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Abstract:

The following document shows the first results from the Comsos SOFC installations, in terms of energy performance (normalised power-efficiency curves) and environmental performance (pollutants emissions).

Keyword list: SOFC systems, operation, performance analysis, efficiency, emissions

Summary

1. Comsos installations

The present document is focused on the performance of the first SOFC installations until September 2022. Up to this date, the status of the Comsos installations is:

- 7 SOFC units have been installed worldwide (Taiwan, Italy, China and Austria as shown in the map shown below)
- 450 kW (~ 25 units in total) are under commissioning and will be in operation by spring 2023.
- More than 25,000 hours of operation have been reached in September 2022.

The data of this document are referred to both Site Acceptance Tests (SAT) and field operation measurements. Furthermore, emissions analyses have been performed with the instrumentation described in D4.4 (Verification plan of the installed systems).

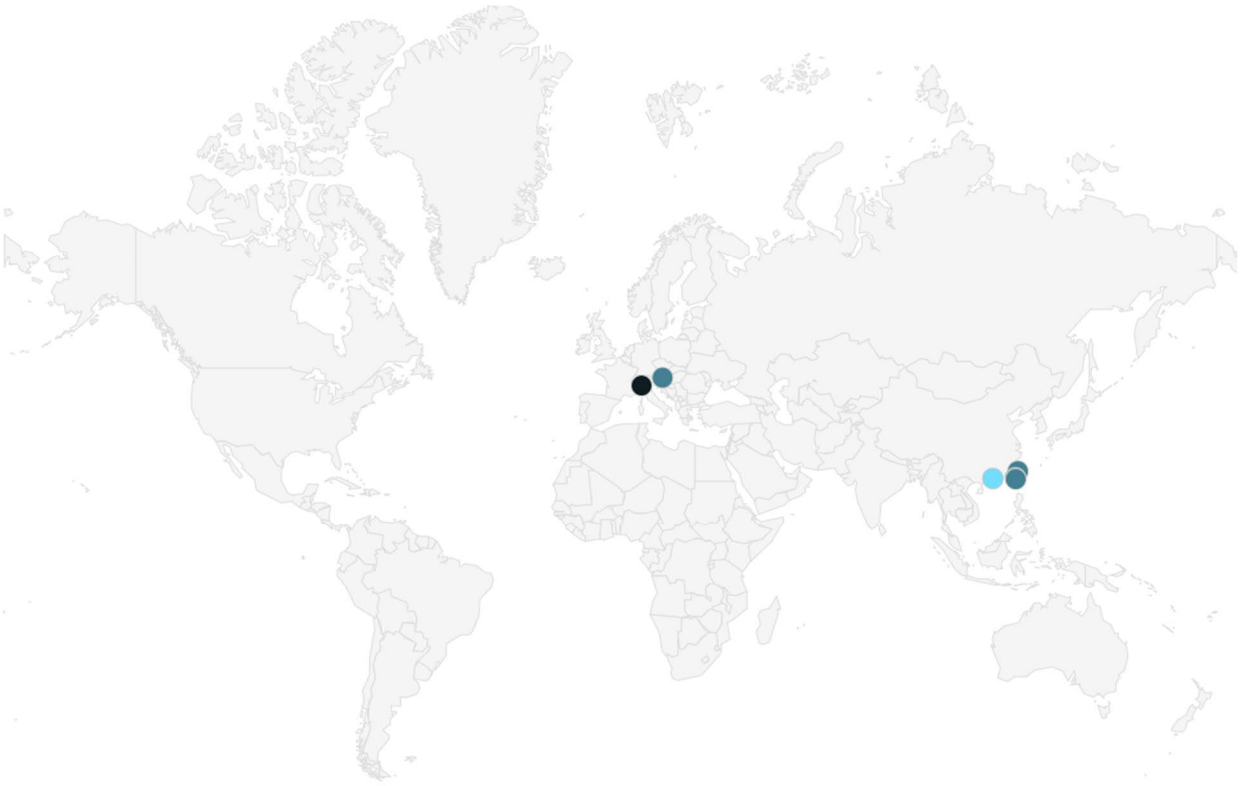

Figure 1. Comsos installations.

a)

b)

c)

Figure 2. Comsos installations in Taiwan (a), Italy (b) and China (c).

2. Energy performance

Results from the SOFC operation are presented below. The performance of the SOFC systems is provided as power-efficiency curves normalised over the system size. The data are presented for different SOFC modules (SOFC #1, SOFC #2 and SOFC #3), both during SAT and during field operation. The difference in the performance of the different SOFC modules can be due to the different stack implemented, different BoP and different operational modes of the producers involved in the project. The data are all normalized compared to the nominal system power in order to avoid pointing out difference in the performance of the three SOFC manufacturers involved in the Comsos project.

Results in terms of net AC electrical efficiency are available in the figures below. SOFC manufacturers provided datalog from their operation sites, with a 1-minute, 15-minutes or 1-hour time step). The data already included net AC electrical power and themal power, together with neat AC and thermal efficiency. Efficiency values have been verified when sufficient information on the input fuel flow (flow rate and composition) was available. For what concerning thermal efficiency, this value is usually calculated through indirect measurements (the exhaust flow rate is not measured and/or sometime the temperatures are measured on the water side). Furthermore,

Figure 3 and Figure 4 show electrical and total (electrical + thermal efficiency) for two different SOFC modules. SOFC #1 performance are referred to a SAT test of this system, while SOFC #2 performance are related to more than 5100 hours of operation on site. The efficiency values are given as a function of the modulation range, expressed as the ratio between the electrical production and the nominal power of the SOFC module. Electrical efficiency is presented in the complete modulation range (0-100%), while thermal efficiency is restricted to the 50-100% modulation range since thermal measurement in points with reducing loading rate often led to measurements issues and the measured efficiency is thus not reliable. As can be seen, the efficiency values are always very high, close and higher than 60% for SOFC #1 (Figure 3a) and close to 50% for SOFC #2 (Figure 4a). Furthermore, the efficiency is kept constant and high even at part load (0-50%).

Total efficiency (Figure 3b and Figure 4b) is also constant and stable at nominal power and also at part load, with values around 80-90% for SOFC #1 and higher than 70% for SOFC #2.

Figure 5 shows the AC net electrical efficiency for SOFC #3. These SOFC units, as often occurs for the technology, can be installed in parallel to reach a higher production rate. Data are referred to a single SOFC module (Figure 5a, measured during the emissions analysis test at the producer site) and to a series of 6 modules in field operation (Figure 5b, referred to 3400 hours of operation on site). The power-efficiency curve of a single SOFC module (Figure 5a) is similar to the ones discussed above with a peak efficiency above 60% and stable value at part load. What is interesting to note when analysing the results for the plant composed of different modules in series (Figure 5b) is the even more stable efficiency at reduced load compared to the

behaviour of a single system. Thanks to the parallel mode operation, the SOFC technology can guarantee better performance even at lower operating point (even < 50%).

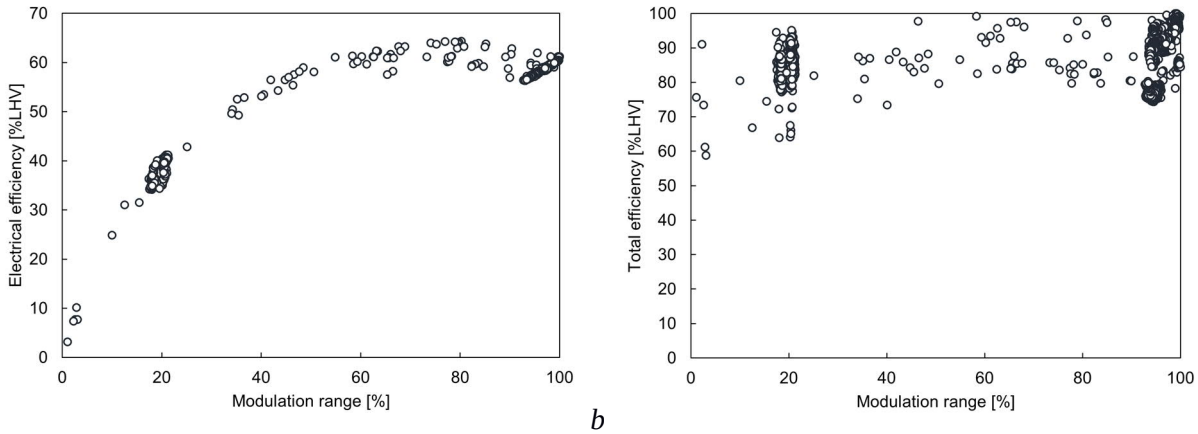

Figure 3. SOFC #1 performance (electrical and total efficiency) during field operation (2100 hours of field operation).

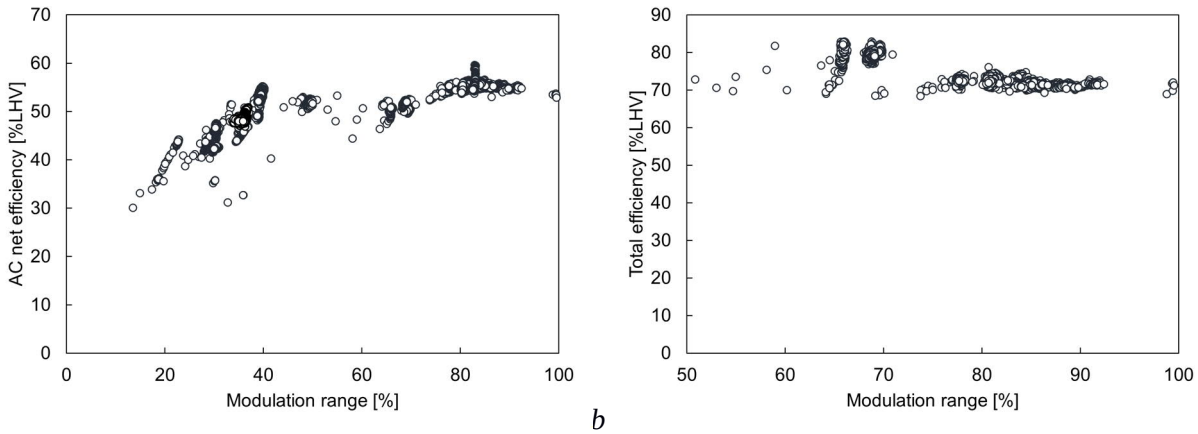

Figure 4. SOFC #2 performance (electrical and total efficiency) during field operation (5100 hours of field operation).

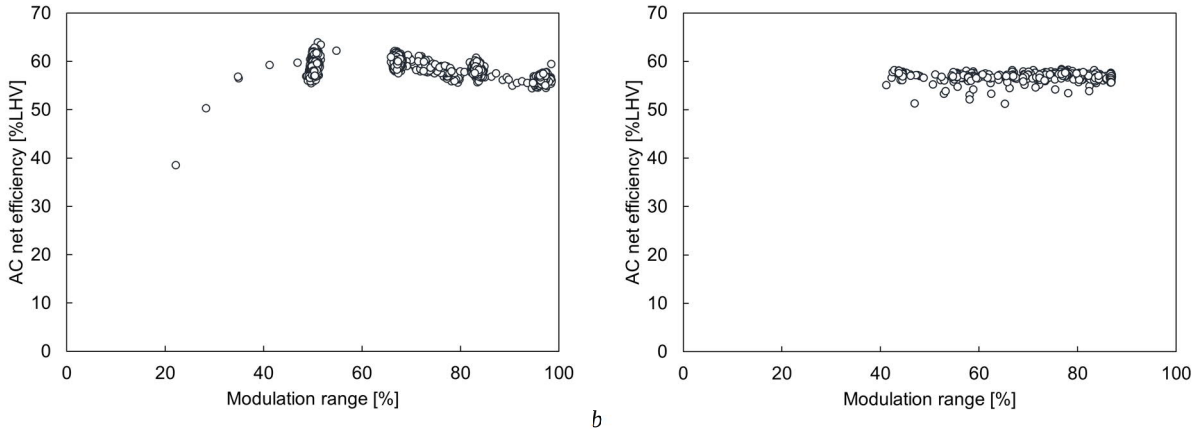

Figure 5. Electrical efficiency for a single SOFC #3 module (left, SAT) and for a set of SOFC #3 modules in parallel (right, 3400 hours of field operation).

3. Environmental performance

According to the 2022 air quality report from the European Environmental Agency [1], residential, commercial and institutional energy consumption was the principal source of particulate matter in 2020 (Figure 6 and Figure 7). The manufacturing and extractive industry was also a significant source, while agriculture was an equally important source of PM10. Between 2005 and 2020, emissions of particulate matter, PM10 and PM2.5, fell by 30% and 32%, respectively. In 2020, road transport was the principal source of nitrogen oxides, responsible for 37% of emissions. Emissions of nitrogen oxides fell by 48% between 2005 and 2020. The energy supply sector was the principal source of sulphur dioxide, responsible for 41% of emissions in 2020. Emissions of sulphur dioxide fell by 79% between 2005 and 2020.

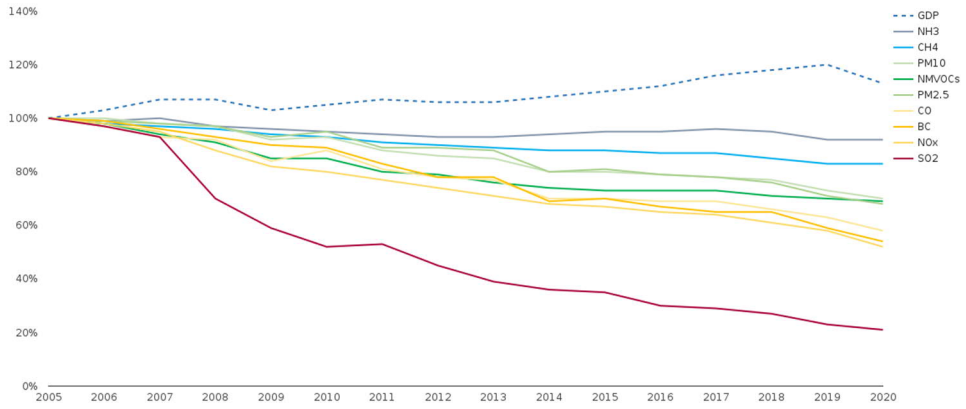

Figure 6. 2005-2020 Trends in EU-27 emissions of NH_3, CH_4, primary PM_{10}, NMVOCs, primary $PM_{2.5}$, CO, BC, NO_x and SO_2, as percentages of 2005levels, set against EU-27 GDP as a percentage of 2005 GDP [1].

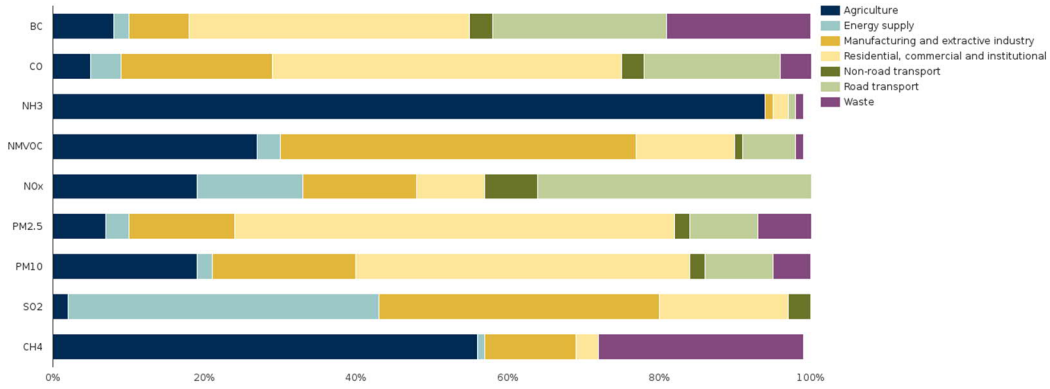

Figure 7. Contributions to EU-27 emissions of BC, CO, NH_3, NMVOCs, NOx, primary PM_{10}, primary $PM_{2.5}$, SO_2 and CH_4 from the main source sectors in 2020 [1].

Results from the Comsos emissions analysis performed by VTT are presented below. Data are referred to NOx, CO and PM emissions.

From VTT measurements, data in ppm level for CO and NOx where available, together with exhaust flow rate composition and power produced (net AC) in the same time period (which was 1 minutes in all the emissions analysis). Specific measurements concentration (expressed in mg/kWh) have been evaluated based on the following equation:

$$y_{m,i} = \frac{\frac{y_{v,i}}{10^6} \cdot \left(\frac{\dot{V}_{ex}}{22.4} \cdot 60\right) \cdot MW_i \cdot 10^3}{W_{el}} \quad (1)$$

Where $y_{m,i}$ is the specific contaminant concentration on a mass basis (mg/kWh), $y_{v,i}$ is the measured concentration on a volume basis (ppm), $\dot{V}_{ex}$ is the exhaust gas flow rate (in SLPM), MW_i is the molecular weight of the contaminant and W_{el} the produced electrical power output (net AC). The subscript i-th is referred to the contaminants, CO or NOx (for NOx, the molecular weight of NO_2 was used).

Figure 8 and Figure 9 shows the emissions measurements in terms of NOx and CO concentration in the exhaust gases (expressed in mg/kWh). For these two systems (SOFC #1 and SOFC #3) the analyses were done at a variable operating point. Emissions are kept very low even in part load operation (up to 50% of nominal power).

Figure 10 and Figure 11 are indeed referred to SOFC #2, which was kept running at nominal power during the whole measurement period. In this case, particulate matter (Figure 11) was also measured (both in the exhaust gases and in the surrounding ambient air).

Average values in terms of NOx and CO emissions for the three SOFC modules are summarized in Table 1.

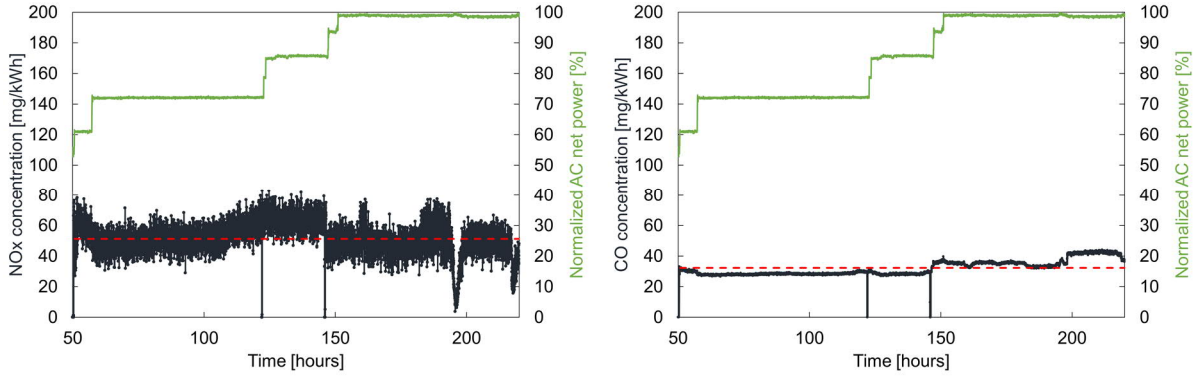

Figure 8. NOx and CO emissions from SOFC #1 at variable power output.

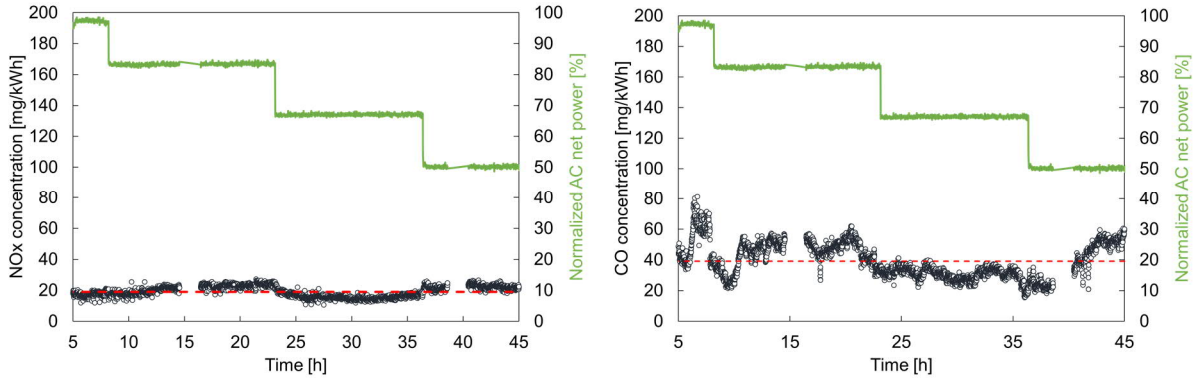

Figure 9. NOx and CO emissions from SOFC #3 at variable power output.

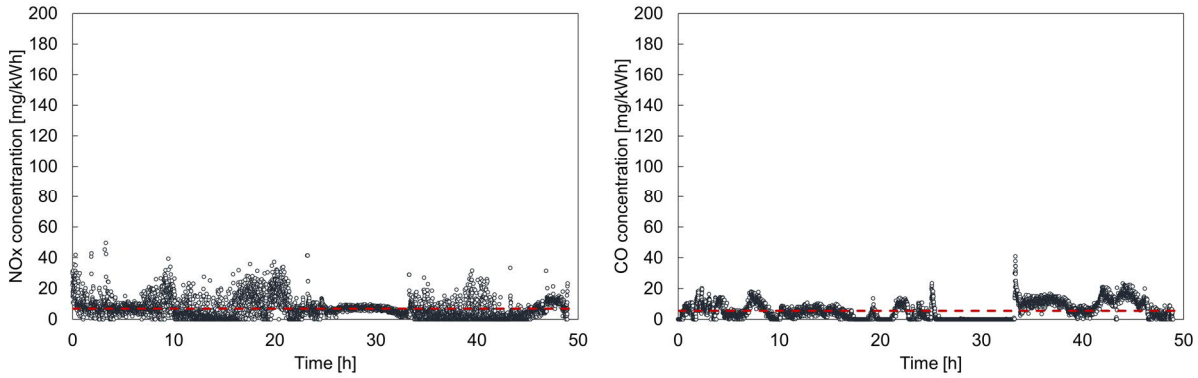

Figure 10. NOx and CO emissions from SOFC #2 at nominal power.

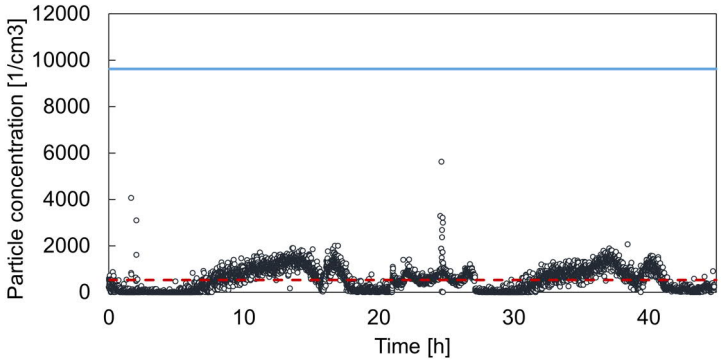

Figure 11. PM emissions from SOFC #2 at nominal power. The light blue line refers to the ambient level PM during the measurement days.

Table 1. Average emissions from Comsos SOFC installations.

System	Average NOx concentration [mg/kWh]	Average CO concentration [mg/kWh]	PM concentration [1/cm^3]
SOFC #1	51.3	32.3	-
SOFC #2	6.91	5.54	531 (ambient: 9626)
SOFC #3	19.0	39.1	-

4. Reference

[1] EEA, Report no. 05/2022: Air quality in Europe 2022, 2022. https://www.eea.europa.eu/publications/air-quality-in-europe-2022/ (accessed January 17, 2023).

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