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FLExibilize combined cycle power plant through power-to-X solutions using non-CONventional Fuels

D6.1 – "Analysis of flow process depending on strategy of hybridation"

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[1] PU = Public
CO = Confidential, only for members of the consortium (including Commission Services)

Executive summary

In a context of high-rate renewable energy sources (RES) penetration, the FLEXnCONFU concept objective is to unlock the situation of low operating hours Combined Cycle Gas Turbine (CCGT) power plants used for fluctuating back up and improve global efficiency and reduce CO_2 emission.

The FLEXnCONFU project will develop and demonstrate in a real power production plant a Power--to–X-to-Power solution. The electricity production will be converted in H_2 or ammonia as carbon free fuels; stored and re-used in the same power plant to respond to varying demand. Innovative development will be brought at different levels:

- Evaluation and adaptation of the different systems (Gas Turbine (GT) ; combustion chamber; combustion procedure…) to reach up to 100% NH_3 and 30% H_2 combustion
- Integration into demonstration site
- Development of innovative balanced of plant to enhance flexibility
- Providing a fast cycling efficient and modular P2A system considering small scale NH_3 reactor
- Development of advanced grid-oriented control strategies.

Two demonstrators will be carried out:

- A Power to Hydrogen solution in Ribatejo Combined Cycle plant (Portugal) where a complete system composed of 1MW electrolyser, compressor and electrolyser will be installed in a real environment
- A Power to ammonia solution at laboratory scale in Savona campus (Italy) connected to a micro gas turbine properly modified to burn up to 100% ammonia

In parallel, a thermo-economic analysis and optimization is performed to evaluate the impact of such a P2X system in the power plants with respect to chosen objective functions such as LCOE, CO_2 emissions, and define the most efficient design. Within this analysis, several plant layouts are being defined and compared and the output of this analysis has been the starting point for this report.

In fact, some thermo-economic evaluations are currently carried out to confirm the relevance of Solid Oxide Cell (SOC) integration (mentioned as "SOC scenarios" in the document) in specific grid market, taking advantage of its thermal integration, higher efficiency and reversible aspect (electrolyser and/or fuel cell mode).

SOC and storage system dimensioning as well as mass and energy balances will depend on the choice of targeted market services, CCGT control strategies, and country chosen. The modeling of the detailed process flow is an important part of the task and will be carried out in the next 18 months.

This report is a preliminary report of the task and is divided into four sections. The first section reminds the context framework and reference cases being evaluating from a thermos-economic point of view. The second section presents a description of the SOC technology. The third section describes the three

"SOC scenarios" that will be studied detailed in the task, and the fourth presents the main KPI that will be calculates through the process simulations.

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Abbreviations

AEL: Alkaline Electrolysis
CCGT: Combined Cycle Gas Turbine
HRSG: Heat Recovery Steam Generator
LCOA: Levelized Cost of Ammonia
LCOE: Levelized Cost of Energy
LCOH: Levelized Cost of Hydrogen
PEMEL: Polymer Electrolyte Membrane Electrolysis
R-SOC: Reversible Oxide Cell
SOEC: Solid Oxide Electrolyzer Cell
SOFC: Solid Oxide Fuel Cell

1. Introduction & Objectives

The global objective of the FLEXnCONFU concept is to demonstrate the economic viability of a **power-to-X-to-power** solution by levelling the CCGT load and increasing the flexibility. To achieve this goal, the concept is based on the conversion of **electricity into hydrogen or ammonia as carbon free fuels. They will be then locally re-used in the same power plant to respond to varying demand**, reducing CCGT environmental impact as well. This will be developed and demonstrated in a real combined cycle plant.

Innovative development of FLEXnCONFU focus on several aspects: adaption of the different system to reach up to 100% NH_3 and 30% H_2 combustion; development of innovative BoP; development of a fast cycling efficient and modular P2A system considering small scale NH_3 reactor; development of advanced grid-oriented control strategies. The project will also develop and demonstrate the feasibility in real demonstrators; a Power to Hydrogen solution installed in Ribatejo Combined Cycle plant of 1MW electrolyser; and a second demonstration of power to ammonia solution at laboratory scale connected to a micro gas turbine.

The FLEXnCONFU concept is simultaneously evaluated from a thermo-economic point of view to identify under which market condition, strategy, and country the FLEXnCONFU concept would be more relevant compared to an unmodified CCGT. Extra scenarios, which could bring additional value in terms of environmental impact, flexibility, and economical gains, have also been listed in the project (RES supply, NH_3/H_2 market, FC integration…); the most relevant ones are reminded in the Chapter 3.

The present part of the project focuses on three alternative scenarios based on Reversible Solid Oxyde Cell (R-SOC) system integration. As describe in Chapter 4, the SOC system can be used in **3 different modes**: fuel cell mode (SOFC) fed by H_2 or NH_3; electrolysis mode (SOEC); and reversible mode (R-SOC). Using the electrolyser in FC mode, ammonia or hydrogen could feed the fuel cell to boost the yield up to 60/65% and **increase the global efficiency** of the power plant will. The electolyser mode (P2P) combined with the CC could be utilized when flexibility services are required based on the electrical market conditions. **The global P2P/SOFC/CC system can be considered as a flexible asset to better manage the whole system.**

The different functioning modes are being evaluated step by step:

i) Integration of SOFC to the plant to produce electricity from ammonia or hydrogen generated by a PEM electrolyzer solution;
ii) Replacement of PEM electrolyzer by SOEC;
iii) Hybridization of R-SOC for both H_2/NH_3 and electricity production.

For each scenario, the different subsystems capacity will be calculated to estimate under which conditions, and for which specific market, the CCGT plant performances would be improved in terms of flexibility and environmental impacts. The different SOC scenarios will be compared with the FLEXnCONFU reference regarding these key parameters.

The objectives of this first deliverable are to remind the FLEXnCONFU base case and other reference cases considered; to introduce the specificities of SOC functioning for each mode; to inventory the possible SOC integration scenario; to identify the main parameters that will be needed for further modelling and define the main KPI. The results of this activity will be the starting point to model the different scenarios and perform some dynamics and optimization simulations. So far, detailed flow processes data are not presented in that document and will be further defined and presented in the final deliverable.

2. Task planning

2.1. Dependencies on other tasks

Within the project, this task will interact with other ongoing work packages:

- Task 1.3: "Thermo-economic modelling and optimization":
  - This task will study from an economic point of view the FLEXnCONFU concept at industrial scale. The analysis will be performed in selected markets and based on existing and forecasted energy markets and prices. Some additional options such as NH_3 or H_2 market and renewable energy consumption can be considered.
  - Interaction: specific attention will be paid to take similar hypothesis so as to be able to compare the different results as much as possible.
- Task 1.4: "Most promising EU electrical market for FLEXnCONFU enhanced CC and related technical/grid requirements":
  - The aim of this task is to understand which the best EU electrical markets are where to promote the potential of FLEXnCONFU concept.
  - Interaction: the market electricity and methane price history will be used as an input parameter
- Task 6.4: "Other uses for the H_2 and O_2 produced to enhance P2H potential and profitability":
  - This task aims to identify and explore possible roles for Hydrogen in decarbonizing the major sectors of the economy through a techno-economic benchmarking of the potential market of P2X applications.
  - Interaction: when considering options of H_2/NH_3 market sale, the prices of H_2 on other markets will be needed.
- Task 6.1: "Scale-up of FLEXnCONFU concept":
  - In this task, preliminary design of full scale FLEXnCONFU layout for both P2H and P2A solutions will be performed.
  - Interaction: "SOC scenarios" will be evaluated at industrial scale; industrial specifications of the different components will be potentially used for the scenario modeling.

2.2. Contribution from partners

In this task, four partners are involved CEA, EDPP, RINA-C, and UNIGE:

- **EDP Gestão da Produção da Energia, S.A** (EDPP): will contribute by bringing the knowledge of CCGT in the optic of thermal hybridization with a SOFC or SOEC.
- **Università Degli Studi di Genova** (UNIGE): will bring its knowledge about the ammonia process, mainly in the use of ammonia in fuel cells, and its production and storage
- **RINA Consulting SpA** (RINA-C): will act as coordinator of the WP6 and will support for the layout definition
- **Commissariat à l'Energie Atomique et aux Energies Alternatives** (CEA) (Task 6.3 leader): will perform simulation and technico-economic evaluation of the different case studies, comparing them with the reference cases.

3. Context and framework

Techno-economic analysis of FLEXnCONFU concept is conducted by KTH partner in the first part of the project. The task is in under progress and results will be provided by beginning of 2022. The techno-economic evaluation of the "SOC scenarios" will be compared with the FLEXnCONFU layouts and one complementary concept described by KTH in a preliminary report[2] and presented below. Similar hypotheses might be taken to have the most relevant comparison.

3.1. Reference Case 0: test site

The reference case considered is a CCGT plant without power-to-x-to-power system. As the demonstrator site chosen for the project is the Ribatejo plant of 400MW in Portugal, the same power level will be taken for techno-economic assumptions.

3.2. Reference Case 1: FLEXnCONFU case at industrial scale

The configuration of the two first layouts are the ones proposed for the demonstration site in EDP's power plant in Ribatejo and for the demonstration site in UNIGE's laboratory in Savona projected at industrial scale.

In the Power-to-Hydrogen-to-Power configuration, electricity from the CCGT is used to produce hydrogen in a PEM electrolyser. The amount of hydrogen produced depends on the size of the electrolyser (1 to 200 MW) and how the system is operated. The hydrogen is then compressed and stored in gaseous form at 300 bar. Different storage capacities are under investigation, all within a range that enables full production of the electrolyser for a few hours a day.

In the Power-to-Ammonia-to-Power electricity from the CCGT is used to produce hydrogen in a PEM electrolyser, and to power an ammonia synthesis unit. The latter uses nitrogen and the hydrogen delivered by the electrolyser to produce ammonia at low pressure (<35bar) and low temperature (<300°C). This ammonia is then stored in liquid form at 20 bar in tanks with capacities enough to enable full production of the synthesis unit for a few hours a day.

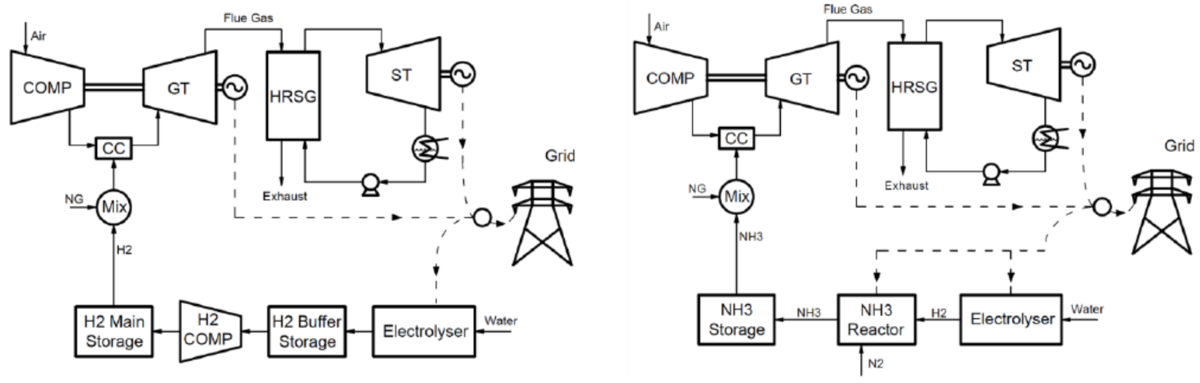

Figure 1 FLEXnCONFU layouts studied by KTH

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[2] Techno-economic Modelling and Optimisation – Model Principles and Methodology; Jose Garcia / Rafael Guedez – (KTH)

3.3. Reference Case 2: additional layouts defined

Two additional layouts described below could also be further studied by KTH in the first part of the project. The additional aspects mentioned would bring improvements in terms of flexibility, environmental considerations and economic performance, they will also be considered for the "SOC scenarios". They take into account:

- The participation in a hydrogen or ammonia market, either by injecting it into the natural gas grid or by selling it for industrial purposes. For preliminary studies, KTH considered a fixed price of hydrogen and ammonia. The possible valorization of the oxygen and hydrogen produced by the FLEX&CONFU system will be studied in another part of the project by CNET. The oxygen could for example be used in the CCGT to function in oxy-combustion or with enriched air.
- More efficient electricity production using fuel cell with H2 and/or NH3. However thermal coupling of fuel cell with the CCGT isn't considered.
- Renewable energy (wind and solar) supply for electrolyzer functioning. 2 options are defined:
  - Large scale power plant: in that case the renewable electricity surplus is used for hydrogen or ammonia production as flexibility storage
  - Small power PV plant dedicated to hydrogen/ammonia production
- The scenarios studied by KTH are being studied for:
  - Day Ahead Market
  - Intra Day market
  - Country-based markets.

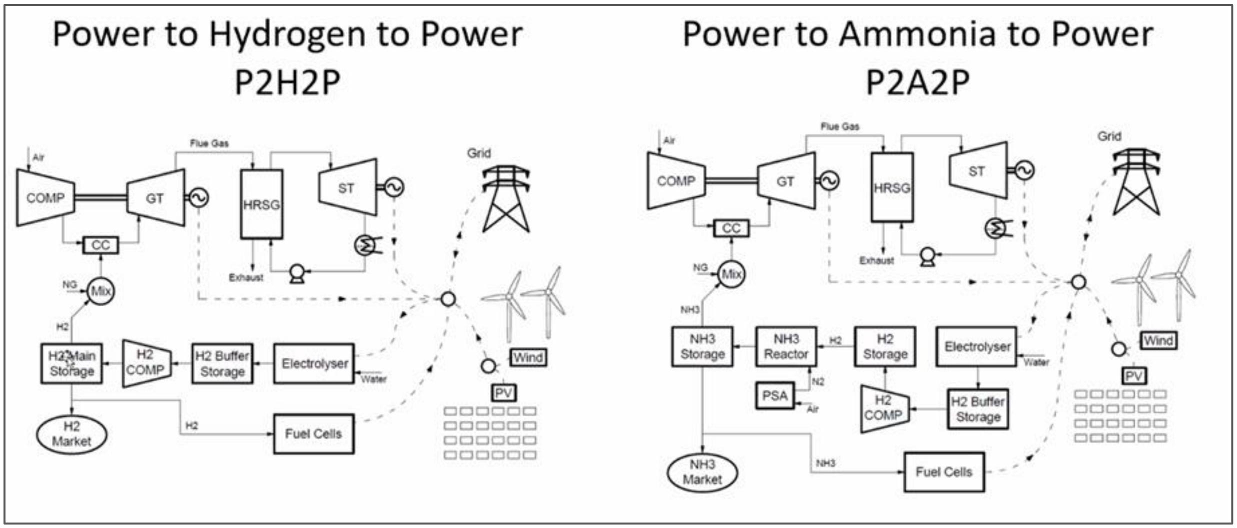

Figure 2 Layouts with additional fuel utilization and RES studied by KTH

3.4. Study case: SOFC, SOEC and R-SOC scenarios

This present work will investigate the replacement of the PEM by Solid Oxide Cell system (SOC). That technology is able to work either as an electrolyzer (SOEC), a fuel cell (SOFC), or as both (R-SOC). SOC systems work at high temperature (800°C) and need steam supply. It has to be thermally integrated with the CCGT to improve global efficiency. The present document lists the different systems that will be further simulated and optimized. The detailed flow sheets and techno-economic performances will be presented in the second deliverable.

4. Presentation of SOC technology

SOCs are electrochemical devices that can directly convert fuel into electricity (fuel cell mode – SOFC) or electricity into fuel (electrolysis mode – SOEC) or in reversible mode (R-SOC). The aim of the study is to evaluate the integration of R-SOC in the process flow **with these three different modes.** This section describes **general characteristics of SOC** for each mode, independently of the case studies.

4.1. SOEC general description

High-temperature electrolysis using Solid Oxide Electrolysis Cell (SOEC) technology is operated at **temperatures range from 700 to 900°C and is therefore fed with steam instead of water.** The cells developed are made of ceramic assembled in stacks. The main components of a SOC are the hydrogen electrode, in which the hydrogen oxidation/steam reduction reactions take place, and the oxygen electrode, in which oxygen is consumed. Between the two electrodes, the solid electrolyte ensures the migration of oxygen vacancies from one electrode to the other.

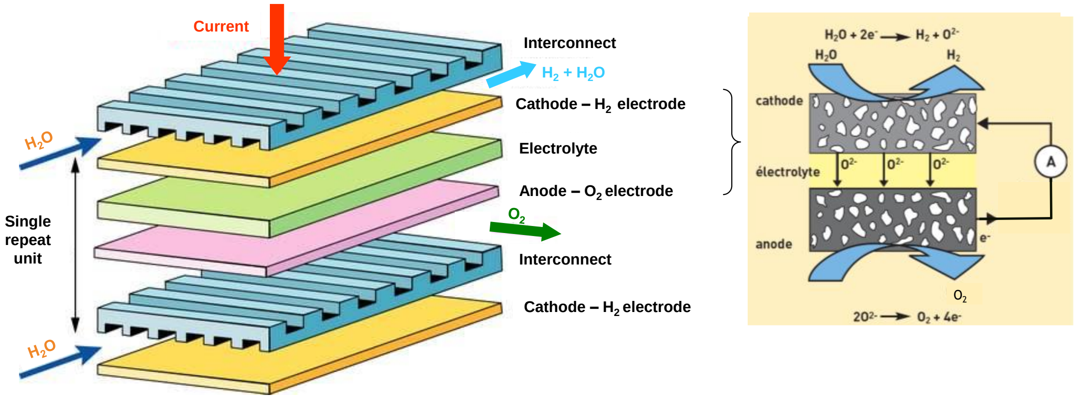

Figure 3 Description of SOC cell and stack

At cell level, SOEC can operate in three different modes depending on the **voltage applied to the cell**:

- **Thermoneutral range (1.29V):** at that voltage, the heat generated through irreversible losses (ohmic current and activation phenomenon) is equal to the heat required by the reaction.
- **Endothermicity (<1.29V)**: when the voltage applied to the cell is below the thermoneutral voltage, the endothermicity of the reaction is the dominant phenomenon, **resulting in gas cooling.** To maintain the process, the stack has to be heated through external means.
- **Exothermicity (>1.29V):** at the opposite, if the voltage is higher than the thermoneutral point, the heat produced by the irreversibility of the system (ohmic loss and activation phenomenon) will exceed the consumption of the electrochemical transformation which leads to an **increase in the temperature of the gas** through the stack.

In general, the targeted voltage is slightly above the thermoneutral one (1,29V), to counter the heat loss of the enclosure.

A typical overall SOEC system is reported in **Error! Reference source not found.** including the different components:

On hydrogen side (cathode):

- First, demineralized water (network water and recycled water) is pressurized and transformed into steam through a steam generator. The produced steam is slightly superheated (~10°C above boiling point), with a pressure range of 2 to 3 Bara.
- That steam is then heated by recovered heat from electrolyzer. As heat exchangers are not perfect, steam temperature is then raised **up to 700°C/800°C** by electrical heater.
- Hot steam is partially consumed in the electrolyzer to produce H2. **The conversion rate** is in a **range of 50-80%.** Below 50%, the system tends to be inefficient; above 80% the **risk of stack degradation** is more important.
- Humid H2 is then cooled, through internal heat recovering followed by a condenser. It is then dried and compressed, ready to be stored.

On the air side (anode):

- Humidity and dust are removed from ambient air, which is then compressed in a range of 2 to 3 Bara.
- Compressed air is heated up by recovered heat from electrolyzer. Similar to steam, an electric heater is required to reach the stack inlet temperature (700-800°C).
- Air flow is enriched in the electrolyzer by the oxygen produced by the cells. **The oxygen molar fraction reaches 30 to 40%.**
- Enriched air is cooled down through heat recovery and can be valorized or evacuated.

SOEC can also be used without air sweep in the anode side; pure oxygen is recovered allowing other side-product use (such as oxy-combustion).

Regarding FLEXnCONFU project, **thermal interaction with GT and ammonia production** is an important parameter to supply the required heat for steam production and improve global system efficiency.

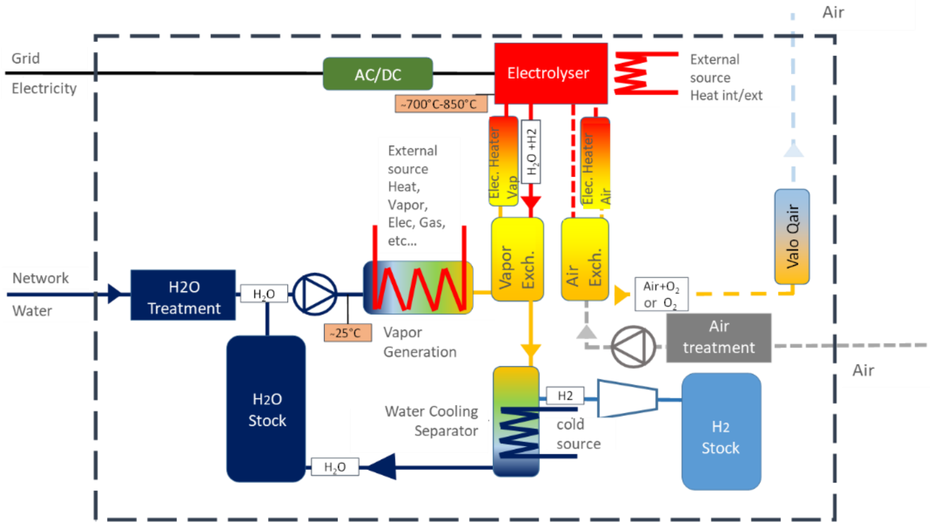

Figure 4 Overall electrolysis system with components

As an example, Figure 5 illustrates heat flow range engaged for an electrolysis system made of 100kW (DC) stacks.

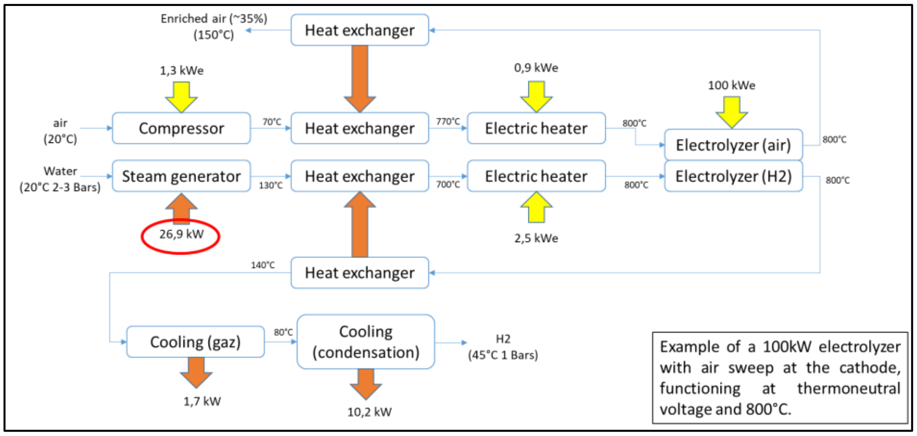

Figure 5 Example of the heating and cooling needs in a 100kW electrolysis system

Compared to AEL and PEMEL (water electrolysis), SOEC (steam electrolysis) has the advantage to need **lower electricity leading** to **higher efficiency:**

- the split of the steam molecule into hydrogen and oxygen is **less energy consuming** than the water molecule split as shown in Figure 6 (red circle) and Figure 7
- the higher the reaction temperature, the lower the electricity demand (replaced by heat power)
- to give an order of magnitude, steam electrolysis needs **roughly 70% electricity/30%heat**, and water electrolysis 85% electricity/15% heat.

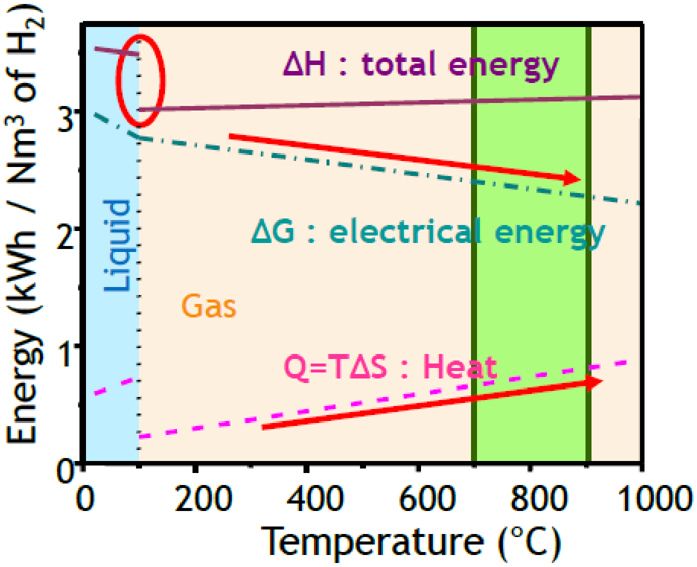

Figure 6 Typical range of performance represented by i-V curves achieved with SOEC technology compared to other water electrolysis technologies (alkaline and PEM water electrolysis)

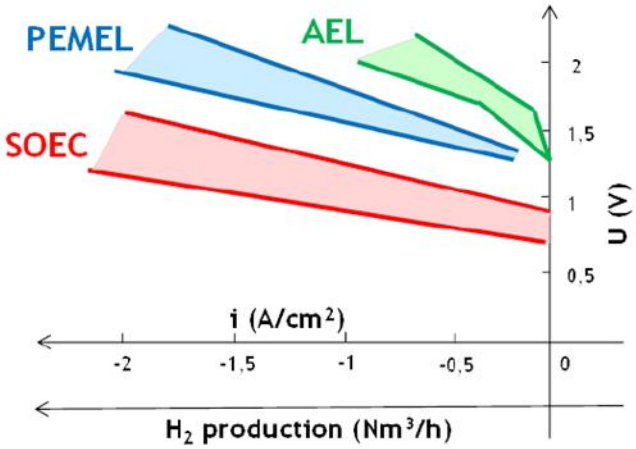

Figure 7 Energy consumption for the electrolysis reaction as a function of temperature, enthalpy (ΔH), Gibbs enthalpy (ΔG) and entropy (TΔS). Alkaline and PEM electrolysis operate in the blue shaded „liquid "part of the figure, whereas SOEC operates in the green shaded part of the „gas "section in the figure

So far, SOEC technology **is less mature** than AEL or PEMEL solutions and is **not yet commercially available at large scale**. Capital costs are currently more expensive than AEL and PEMEL. The main challenge for SOEC remains to **decrease the degradation rate** and to reach in 2030 a target performance/degradation combination of 1.5 A/cm² current density with a degradation rate as low as 0.5%/1000h. In parallel, **larger units will have to be deployed** in-field for assessing their relevance in various use-cases. Table 1 summarizes the targets fixed for each technology:

N°	**Parameter**	**Unit**	**Type**	**SoA**	**Targets**	
					2024	*2030*
System level						
1	Electricity consumption @ nominal capacity	kWh/kg	AEL	50	49	48
			PEMEL	55	52	50
			SOEL	40	39	37
	Heat demand @ nominal	kWh/kg	SOEL	9.9	9	8
2	Capital cost	(€/kW)	AEL	600	480	400
			PEMEL	900	700	500
			SOEL	2130	1250	520
3	O&M cost	€/(kg/d)/yr	AEL	26	20	16
			PEMEL	41	30	21
			SOEL	180	130	45
4	Hot idle ramp time	s	AEL	60	30	10
			PEMEL	2	1	1
			SOEL	600	300	180
5	Cold start ramp time	s	AEL	3600	900	300
			PEMEL	30	10	10

			SOEL	12	8	4
6	Footprint	m2 /MW	AEL	80	60	40
			PEMEL	50	40	25
			SOEL	n/a	150	50
Stack Level						
	Degradation	%/1,000hrs	AEL	0.12	0.11	0.10
			PEMEL	0.19	0.15	0.12
			SOEL	1.9	1	0.5
	Current Density	A/cm2	AEL	0.6	0.7	1
			PEMEL	2.2	2.4	3.5
			SOEL	0.6	0.85	1.5
	Use of critical raw material	Mg/W	AEL	0.6	0.3	0
			PEMEL	2.7	1.25	0.3
			SOEL	n/a	n/a	n/a

Table 1 KPIs comparison for EAL, PEML, SOEL [3]

4.2. SOFC general description

Solid oxide fuel cell (SOFC) is similar to SOEC composed of two electrodes connected through an electrolyte. That electrolyte allows the migration of O^{2-} ion when under an electric field. On the cathode side, oxygen is transformed into O^{2-} ions. On the anode side, the dihydrogen molecules react with the O^{2-} ions after they have migrated, producing steam.

$$\begin{gathered}\text{Anode side: } H_2 + O^{2-} \rightarrow H_2O + 2\,e^- \\ \text{Cathode side: } {}^1\!/_2\, O_2 + 2\,e^- \rightarrow\ O^{2-} \\ \text{Overall reaction: } H_2 + {}^1\!/_2\, O_2 \rightarrow H_2O \qquad \Delta H_f^o = 241{,}6\ \text{KJ/mol}\end{gathered} \tag{1}$$

Contrary to the SOEC, **the fuel cell mode always works at an exothermic voltage**:

- Part of the chemical energy produced by the reaction is recovered as electric current, whose power depends on the operating point of the stack.
- The rest of energy is recovered as heat and has to be extracted from the stack. It can be done using the same airflow as for the oxygen supply, or by other solutions (inert fluid going through the stacks or radiative heat exchangers close to the stack). This heat is **partly recovered for inlet gases preheating**, with an excess available for other uses.

At the system level, several options can be considered:

- Open fuel loop system: the unreacted gases (hydrogen or ammonia) released from the fuel cell are burned, for example in the gas turbine or a burner for steam cycle system
- Closed fuel loop system: the unreacted gases are cooled down, partially dried, and reinjected as an inlet in the fuel cell. **In that case the overall fuel consumption of the system will be higher than the open loop system.**

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[3] *Strategic Research and Innovation Agenda, Final Draft, Hydrogen Europe, 07/2020*

The overall direct electric efficiency of a fuel cell is around 60-70% of LHV. It tends to be more efficient than the one for the CCGT, especially when the fuel cell's excess heat is recovered in the **HRSG of the CCGT to produce more electricity.** The closed fuel loop system is more efficient than the open one in that case since most of the fuel is consumed directly by the fuel cell. However, if there is some incondensable unreactive components in the fuel, such as nitrogen, a closed loop **will suffer their accumulation.** These incondensable gases will have to be purged to limit their accumulation, **along with part of the fuel, reducing overall fuel consumption in the SOFC system.**

In the case of hydrogen production, **the closed loop option will be preferentially considered,** as it is less dependent on the gas turbine and would be more profitable to improve the overall fuel cell electric efficiency.

In the case of ammonia, **the most relevant option has to be defined**, since the N2 produced will **not be easily split** from the unreacted hydrogen. If the closed loop option is not relevant, the open loop option will be taken into account.

4.2.1. Focus of SOFC with NH3

Solid Oxide Fuel Cells have the advantage to have **good fuel flexibility** due to the high working temperature, **which favors reforming or cracking** reactions of fuels other than hydrogen without the risk of CO poisoning. This property suggests the possibility of using **alternative fuels** that are easier to be transported and stored than hydrogen which has an unfavorable energy density even in the liquid configuration (LH2) which minimizes its volume (8,5 MJ/l at -253 °C and atmospheric pressure). For this reason, the actual state of the art of this fuel cell type is the use of natural gas, stocked in liquid form ad -163 °C (21 MJ/l). These considerations suggest the possibility of using other fuels such as ammonia (15,6 MJ/l at -33 °C ambient pressure) that contains a large amount of hydrogen (17,6 wt%) and no carbon.

In recent years, numerous studies have been carried out **on the possibility of feeding SOFCs with ammonia and the results reported so far are very promising**. The efficiencies achieved are comparable to those of SOFC fed with hydrogen[4] and sometimes even better, this is due to the cracking reaction which favors a better thermal control of the cell and reduces the exergy destruction.

The ammonia reaction (2) produces H_2 and N_2, the hydrogen reacts in the cell while the nitrogen is inert. This reaction could take place **directly inside the fuel cell** in the direct-ammonia SOFC (DA-SOFC) configuration. The equilibrium of the ammonia cracking reaction is influenced by the temperature but could be supported by nickel-based anode electrolyte, which leads to higher peak power density than with other materials[5]. In stationary condition with 700 K temperature and 1 bar pressure the ammonia is fully converted into its products.

$$NH_3 \leftrightarrow \frac{3}{2}H_2 + \frac{1}{2}N_2 \qquad \Delta H_f^o = 44{,}22\ \mathrm{KJ/mol} \tag{2}$$

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[4] Z. Wan, Y. Tao, J. Shao,Y. Zang, H. You, "Ammonia as an effective hydrogen carrier and a clean fuel for solid oxide fuel cells", Energy Conversion and Management 228 (2021) 113729.

[5] Y. Guo, Z. Pan, L. An, "Carbon-free sustainable energy technology: Direct ammonia fuel cells", Journal of Power Sources 476 (2020) 228454.

In terms of electrolytes used, SOFCs can be further classified into SOFC-O and SOFC-H depending on the ions that moves through the electrolyte (oxygen anion or hydrogen proton). Several studies proved that the average performances of the SOFC-H are 20-30% higher than SOFC-O thanks to the hydrogen concentration that helps the reaction[6-7].The degradation aspects are under study too in order to improve the life cycle time, ammonia is quite aggressive substance, and the material compatibility must be investigated but the degradation rate seems to be the same as the hydrogen fed SOFC[8].

4.3. R-SOC description

By nature, the device is **reversible** and is able to **produce either hydrogen in electrolysis mode or electricity and heat in fuel cell mode.** Thanks to its high operating temperature, its efficiency is high in both modes. However, due to the **electrochemical reaction intrinsic behavior**, **it is impossible to have the same power level between the two modes.**

Figure 8 is an example of a polarization curve obtained on a cell developed in the laboratory to illustrate this phenomenon:

- To avoid a discontinuity between both modes, a composition of 50% H2/50% H2O was used, which explains the rather low current density obtained.
- **The voltage and current density for both modes are different:**
    - For the electrolysis mode, the voltage is at thermoneutral (1,29V), which leads to a current density of around 0.4 A/cm^2 of active cell
    - For the fuel cell mode, the working voltage is 0.85V, with a current density obtained of 0.25 A/cm^2
- As the power consumed by the cell is the product of current density and voltage, the power density for the electrolysis is **around 0.5 W/cm^2, whereas it is only 0.2W/cm^2 for the fuel cell mode.** In that specific case the power density of electrolysis is more than **twice the fuel cell's**.

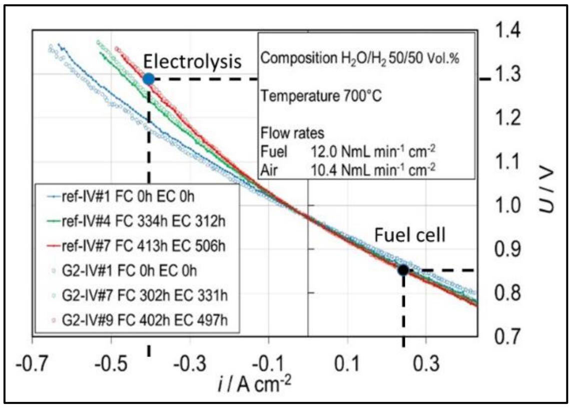

Figure 8 Polarization curve of a 50/50 flow of water and hydrogen over 500h

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[6] F. Ishak, I. Dincer, C. Zamfirescu, "Thermodynamic analysis of ammonia-fed solid oxide fuel cells", Journal of Power Sourcer 202 (2012) 157-165.

[7] F. Ishak, I. Dincer, C. Zamfirescu, "Energy and exergy analyses of direct ammonia solid oxide fuel cell integrated with gas turbien power cycle", Journal of Power Sources 212 (2012) 73-85.

[8] G. Cinti, L. Barelli, G. Bidini, "The use of ammonia as a fuel for transport: Integration with solid oxide fuel cells", AIP Conference Proceedings, 2191 (2019) 020127.

This phenomenon is responsible for **the disparity between the nominal power of a SOEC and a SOFC using the same amount of cells**. It will have to be addressed in the different cases to find the adequate sizing and operation strategy for the system in the case of the R-SOC. It should be noted that this might lead to one mode being underused compared to its potential capacity.

5. Scenario

The different scenarios that will be further studied are described below:

5.1. Scenario 1 - SOFC

In this scenario, **a SOFC** is used to consume part or the total amount of produced H2 or ammonia to generate electricity. The unreacted gas from the fuel is sent to be burned in the CCGT.

Description:

1/ Excess electricity produced by CCGT is used to generate H2 using a PEM electrolyzer system (as for FLEXnCONFU base concept). Depending on the case, the hydrogen will be either stored or converted into ammonia. The amount of hydrogen produced will depend on the electricity surplus produced by the CCGT, which operates above grid injection output to reduce its variations. The hypothesis of overproduction will be the same as the one in the thermo-analysis described in the deliverable D1.3[9] of this project.

2/ The hydrogen produced is stored at ambient temperature and 300 bars, ammonia is stored as a liquid at 20°C and 20 bars. The optimized size of the storage will depend on both PEM production and SOFC needs for the targeted market and CCGT services.

3/ **Hydrogen or ammonia produced is consumed by SOFC** to produce electricity:

- The SOFC efficiency is higher than GT efficiency: for H2 SOFC, a stack electric efficiency in the range of 65-80% of the LHV can be expected
- In "Hydrogen mode", the boundaries of the SOFC system are H2 at 20°C, 2-5 bara and ambient dust-free and dried air
- In "Ammonia mode", the boundaries of the SOFC system are ammonia (more precise conditions will be determined by the future work) and dust-free and dried ambient air
- In both modes, the fuel and inlet air will be preheated internally up to working inlet stack temperature (650-800°C depending on the operating point and technology)
- The temperature of output heat excess will be calculated; depending on that temperature, it could be recovered for steam generation in the HRSG.

4/ The SOFC sizing and optimal operating strategies will be determined regarding the different market and turbine services, which could be:

  - **Spot market:** use the electricity produced by the SOFC on the SPOT market to maximize profits. The admissible price threshold for electricity sale will depend on the hydrogen storage state. It should always offer enough storage capacity to store hydrogen produced by PEM.
  - **Turbine service:** additional turbine services offered by the electrolyzer, can be considered using the SOFC in the system:

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[9] D1.3 – Thermo-economic models, optimisation algorithm and key performance indicators

- Peak shaving: in case of a **short peak demand** exceeding power produced by GT, the **fuel cell provides the amount of electricity surplus needed.** The amount of peak power supply by the SOFC will depend on the fuel cell size.
- Manage Peak Load period: in case of low demand, the fuel cell can provide electricity and therefore make possible for the GT to shut down instead of working at low power and low efficiency for a long time period.

5/ Two additional options (Figure 9 in green) could be evaluated.

  a. Possibility to sell H_2 or NH_3 directly on a dedicated market depending on the price
  b. Possibility to use RES production for green H_2 production

Even if this scenario might not be the most profitable option, it will underline the technical and economical gap with current and forecasted performance of SOFC.

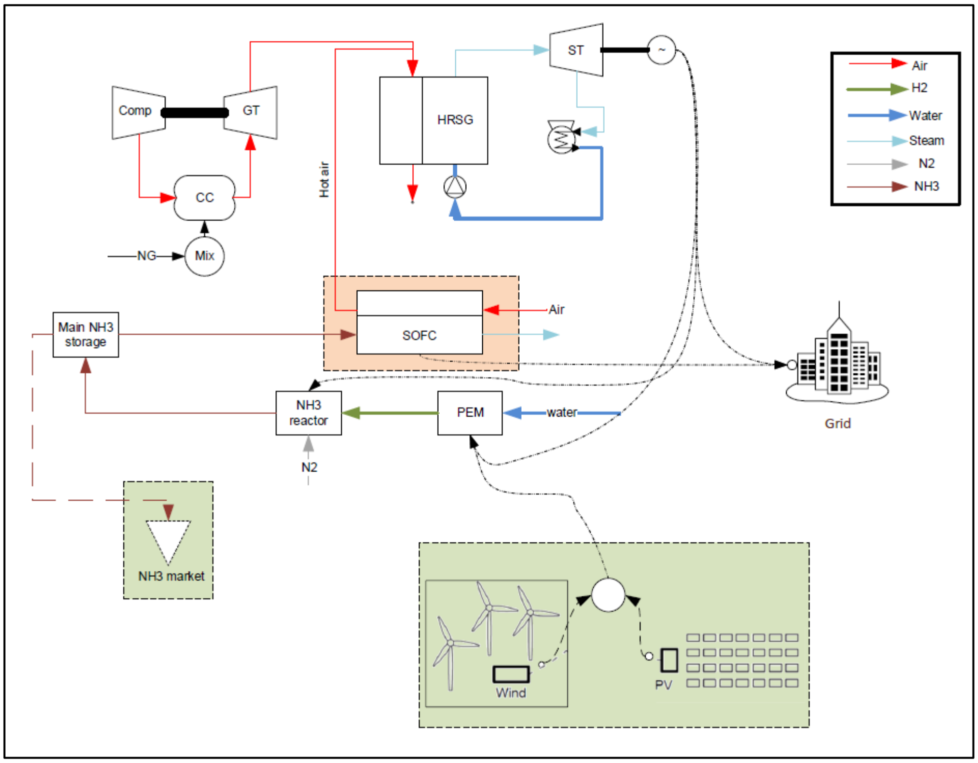

Figure 9 Layout case 1: SOFC used for electricity production through H2 consumption

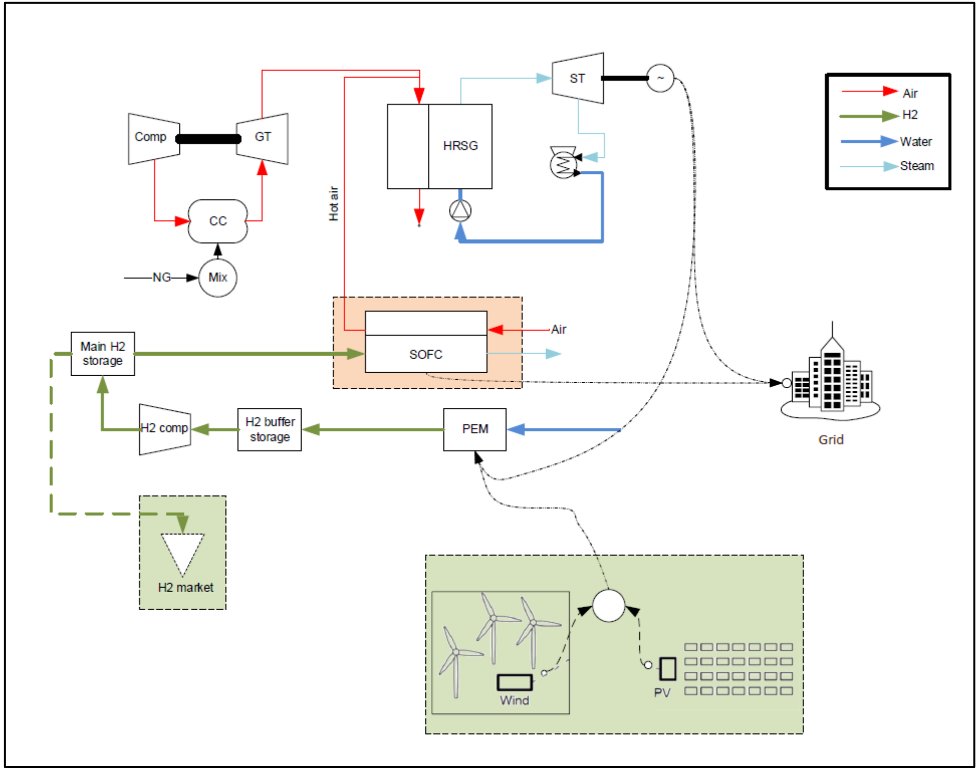

Figure 10 Layout case 1: SOFC used for electricity production through NH_3 consumption

Options for thermal hybridization:

Fuel cell produces excess heat which could be sent to the CCGT to increase its output. It could be used either:

- To produce directly superheated steam to be sent to the Steam Turbine
- To preheat the water injected in the HRSG of the CCGT, increasing its output production

The option chosen will depend on the temperature level achievable with the excess heat from the SOFC, **generally in a range of 200°-400°C**. The precise temperature range will be calculated. In any case, the heat recovery will **increase the electric output of the steam turbine.**

Key parameters:

For this case the main key parameters to be calculated and compared are:

- The Levelized Cost Of Electricity (LCOE) compared to other reference cases
- Increase in CCGT electricity production due to SOFC thermal interaction
- Reduction of operating costs of the CCGT due to optimal control compared to the configuration without FLEXnCONFU system
- CAPEX and OPEX of the SOFC, and operation target to be competitive for these scenarios

5.2. Scenario 2- SOEC

In the second scenario, hydrogen is produced by SOEC instead of PEM electrolyzer system. The main advantage of SOEC compared to **PEM is its higher electric efficiency**, the detailed comparison between the two option will be an output of the study.

Description:

1/ **Electricity and heat from the CCGT are used** to produce hydrogen through the SOEC. The amount of hydrogen produced will depend on the electricity surplus due to GT operational range maximization and its variations reduction over time.

2/ The hydrogen is then compressed and stored at 300 bar and ambient temperature or converted into ammonia and stored in a tank at 20 bar. The optimal size of storage will be defined via simulation.

3/ Then hydrogen or ammonia is injected into the gas turbine up to 30% for H2 mix and 100% for NH3.

4/ Two additional options (Figure 11 in green) could be evaluated.

   a. Possibility to sell H2 or NH3 directly on a dedicated market depending on the cost
   b. Possibility to use RES overproduction for green H2 production

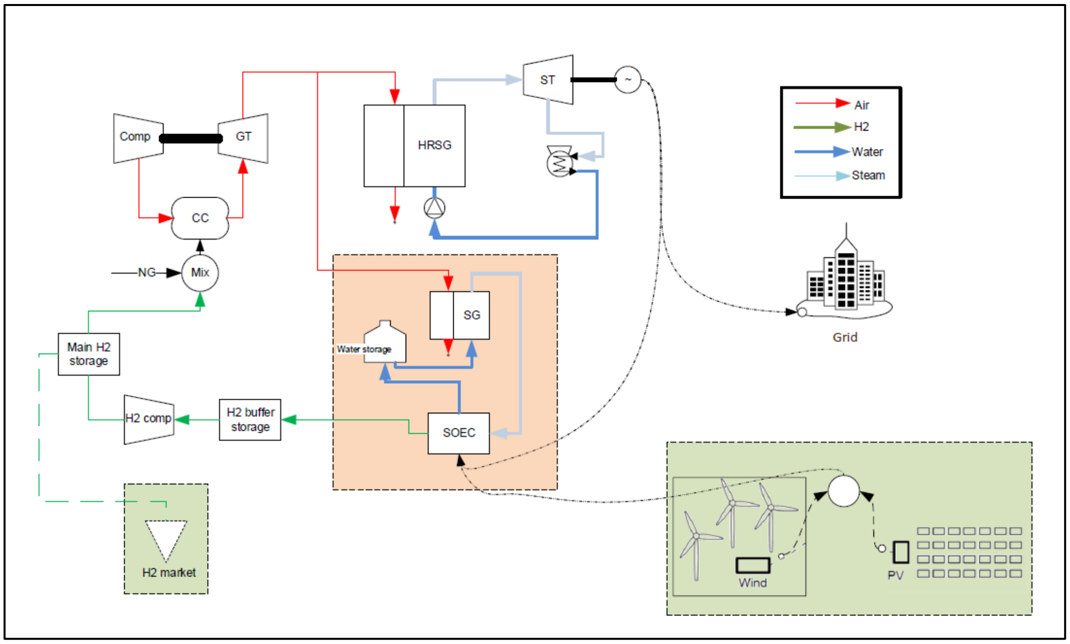

Figure 11 Layout case 2: SOEC replacing the PEM (H2 case)

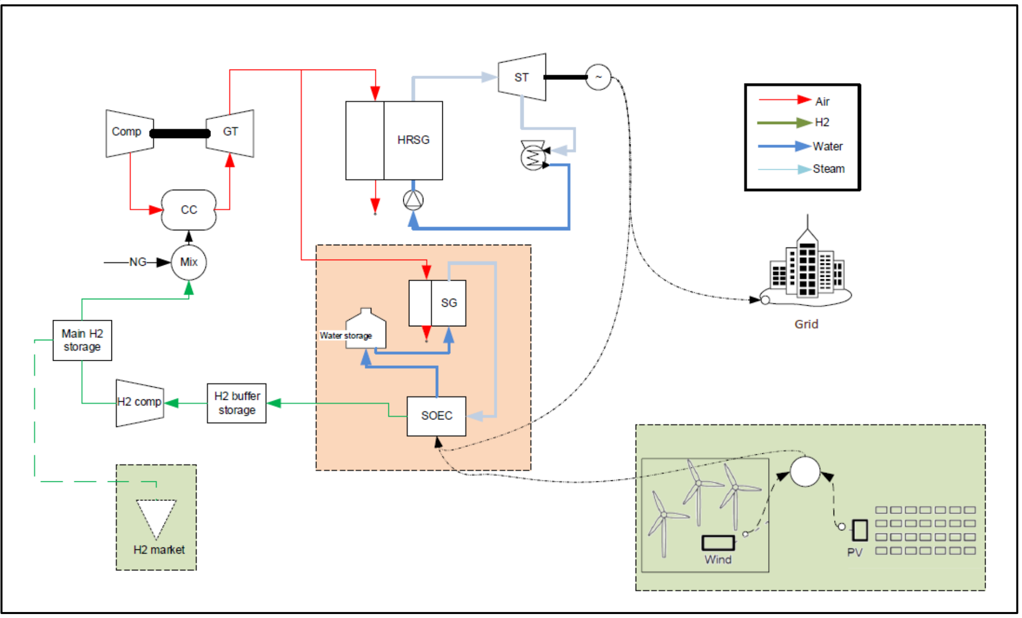

Figure 12 Layout case 2: SOEC replacing the PEM (NH3 case)

<u>**Options for thermal hybridization:**</u>

High temperature electrolysis **consumes heat for the steam generation**. However, the steam quality required to feed the SOEC system is rather low; **3bars and 150°C** is sufficient (and not 700/800°C). The remaining energy necessary for steam heating is generated through heat **recovery from produced enriched air and hydrogen.**

Burning methane or consuming electricity to produce that steam would have negative impacts in terms of CO2 footprint or cost, so using part of the heat produced by CCGT seems to be the best approach to be considered.

Thermal hybridization between the SOEC and the CCGT could be:

- Heat from the **gas turbine**: part of the output flow from the gas turbine could be used to feed a steam generator dedicated to the SOEC.
- Heat from the **steam turbine**: part of the output flow from the steam turbine could be used to feed a steam generator dedicated for the SOEC.
- Direct use of steam from the CCGT would also be an option, but contaminants inside the flow have to be avoided. If the purity level can be achieved, this option can be considered and steam from CCGT can be removed before the condenser.

On one hand the heat removed from the CCGT will negatively impact the CCGT efficiency, on the other hand the SOEC electrical efficiency is higher than the PEM's, the global impact on steam circle will depend on the different size system.

The ammonia reactor **produces heat in a range of 350°C-450°C** which should be **enough** to feed part of the SOEC steam generator needs. The best option whether to use steam in CCGT or steam generator has also to be studied.

Excess heat recovered from the SOEC system is at less 80°C and is too low has to be considered as fatal.

Key parameters:

For this case the key parameters that will be calculated and compared are:

- The LCOH difference between PEM and SOEC solution
- In the case of RES, reduction of electricity CO_2 footprint

5.3. Scenario 3 – R-SOC

The third scenario combines both scenarios 1 and 2. The Solid Oxide Cells is used in both modes: as a mean for hydrogen production and electricity production. This scenario will highlight the advantages and constraints of such a configuration.

Description:

This scenario merges the previous two scenarios and gathers most of the previous information described:

1/ Electricity and heat produced by CCGT is used to produce Hydrogen through the R-SOC system in "SOEC mode". Depending on the case, hydrogen will be either directly stored or transformed into ammonia. The amount of hydrogen produced will depend on the electricity surplus produced by the CCGT, which operates above grid injection output to reduce its variations. The hypothesis of overproduction will be the same as used in task 1.3.

2/ The hydrogen produced is stored at ambient temperature and 300 bars, ammonia is stored at 20°C and 20 bars. The optimized size of the storage will depend on both PEM production and SOFC needs for targeted market and CCGT services.

3/ Part or all hydrogen or ammonia produced is consumed in the R-SOC to produce electricity:

   a. The SOFC efficiency is higher than GT efficiency
   b. In "Hydrogen mode", SOFC system is fed with H_2 at 20°C, 2-5 bara and air
   c. In "Ammonia mode", SOFC system is fed with ammonia
   d. The temperature of output heat excess will be calculated; depending on that temperature it could be recovered for the steam turbine.

4/ The R-SOC sizing and optimal operating strategies will be optimized depending on the most profitable market and services that will be defined. The different markets and turbine services used will be the same as in case 1 and 2.

5/ Two optional components could be evaluated (Figure 13 in green).

   a. Possibility to sell H_2 or NH_3 directly on a dedicated market if needed
   b. Possibility to use RES overproduction for green H_2 production (higher run time on the component, reduced overall CO_2 footprint of the plant)

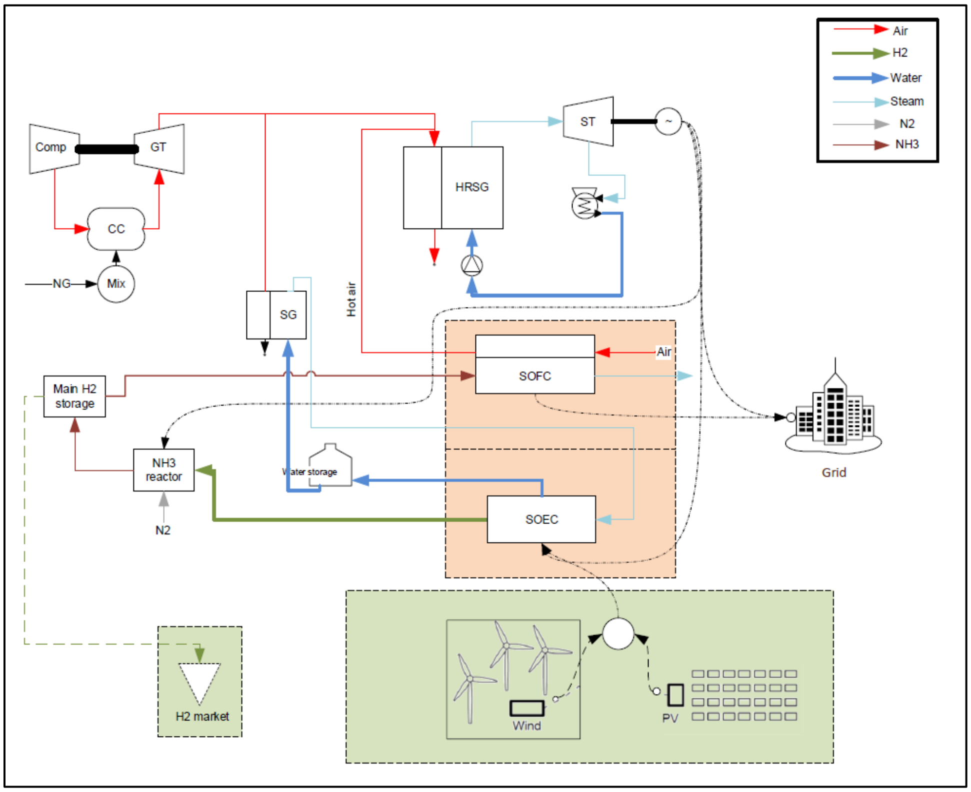

Figure 13 Layout case 3: R-SOC integration (H_2 case)

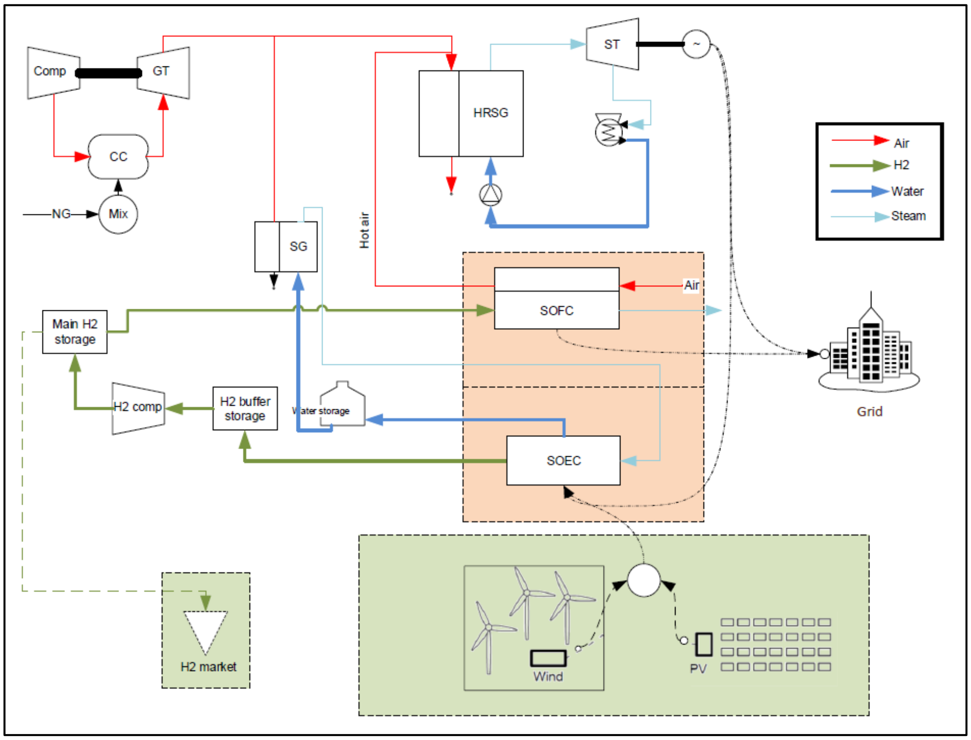

Figure 14 Layout case 3: R-SOC integration (NH_3 case)

Options for thermal hybridization:

This scenario will study the thermal hybridization of the CCGT with both modes of the R-SOC, similar as in scenario 1 and 2:

- In "SOEC mode": recovering part of the heat from the CCGT to feed the steam generator specifically dedicated to electrolyzer.
- In "SOFC mode": supply the CCGT steam cycle with the excess heat from the fuel cell.

The optimal thermal hybridization procedure will be studied through process simulation.

The following table points out the main characteristics of the different scenarios:

	SCENARIO 1	**SCENARIO 2**	**SCENARIO 3**
Configuration	SOFC	SOEC	R-SOC
Main Focus	- Improve electricity production efficiency from H_2/NH_3 - Specify for which market case flexibility is maximized	- Compare H_2 production efficiency between SOEC and PEM	- Find the best control strategy to maximize the revenue (Power-to-Power production vs CCGT support)
Advantage	- Reduce load variation of CCGT - Increase maximal power output of the plant - If all NH_3 or H_2 is consumed through SOFC, retrofit costs of CCGT are reduces (GT, combustion chamber) - Multi-fuel compatibility	- SOEC has better electric efficiency than PEMEL	- Reversible function of R-SOC - Maximize load factor of R-SOC - Capex mutualized for the 2 functions
Drawback	- Costs of additional component - In case of retrofit, CCGT modification for thermal might not be easily feasible depending on the CCGT configuration	- Technology Maturity - Cost - Heat consumption from GT or HRSG and impact on CCGT production	- Technology Maturity - Cost - In case of retrofit, CCGT modification for thermal might not be easily feasible depending on the CCGT configuration
Thermal impact	- Heat from SOFC to CCGT (HRSG) => increase energy production from steam turbine	- Heat from GT or HRSG or ammonia production to SOEC => decrease energy production	- A combination of the two previous cases

Figure 15 Qualitative comparison of the 3 scenarios

5.4. Summary of technical inputs

The following table sums up the different inputs that will be necessary to work on the techno-economic analysis in the different scenarios:

1. INPUT DATA	
CGGT turbine power profile	The following information about the CCGT are required: - Hourly injection profile; - gas turbine efficiencies; - steam turbine efficiencies; - cost due load variation; - start up costs.
Electricity market	The different market prices are needed to be integrated in the scenarios (same timeline as CCGT injection profile): - SPOT market; - Intraday market; - Day-ahead market.
RES market price	An option described will consider the use of Renewable Electricity Sources: - Historical market price of RES - Available volume
H_2 / NH_3 market	H_2 and NH_3 prices produced by PEM using overproduced electricity will be compared with H_2 and NH_3 potential market : - Price of H_2 and NH_3 market in the considered country

2. TECHNICAL & ECONOMIC ASSUMPTIONS	
PEM Capacity (sc.1)	Results from 1.3 optimization : Capacity, cost, efficiency and process control strategy of the PEM case
SOFC, SOEC or R-SOC Capacity	Capacity defined by the optimization modelling
SOFC recoverable heat	Temperature range will be calculated
R-SOC Economic parameters	Investment cost Operating and maintenance cost Replacement frequency Lifetime
Energy consumption	Electricity consumption of electrolyzer / Fuel Cell and sub-systems
Storage capacity	Capacity defined by the optimization modelling
Ammonia Fuel cell characteristics	To have a model of the SOFC using ammonia, following inputs are needed: - Polarization curves of the fuel cell: formula linking current density with cell voltage, temperature and gas flowrate and composition; - Recommended optimal functioning point.
Ammonia process	Operating conditions and cost of its components (reactor and compressors)
Plant heat flow	Plant heat flow to study thermal integration of the different subsystems
Facilities requirement	Additional cold, heat facilities needed
Purchasing price of CH_4	Country dependent

6. Techno-economic assessment methodology and KPI

6.1. General principle

For each case, the techno-economic analysis of the FLEXnCONFU system will be performed following process simulation of the different systems implied.

The most relevant economic indicators of the system are described in the following paragraphs. Several intermediate indicators will be needed and defined during scenario calculation (such as average fuel cell power level or annual functioning time) and will be brought up if relevant.

6.1.1. Levelized cost of hydrogen

The techno-economic assessment of the global system establishes the levelized cost of the final vector of energy (LCOE). For scenario 2, the LCOE considered will be the cost of hydrogen produced with SOEC, which will be compared to hydrogen cost produced with PEM.

It involves capital expenditure (CAPEX) and operating expenses of the system on the overall lifetime from its design to its decommissioning.

The discounted cash flow analysis is a method of valuing a project giving a present value to future cash flows incoming and outgoing. This method allows reflecting the "time value of money" meaning that money available or spent immediately has more important value than money available or spent in the future. The levelized cost is based on the principle of equality between income and expense during overall lifetime project. It allows determining the average selling price of the energy produced by the system, in order to cover all expenses without commercial margin. This cost is calculated by the following formula:

$$LCOH\ (\frac{€}{Kg}) = \frac{CAPEX + \sum_{i=1}^{n} \frac{Opex_i}{(1+\alpha)^i} + \sum_{i=1}^{n} \frac{Variables\ expenses_i}{(1+\alpha)^i}}{\sum_{i=1}^{n} \frac{KgH2}{(1+\alpha)^i}}$$

Or in €/MWh, considering H2 LHV

$$LCOH\ (\frac{€}{MWh}) = \frac{CAPEX + \sum_{i=1}^{n} \frac{Opex_i}{(1+\alpha)^i} + \sum_{i=1}^{n} \frac{Variables\ expenses_i}{(1+\alpha)^i}}{\sum_{i=1}^{n} \frac{Equivalent\ energy\ of\ produced\ H2_i}{(1+\alpha)^i}}$$

Where:

CAPEX: Capital expenditure of SOEC only
OPEX: Operational expenditure of SOEC including O&M
Variables expenses: input consumption (water and electricity)
n: operating time
α: discount rate

6.1.2. Levelized cost of ammonia

Similar to the levelized cost of hydrogen, the levelized cost of the ammonia produced can be calculated using the LHV of the ammonia:

Similarly, the levelized cost a hydrogen, scenario will compare the cost of ammonia produced by the ammonia electrolysis and ammonia system with the one of current (or trending) ammonia market price.

$$LCOA\ (\frac{€}{Kg}) = \frac{CAPEX + \sum_{i=1}^{n} \frac{Opex_i}{(1+\alpha)^i} + \sum_{i=1}^{n} \frac{Variables\ expenses_i}{(1+\alpha)^i}}{\sum_{i=1}^{n} \frac{KgNH3}{(1+\alpha)^i}}$$

Or in €/MWh

$$LCOA\ (\frac{€}{MWh}) = \frac{CAPEX + \sum_{i=1}^{n} \frac{Opex_i}{(1+\alpha)^i} + \sum_{i=1}^{n} \frac{Variable\ expensises_i}{(1+\alpha)^i} -}{\sum_{i=1}^{n} \frac{Equivalent\ energy\ of\ produced\ NH3_i}{(1+\alpha)^i}}$$

6.1.3. Levelized cost of energy (case 1.1 and 1.2)

The techno-economic assessment of the global system establishes the levelized cost of the final vector of energy (LCOE) which is electricity directly produced by SOFC. In case 1.1 and 1.2 we consider all hydrogen or ammonia consumed by SOFC for electricity production.

It involves capital expenditure (CAPEX) and operating expenses of the system on the overall lifetime from its design to its decommissioning.

$$LCOE_{SOFC}\ (\frac{€}{MWh}) = \frac{CAPEX + \sum_{i=1}^{n} \frac{Opex_i}{(1+\alpha)^i} + \sum_{i=1}^{n} \frac{Variable\ costs_i}{(1+\alpha)^i} - \sum_{i=1}^{n} \frac{Income_i}{(1+\alpha)^i}}{\sum_{i=1}^{n} \frac{Equivalent\ energy\ of\ consumed\ H2\ or\ NH3_i}{(1+\alpha)^i}}$$

The equivalent energy of H2/NH3 consumed will be the Lower Heating Value of the consumed hydrogen/ammonia (in kWh/kg) multiplied by the total amount used that year.

6.1.4. CCGT efficiency and reduction of operating costs

The main objective of the FLEXnCONFU concept is to reduce the operating costs of the CCGT and maximize its efficiency by maintaining an output as steady as possible.

The base function of the CCGT will therefore be compared with the upgraded strategy of the FLEXnCONFU. Both the average CCGT efficiency and operation cost will be intermediary results of the simulation.

7. Conclusions

R-SOC main characteristics and description have been detailed for each mode: electrolyzer mode (SOEC), fuel cell mode (SOFC), or both (R-SOC).

Thermal behavior of these systems has been highlighted and their integration into the plant will be an important aspect of the study for the different scenarios.

The base cases that will be considered to evaluate any positive or negative impact with "SOC scenarios" are reminded and are:

- A 400MW CCGT power plant without Power-to-X-to-Power system
- The FLEXnCONFU concept at industrial scale
- Complementary layouts with RES production and NH_3/H_2 market

The three scenarios have been described from a general point of view and preliminary flow sheets established:

i) Integration of SOFC in the power plant to produce electricity from ammonia or hydrogen
ii) Replacement of PEM electrolyzer by SOEC
iii) Hybridization of R-SOC (reversible mode) for both H_2/ammonia production and electricity production

Only the main KPI are described: levelized cost of energy (case 1.1 and 1.2), levelized cost of hydrogen, levelized cost of ammonia. Several intermediate indicators might be needed and defined during scenario calculation.

The next step of the study could be summarized as:

- Gather all input parameters listed
- Define components main characteristics and models
- Model the different scenarios and their thermal interaction with CCGT
- Test the different options for the operating strategies
- Choose the best options for optimization
- Establish techno economical KPIs for each scenario considered