pressure of 3.5bara and temperature of 525°C to drive the syngas compressor. The turbine design expansion ratio is 2. However, an expansion to ambient pressure is possible to achieve even higher turbine power if needed. The CTU is supported dynamic gas bearings, namely two herringbone-grooved journal bearings and a two-sided spiral-grooved thrust bearing, that allow an oil-free, low-wear, high-temperature and high-speed operation (nominal rotational speed of 210krpm). The bearing and rotor designs were identified coupling an artificial neural network based surrogate model of the rotodynamic system to an evolutionary optimization algorithm. The objectives were to minimize the mechanical losses and to maximize the robustness of the machine against manufacturing and operational deviation, under the constraint of technical feasibility. Further, a validated 1D heat model based on Olmedo et al.[3] has been established for the CTU system, where the results indicate a build-up of heat within the CTU system due to the windage losses at the gas bearings, thus leading to unwanted thermal gradients. To mitigate these thermal gradients inside the machine, which could potentially damage the bearings, the

[1] Pérez-Fortes, M., He, V., Nakajo, A., Schiffmann, J., Maréchal, F. and Van herle, J., 2021. "Techno-Economic Optimization of an Integrated Biomass Waste Gasifier-Solid Oxide Fuel Cell Plant". Front. Energy Res. Vol.9 2021
[2] Wagner, P.H., Van Herle, J. and Schiffmann, J., 2020. "Theoretical and experimental investigation of a 34 Watt radial-inflow steam turbine with partial admission". ASME Turbo Expo 2020
[3] Olmedo, L.E., Liu, W., Gjika, K., Schiffmann, J., 2023. "Thermal management for gas lubricated, high-speed turbomachinery". Applied Thermal Engineering Vol.218 2023

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housing and thus the rotor are actively flushed with steam at 1.25bara and 412°C. The nominal operating conditions as determined from CFD simulations and the used materials are shown in

Syngas compressor parameters	Design point
Syngas flow rate, kg/h	18.23
Compressor inlet temperature, C	350
Compressor outlet temperature, C	426
Compressor inlet static pressure, bara	0.81
Compressor outlet static pressure, bara	1.16
Delta P compressor, mbar	350
Compression power, W	730
Isentropic total-to-total full stage compression efficiency	0.75
Compressor material	Ti Grade 5 with high-temperature anti-corrosive coating
Turbine inlet temperature, C	525
Turbine outlet temperature, C	429
Turbine inlet static pressure, bara	3.5
Turbine outlet static pressure, bara	1.75
Turbine steam mass flow rate demand, kg/h	72
Turbine power, W	2324
Isentropic total-to-static full stage expansion efficiency	0.49
Turbine material	Ti Grade 5 with high-temperature anti-corrosive coating
Gas bearings steam inlet temperature, C	412
Gas bearings steam inlet pressure, bara	Max. 1.25
Gas bearings steam inlet mass flow, kg/h	8
Rotational speed, rpm	210 000
Windage losses, W	960
Rotor and bushing material	Tungsten carbide

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Design choices have been made to achieve a high feasibility, manufacturability and robustness, as well as a wide operating range. The final CTU design is shown in Figure 5.

Table 10: Nominal operating conditions of the steam driven syngas compressor

Syngas compressor parameters	Design point
Syngas flow rate, kg/h	18.23
Compressor inlet temperature, C	350

Compressor outlet temperature, C	426
Compressor inlet static pressure, bara	0.81
Compressor outlet static pressure, bara	1.16
Delta P compressor, mbar	350
Compression power, W	730
Isentropic total-to-total full stage compression efficiency	0.75
Compressor material	Ti Grade 5 with high-temperature anti-corrosive coating
Turbine inlet temperature, C	525
Turbine outlet temperature, C	429
Turbine inlet static pressure, bara	3.5
Turbine outlet static pressure, bara	1.75
Turbine steam mass flow rate demand, kg/h	72
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Gas bearings steam inlet temperature, C	412
Gas bearings steam inlet pressure, bara	Max. 1.25
Gas bearings steam inlet mass flow, kg/h	8
Rotational speed, rpm	210 000
Windage losses, W	960
Rotor and bushing material	Tungsten carbide

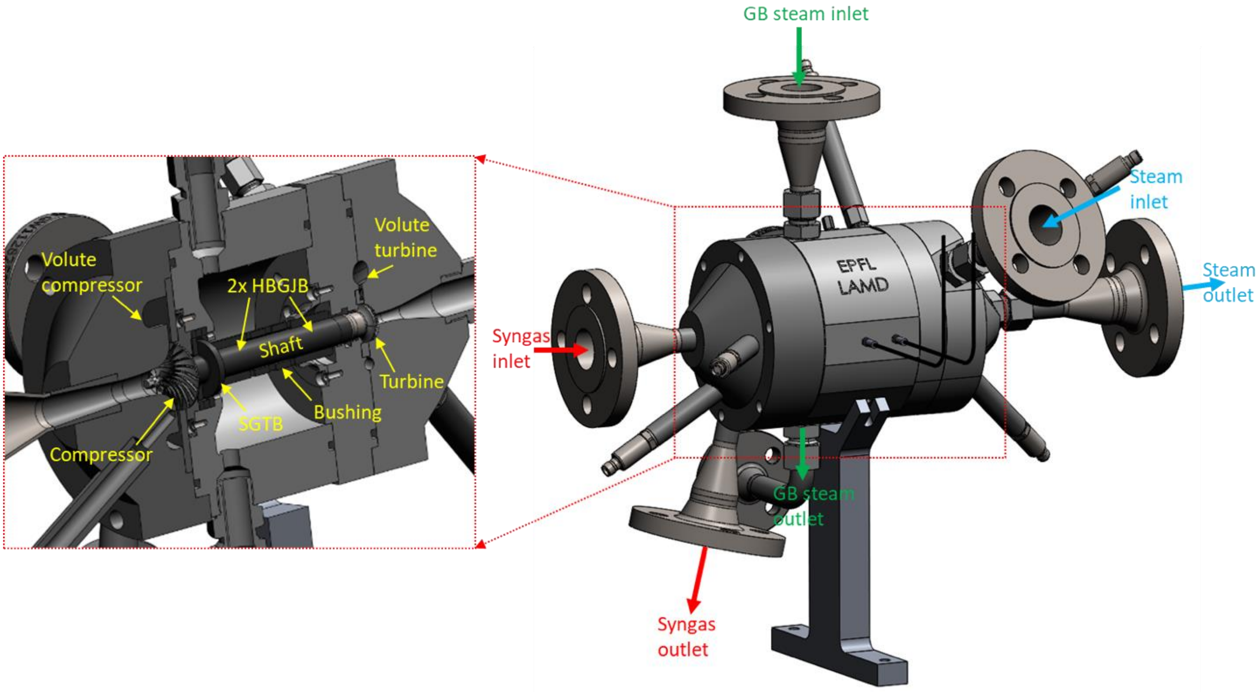

Figure 5: Novel syngas compressor design supported on gas-lubricated bearings.

2.3. EPFL IN-HOUSE TESTS

The in-house tests at EPFL LAMD involve the turbine operated under partial admission using overheated steam or pressurized air at the turbine side and ambient air at the compressor side. These tests were performed for the in-situ rotor balancing, the investigation of the start-up/shut-down, and the static/dynamic behavior of the syngas compressor system. The in-house test rig is shown in Figure 6.

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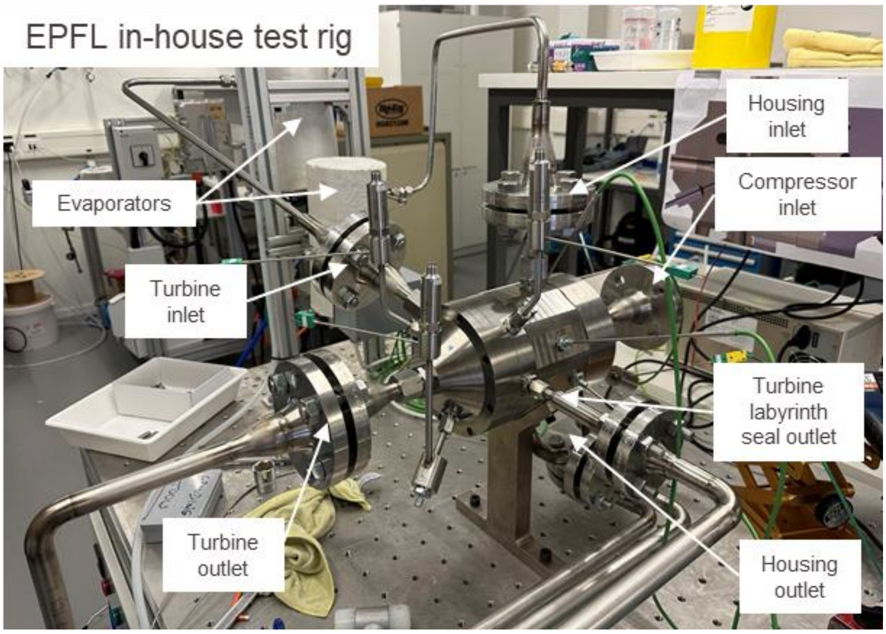

Figure 6: EPFL in-house test rig for the turbofan

From the in-house experiments, the following conclusions have been made:

1. With the balanced turbofan, speeds up to 60krpm have been reached, indicating a stable and smooth behavior at nominal speed.
2. The static steam tests (turbofan not running) at up to 300°C have shown good geometrical alignment of the turbofan system at high temperatures under thermal expansion, as well as leakage-free sealings.
3. The dynamic steam tests, involving the active flushing of the gas bearings with steam were successful. However, due to limitations of the small steam generator, these tests were only conducted under off-design conditions (steam conditions: <150°C & <1.5 bara, rotor speed <35 krpm, partial admission turbine).
4. The dynamic steam tests also demonstrated that the gas bearings work best under ambient pressure, eliminating the need for orifices at the housing outlet.
5. During the long-term steam tests, a risk of contamination in the gas bearings has been identified, originating from the evaporator. Therefore, it is crucial to ensure that the filters function correctly, the deionized water meets the highest quality standards, and the steam generator is thoroughly cleaned and free from contaminants before using it at the pilot plant.

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6. A measure to avoid an uncontrolled start-up during the heat-up of the steam to the turbine (10kg/h, 300°C) is to slightly increase the pressure and/or the mass flow of the forming gas at the compressor side.

The full syngas compressor system, including proximity probes, pressure and temperature sensors, and other equipment, as well as a 3D printed model of the CTU (see Figure 7) have been sent to WT for its integration into the Hygear container.

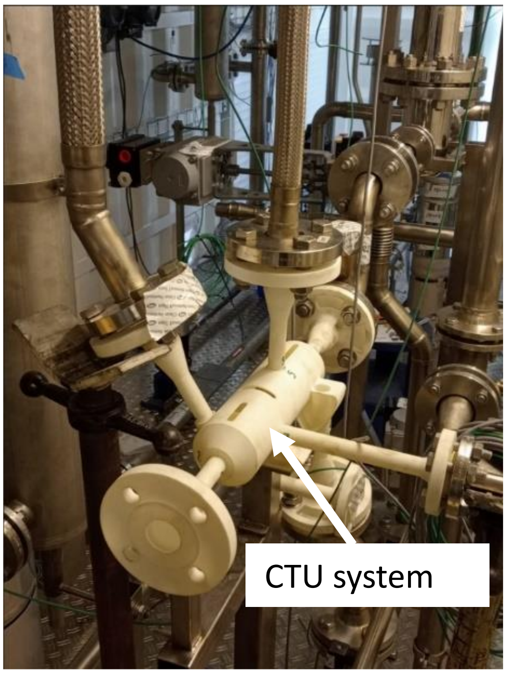

Figure 7: 3D model of CTU system integrated into container

2.4. PILOT PLANT INTEGRATION

The dual bubbling fluidized bed gasifier is designed to process up to 20 kg/h of biomass (100 kWth). A picture of the pilot plant is shown in Figure 8. A schematic representation of the solid bed material circulation scheme and the main dimensions of the reactor are reported in Figure 9.

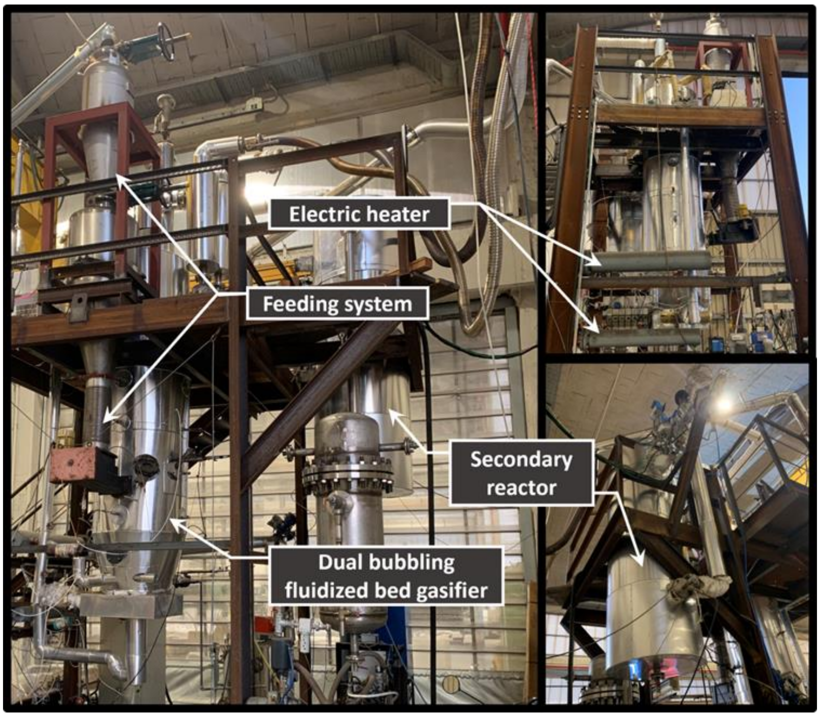

Figure 8. Picture of the pilot plant.

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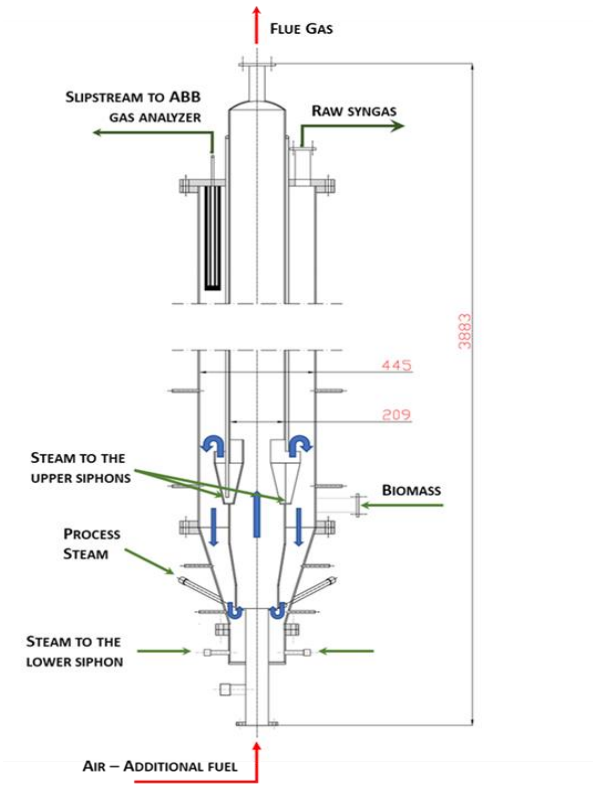

Figure 9. Reactor sketch (dimension in mm) highlighting solid bed material circulation.

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WT with the available plant design information purchased all required materials for the integration and completed all construction works related to DBFB Gasifier freeboard with integration of 2nd TAR reformer by month 51. All construction works related to integration of GCU was put on hold until the arrival of the GCU container in august. Final integration works has been carried out during month 54 (end of august) and 55 (mid-September) (Figure 10).

Figure 10. Aspect of second Tar reformer at Walter Tosto.

You can see below some pictures taken during the works performed at Walter Tosto facilities for the integration of gasification unit with the container including turbofan, gas cleaning unit and SOFC.

Figure 11 Hygear container arrived at WT

Figure 12Hygear container positioned near the gasifier

Figure 13 Hygear container connection realization

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2.5. CONCLUSION

A novel high-speed high-temperature CTU system for the coupling between the biomass gasifier and the SOFC has been developed and preliminarily tested in-house, showing promising results. For the full characterization of the CTU, experiments involving the complete pilot plant are planned and the required preparations are currently under way.

The developed CTU and the concept of converting waste heat to compression power (and electrical power, if a generator is added), as well as the obtained theoretical, numerical and experimental results are not only applicable to the BLAZE plant, but can also be extended and applied to other small-scale high-temperature energy systems (such as gas turbine engines, organic Rankine cycle turbines, high-temperature heat pumps), combined cycles (such as SOFC-GT hybrid systems, as extensively discussed by He et al.[4]), to the mobility sector (turbochargers[5]) or district heating systems (in particular, by replacing expansion valves to valorize expansion power to compression power and/or electricity[6]). The novel, highly integrated design process can also be used by engineers and scientists in similar domains. In fact, a publication on the detailed design methodology and numerical results is currently in progress.

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