PROJECT FINAL REPORT

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1.1 Executive summary

ADEL (ADvanced ELectrolyser for Hydrogen Production with Renewable Energy Sources) aimed at developing a new steam electrolyser concept. The approach was to lower the electrolyser operating temperature to increase its lifetime and to couple flexibility with thermal sources. The challenge is to maintain satisfactory performance and to optimise the energy transformation efficiency at the level of the complete system, including the heat and power source. Efforts comprised materials, cell and stack development and their testing under conditions derived from the renewable energy availability, the design of electrolyser units including the balance of plant components, and the conceptual integration of such units in case studies. The following main results have been obtained:

- The developed Generation 2 components show improved performance. Electrolyser stacks generally behave very well under load cycling conditions, but their base degradation rates remain above the project goal.
- Post-test SEM examinations show an alteration of the electrolyte/cathode interface but neither anode delamination nor chromium poisoning under electrolyser operating conditions. Possible degradation mechanism could be Ni removal from the interface. The phenomena is not sufficiently understood, and within the project, it was not possible to quantify to what extent this phenomenon explains the degradation (corrosion?).
- By coupling system simulation work with material development activities, specific test protocols were defined from the system requirements to test stacks under transient conditions and to define a realistic system operating window from materials constraints.
- System modelling shows that the electrolyser operating temperature (700 vs 800°C) has little impact on the efficiency and cost. The initial design temperature of 600°C is too low for SOE from a materials performance side. Pressurised operations have also limited impact as long as sweep air is used, as savings are set off by air pressurisation. As a consequence, optimised durability and performance is the critical couple to optimise, independent from electrolyser operating temperature.
- The allothermal source of heat is mainly required for steam generation. Consequently a large variety of heat sources can be considered. High temperature coupling provides limited efficiency gains with respect to the increased complexity and cost.
- High temperature electrolysers present very high power conversion efficiencies, decent load following capabilities and high capital costs. Different opportunities for electrolysis were controversially discussed:
    - Grid balancing cases compete with Smart grids as strong alternative.
    - Chemical storage (power to gas) as alternative for energy transport in the context of power-lines congestion or seasonal electricity storage with increased solar electricity production.
    - Distributed hydrogen production for fuel cell cars, although hydrogen is currently considered more as a chemical than an energy carrier. Synthetic fuels derived from co-electrolysis using CO_2 would couple renewable energy to standard energy markets more directly.
- Hydrogen production costs with high temperature electrolysis from renewable energy sources range from 6-17 €/kg calculated for four scenarios and are not yet fully competitive. The major cost is still the stack related to the limited lifetime. Another substantial cost part is the equipment for harvesting the renewable energy.
- The specifications of a demonstrator coupling an ADvanced ELectrolyser with a solar tower were elaborated.

The project achieved its objectives to a large extent, lacking progress in durability. Further activities in this field should focus on optimising performance, lifetime and costs independent from temperature constraints, and include a technology demonstration under real conditions.

1.2 Summary description of the project context and the main objectives

1.2.1 Context

The ADEL project (ADvanced ELectrolyser for Hydrogen Production with Renewable Energy Sources) proposes to develop a new steam electrolyser concept. This so-called Intermediate Temperature Steam Electrolysis (ITSE) aims at optimising the electrolyser life time by decreasing its operating temperature while maintaining satisfactory performance level and high energy efficiency at the level of the complete system including the heat and power source and the electrolyser unit. The relevance of the ITSE is an increased coupling flexibility. Improved robustness and operability will be assessed both at the stack level based on performance and durability tests followed by in depth post test analysis, and at the system level based on flow sheets and global energy efficiency calculations.

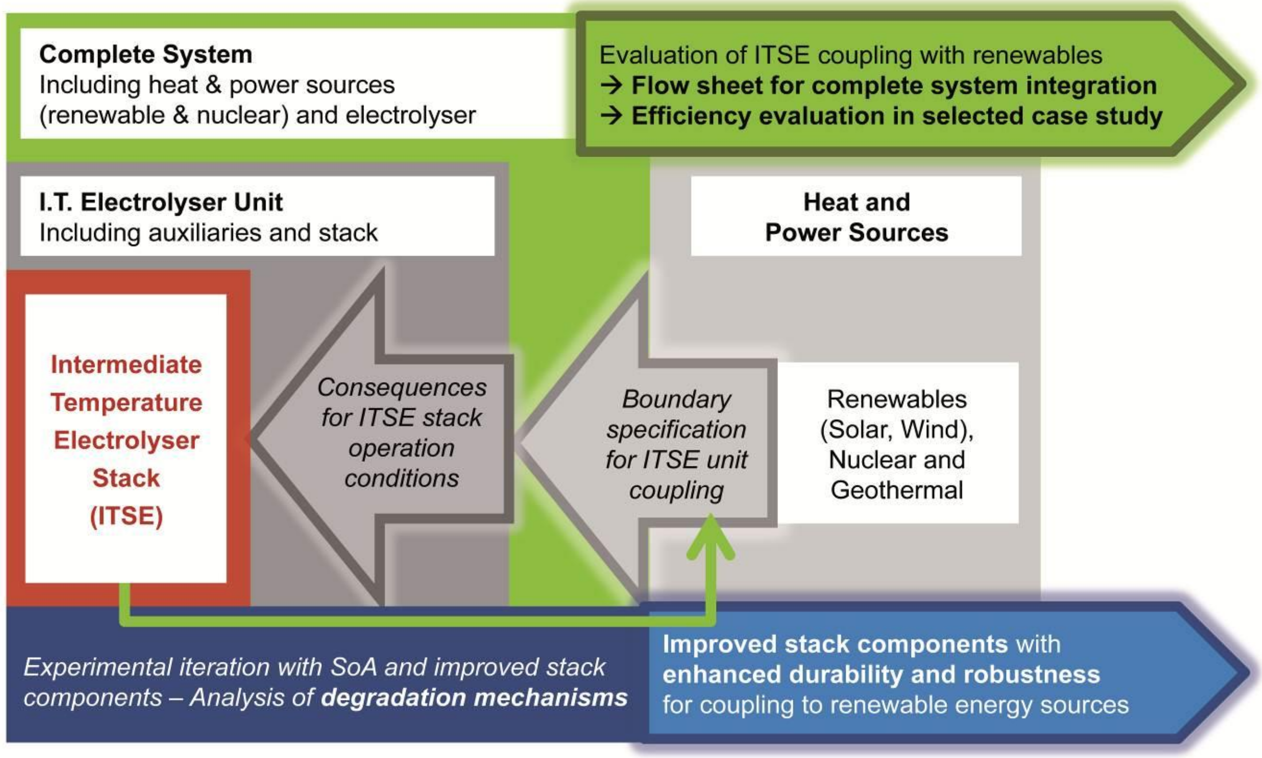


Figure 1-1: Concept of the ADEL project

Coupling of the Intermediate Temperature Steam Electrolyser unit (ITSE) and renewable or nuclear energy sources is studied from point of view of the stack component to the complete system. Flow sheets bridge the gap between the two scales.

1.2.2 Main objectives

High Temperature Steam Electrolysis (HTSE) stands for a promising process of large-scale centralised hydrogen production. It is also considered as an excellent perspective for efficient use of renewable solar or geothermal energy sources. Indeed, the concept of integrating renewable energy with hydrogen systems was given serious consideration in the 1970s. Numerous studies have been reported on the hydrogen production systems from solar energy, wind energy and biomass in the literature. Most of the water electrolysis technologies to date have used alkaline or acidic electrolyte systems for hydrogen generation. Typical system efficiencies quoted are in the 55-75% range and current density is typically around 0.3-0.4 A/cm^2 due to technical difficulties in maintaining the electrolyte balance and keeping hydrogen and oxygen separated. The electrolysis technology based on polymer electrolyte membranes does not use a corrosive electrolyte and can accept large power input variations allowing direct integration with intermittent energy sources. However, the cost of such systems is expensive (~7€/kg - Based on Proton Energy system costs (Hydrogen production of $6m^3/h$ with an expected lifetime of 10 years) making this coupling acceptable for limited cases only such as isolated islands. Electrolysers based on solid-oxide cell technology offer the possibility of using heat generated from various sources in order to reduce the electric energy input and enhance the electrolysis efficiency. However, this technology will bring significant economical improvement and will be competitive regarding alkaline or PEM technology only if an increase of the electrolyser life time can be obtained (> 3 years).

Sources of degradation that affect the solid oxide electrolyser cells and stack lifetime come from the high operating temperature (800 – 1000°C). Indeed, this temperature range enhances chemical species evaporation and diffusion, resulting in the formation of secondary isolating phases, as well as in a decrease of the mechanical stability of ceramic and metal components.

To increase the electrolyser durability, one possible solution is to decrease the operating temperature of the electrolyser. The resistances of cells, interconnects and contact layers will tend to increase and to limit the electrolyser performance, but at the same time, all parasitic phenomena such as interdiffusion, corrosion or vaporisation responsible for cell and stack degradation will be significantly slowed down. Moreover, thanks to the progress achieved in the field of SOFC, in particular in FP6-SOFC600, cells and interconnect coatings are now available that allow reaching at 600 °C equivalent performance that classically are obtained at 800°C [15].

In addition, this operation temperature reduction will open the door for extended operation modes. With the currently developed HTSE technology, the operation temperature is too high to benefit significantly from external heat sources and most of the energy required for H_2 production is provided as electricity (auto-thermal operating mode). In contrast, decreasing the electrolyser operation temperature will allow a significant part of the required energy to be provided, as heat the rest being provided as electricity (allo-thermal operation mode), giving flexibility for coupling the electrolyser with various heat sources and potentially increasing the energy efficiency of the complete system. As a consequence, if the electrolyser can operate close to 600°C, heat sources such as Solar Concentration sources or Nuclear High Temperature Reactor could directly feed the electrolyser, whereas other heat sources would need a limited heating step. In that case allo-thermal operation can be considered to increase the overall system energy efficiency.

In the ADEL project, it is thus proposed to increase the electrolyser lifetime decreasing its degradation rate to less than 1%/1000hrs by taking advantage of the outcomes of:

- the ended FP6-Hi2H2 project which addressed the possibility to operate SOFC components in the electrolyser mode and the identification of main bottlenecks,
- the running SOFC600 project that has produced innovative cells and interconnect coatings for operation at 600°C. When transposed and adapted to ITSE conditions, they offer a good potential to reach low cell degradation rate a in the range of 0.5%/1000hrs,
- the running FP7-RELHY project focused on the improvement and scaling up of current components to achieve a HTSE stack with degradation rate close to 1%/1000hrs

Special attention will be given in the ADEL project to sealing methods in order to increase the mechanical durability of the single repeating unit and to the association interconnect /coating in order to limit the cell ASR and allow current densities across the cell as high as $2A/cm^2$.

To have an exhaustive and quantified analysis of the integration of this “new generation ITSE” with different heat and power sources like wind, solar, geothermal and nuclear, flow sheets will be produced with adjustable parameters. For selected cases in depth energy efficiency evaluation will be performed and translated into first specifications for a demonstrator.

High energy efficient and sustainable hydrogen production is a major concern of the ADEL project, in line with the priorities of the MAIP to "*develop a portfolio of **cost-competitive**, **high energy efficient** and **sustainable hydrogen production** - Long-term and breakthrough orientated research will aim at improving efficiencies of technologies for water splitting using high temperature electrolysers based on solar, nuclear or waste heat.*"

Special attention is given to the **energy efficiency** of the High Temperature Electrolyser unit coupled to carbon-free energy sources (renewable and nuclear) with two dedicated work packages. Further, all the energy sources considered in the ADEL project are carbon-free: either renewable such as solar, wind and geothermal, or nuclear. Different operation modes are considered in order to value available heat and decrease the electricity weight in the total cost. In addition, at the electrolyser stack level, the operating temperature is reduced to slow down degradation mechanisms and increase the electrolyser lifetime. **Cost effectiveness** is addressed in the ADEL project through electrolyser durability and coupling efficiency.

1.3 Description of the main S & T results/foregrounds

1.3.1 WP1 - Stack components optimisation for durability and robustness

WP1 aimed at evaluating State-of-the-Art components and then improving materials and components under ADEL-specific operating conditions. The relevant performance criteria were defined from the systems point of view (WP2), confronting "materialists" with "systemists".

Common test protocols

Common tests protocols were defined around 700°C for state-of-the-art (SoA) and second generation (2G) components. SRUs and short stacks were provided by different partners with various designs. In the ADEL approach, distinct tests were dedicated to performance measurements, durability in steady state conditions close to thermoneutral voltage (VTN) and upon transient conditions. Especially, different load cyclings were defined with different operating voltages, plateau durations at each voltage and a quick speed of current change as shown in Figure 1-2..

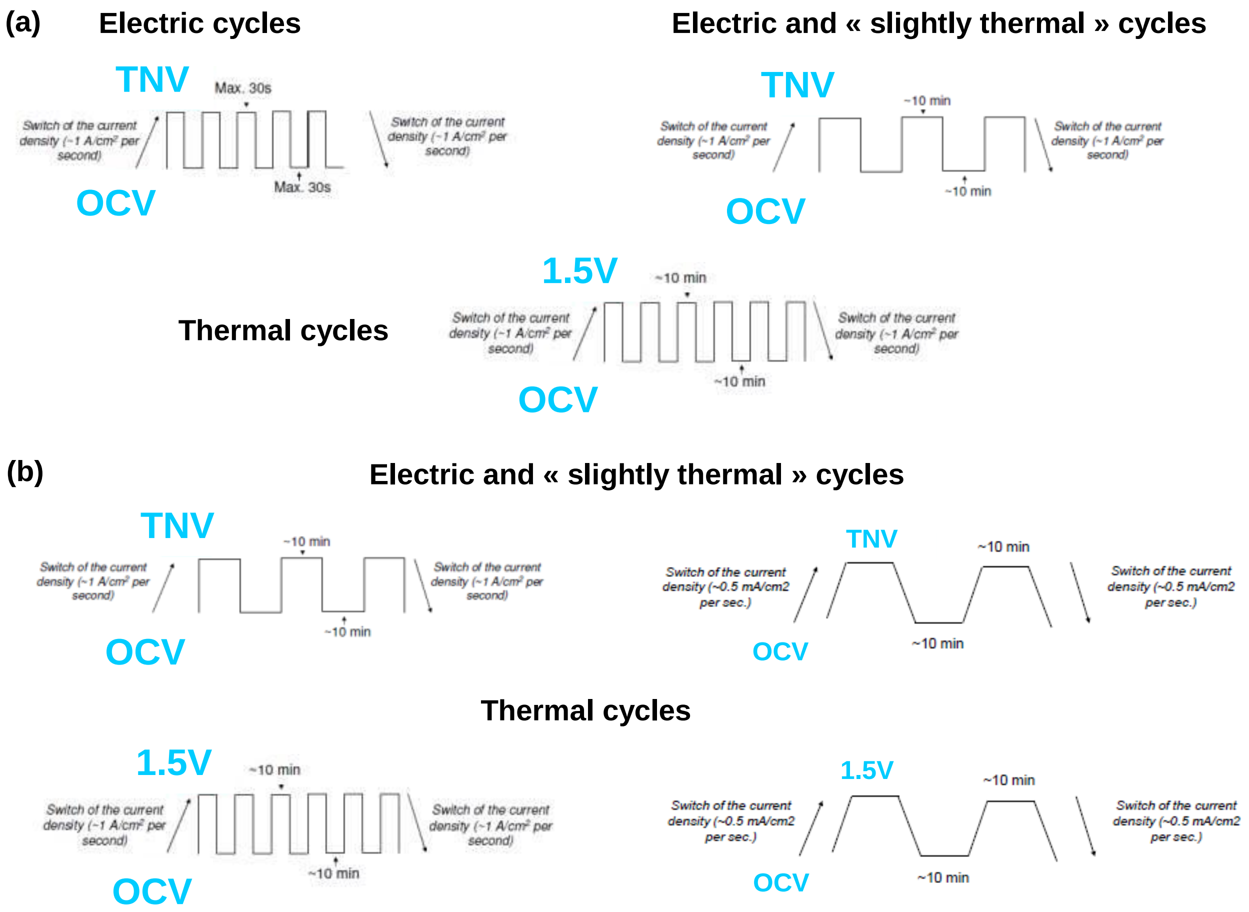
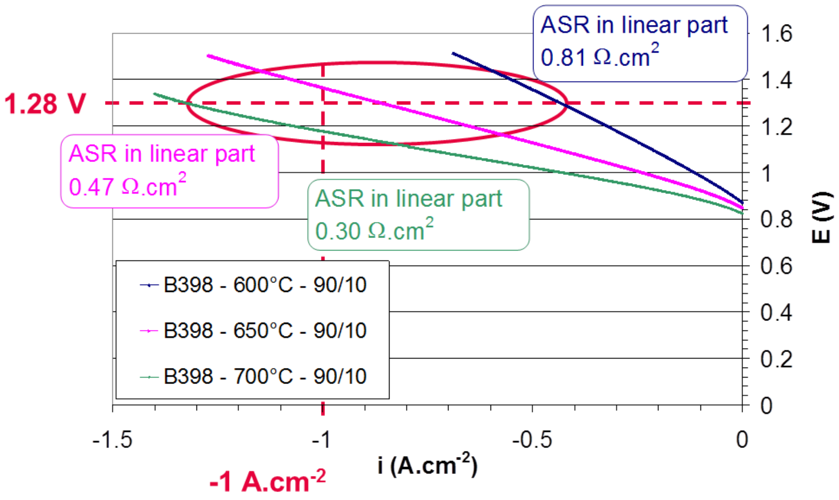


Figure 1-2: ADEL load cycling performed for testing upon transient operating conditions. (a) SoA testing campaign, (b) 2G testing campaign.

In regard to microstructure characterisation of fresh and aged samples, a common protocol was also defined and followed by each involved partner in both testing campaigns.

Single cell testing
At the single cell level, the electrochemical core of the stack, very good performances were achieved around TNV at intermediate temperature (700 and 650°C) with **SoA** Ni-8YSZ/8YSZ/LSC cells from FP6-SOFC600 (see Figure 1-3). At 700°C, current density as high as -1.33 A/cm² was measured at VTN and high steam conversion rate (SC = 92%). However, the performance at 600°C was too poor.



	i at 1.28 V ($mA.cm^{-2}$)	SC at 1.28 V (%)
700°C - 90/10	1330	92
650°C - 90/10	865	60
600°C - 90/10	434	30

Figure 1-3: Electrochemical performances of a SoA FP6-SOFC600 cell between 600 and 700°C with 90vol.% H_2O/10vol.% H_2 cathodic gas flow

2G electrode supported cells from SP with LSC or a nickelate as oxygen electrodes tested at JRC (see Figure 1-4) showed an increase of performance compared to the SoA ones from SP at 700°C: -0.7 A/cm² with 2G LSC oxygen electrode and -0.34 A/cm² with SoA LSCF-GDC one at thermoneutral voltage, 30% and 23% of steam conversion respectively. Nevertheless, performance stayed lower than for the cells from FP6-SOFC600 tested in the SoA testing campaign. Microstructural characterization of both cells at EMPA highlighted different features that could explain the performance difference and could be improved on current SP cells: mainly electrolyte thickness (thinner electrolyte in FP6-SOFC600 cells) and density (less and smaller pores in FP6-SOFC600 cells), oxygen electrode grain size (finer microstructure in FP6-SOFC600 cells).

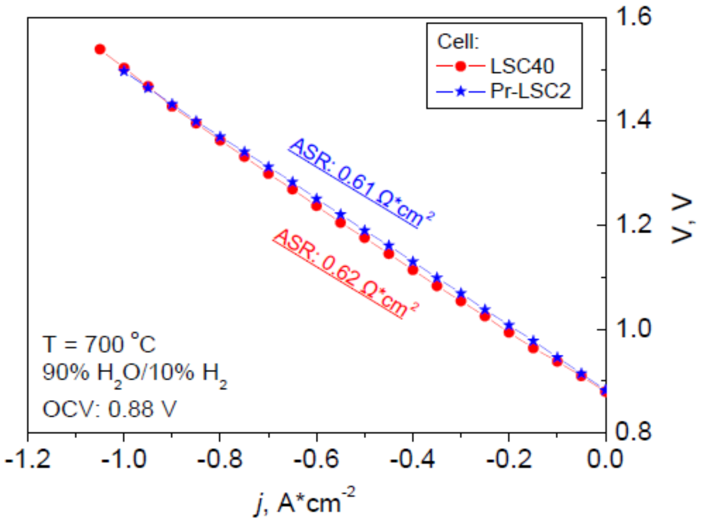


Figure 1-4: Performances at 700°C of 2G single cells from SP. LSC40 = LSC oxygen electrode, Pr-LSC2 = nickelate oxygen electrode with a LSC contact layer

Metallic interconnect coatings

At the cell / interconnect coating interface, compatibility between oxygen electrode (GDC-LSCF, LSC) and contact coating (LSMC, LNF) materials was checked. *In-* and *ex-situ* XRD characterisation was performed after thermal treatments simulating intermediate temperature steam electrolysis (ITSE) operation (700°C, 200-3000h) and glass sealant forming treatment (920°C, 1h30) in pure O_2. No chemical reaction was evidenced between all coatings and all oxygen electrodes tested (see an example in Figure 1-5).

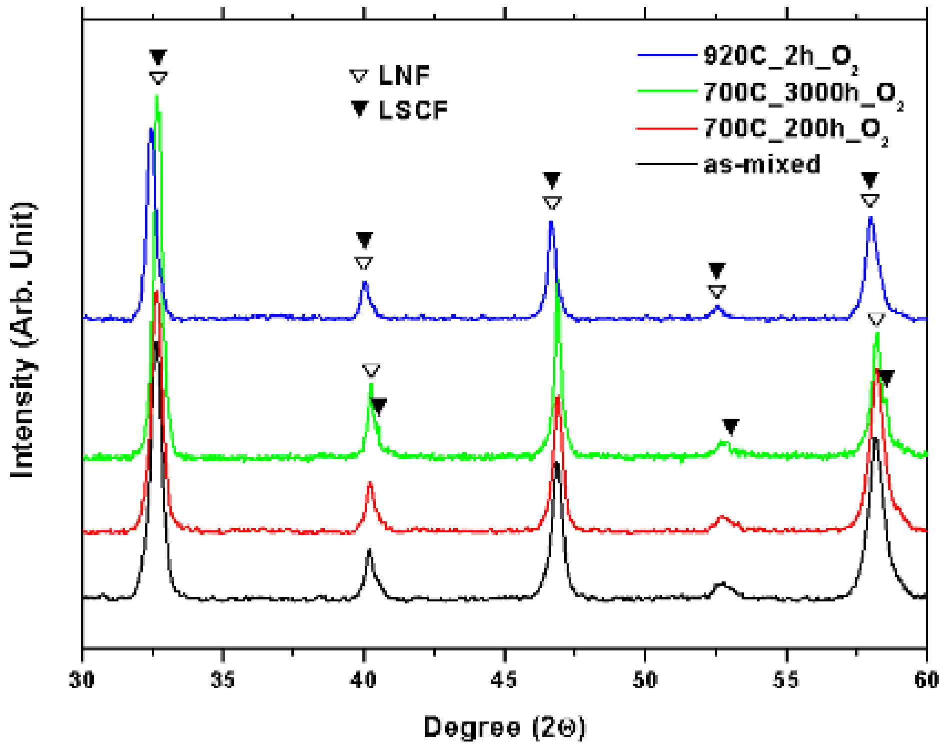


Figure 1-5: XRD measurements on LSCF / LNF pellets after different thermal treatments at 700 and 920°C

At interconnect and coatings level, high efficiency of a dense Mn-Co oxide protective layer directly deposited on the interconnect before the contact layer was demonstrated. Cr poisoning of the oxygen electrode was prevented even after 3000h at 700°C: no Cr species coming from the interconnect were detected in the contact layer (see Figure 1-6).

Those results were also confirmed by **Cr evaporation testing** after 500 hours at 700°C in pure O_2 (see Figure 1-7) and additional **EDS analyses** (see Figure 1-8), showing that contact coatings alone were less efficient to protect the oxygen electrode from Cr poisoning.

Further, **ASR measurements** carried out on SoA (GDC-LSCF) and 2G (LSC) symmetrical cells showed that the most efficient interconnect coatings didn't affect the contact resistance: their use didn't lead to any additional ohmic resistance compared to an ideal gold grid contact. Results presented in Table 1-1 are consistent with values available from SOFC600 European project (0.11 Ω.cm² at 600°C).

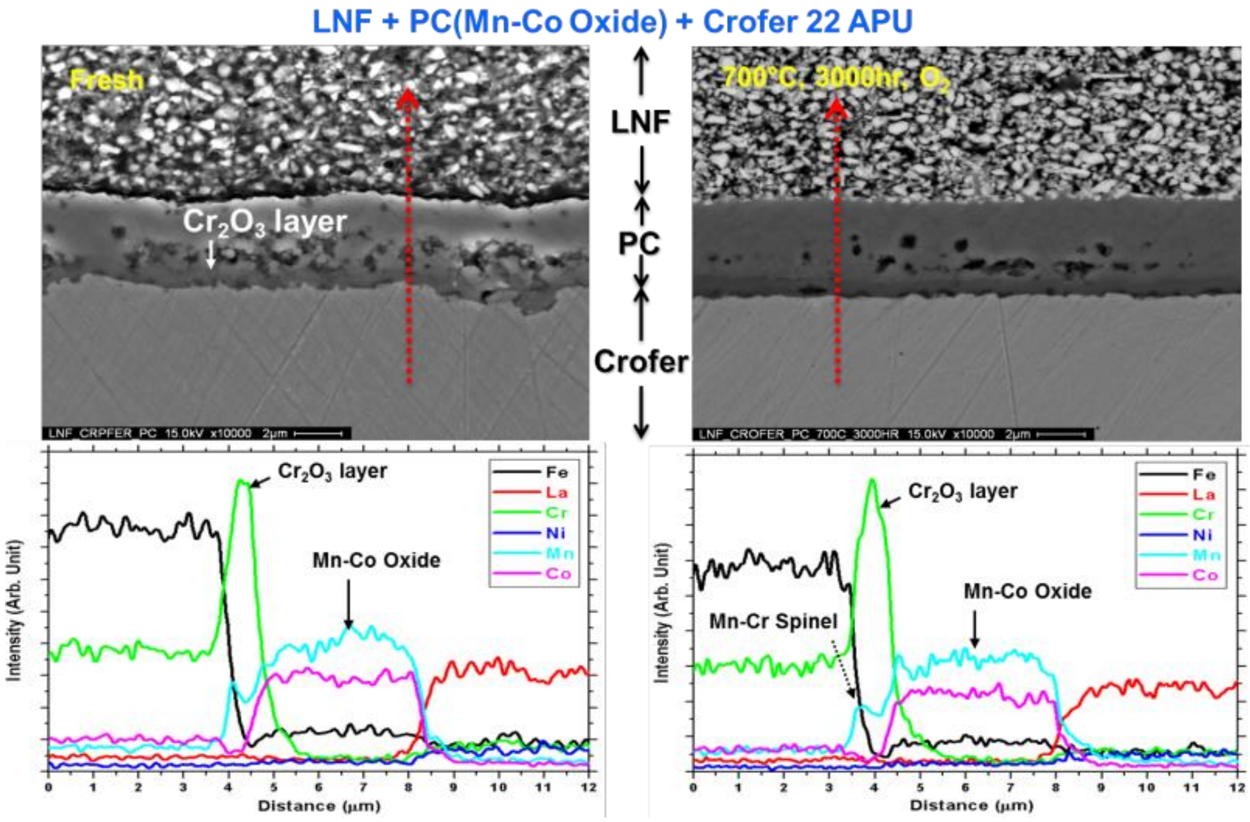


Figure 1-6: SEM observations and EDS analysis (line scan) of a Crofer 22 APU / Mn-Co oxide / LNF sample before and after 3000h at 700°C in pure O2

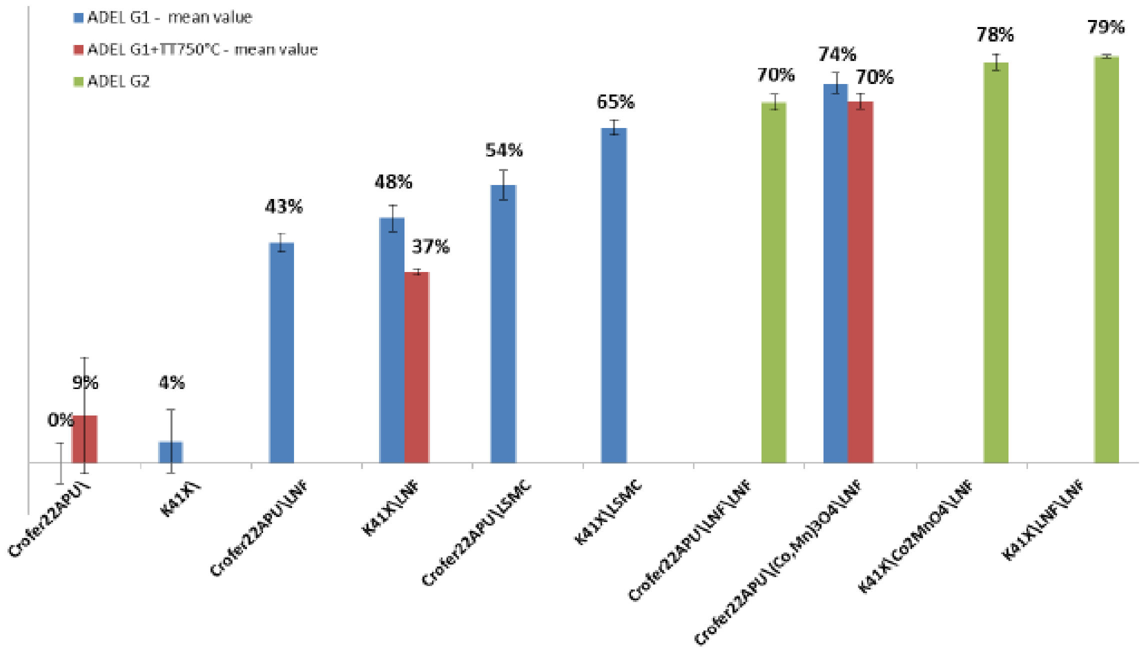


Figure 1-7: Reduction of Cr volatilisation from bare Crofer 22 APU

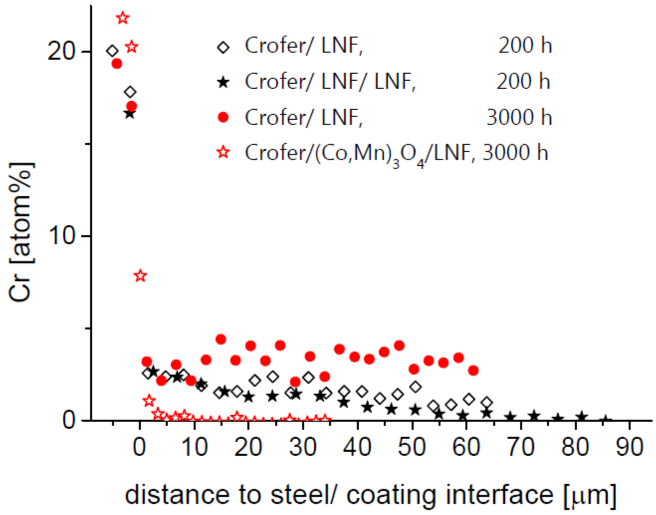


Figure 1-8: Cr content in coatings on Crofer 22 APU substrates after different annealing time in pure oxygen at 700°C

Table 1-1: ASR at 700°C obtained on SoA (GDC-LSCF) and 2G (LSC) symmetrical cells with Mn-Co oxide and LNF as protective and contact coating respectively. Rscell is the ohmic resistance measured by electrochemical impedance spectroscopy (EIS) and RYSZ the electrolyte resistance

O_2 electrode	Electrolyte	1/2 (Rs_{cell}-R_{YSZ}) [$\Omega.cm^2$]
GDC-LSCF	3YSZ	**0.21**
LSC *	3YSZ	**0.04**

* with Au grid 0.03 $\Omega.cm^2$

Sealing

At sealant level, **leak tests** of glass (Schott GM31-107) and ceramic glass (Schott G018-311) seals applied between cells and interconnects were carried out. For instance, Figure 1-9 shows that for an overpressure higher than 200 mbar, the leak stayed below the evaluation criterion for 150h at 700°C. Those results confirmed the usability of the tested seals for ITSE application.

Further, satisfactory tightness was maintained with a glass ceramic sealant (Schott G018-311) under 15 thermal cycles between 800°C and room temperature at small size scale as presented in Figure 1-10. Tightness level wasn't modified by thermal cycles for both different heating/cooling ramps used (10 cycles at 1°C/min and 5 cycles at 5°C/min). The leak increase measured when temperature decreased corresponds to normal thermal evolution of gas properties.

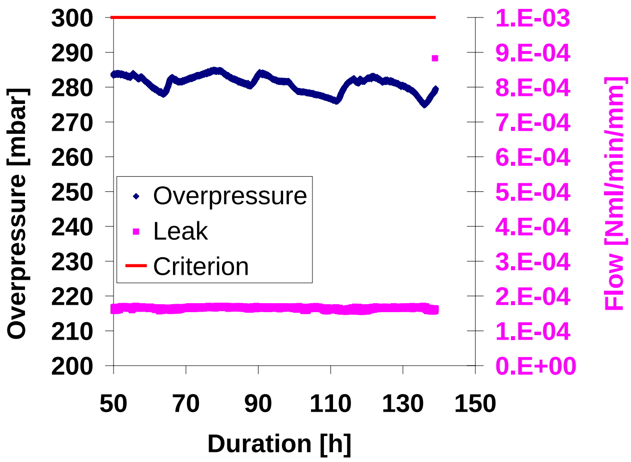


Figure 1-9: Leak evolution with time for an overpressure of 200 mbar at 700°C. The leak criterion of 10-3 Nml/min/mm corresponds to 1% of H2 production

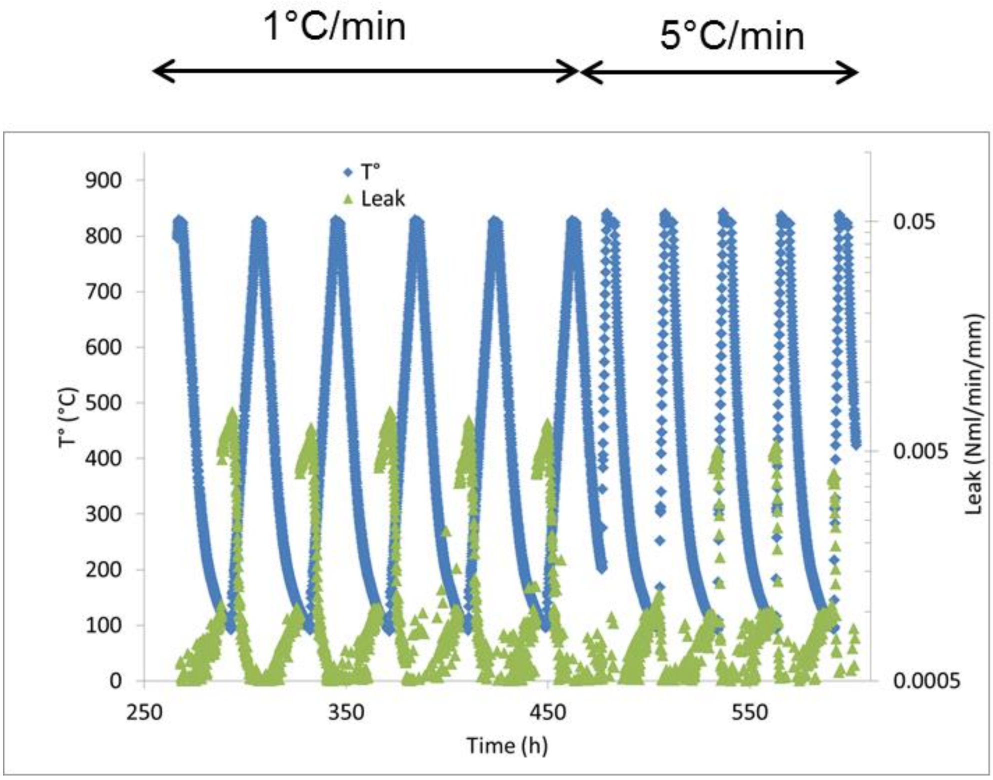


Figure 1-10: Leak evolution with time for an overpressure of 20 mbar between 800°C and room temperature for two different heating/cooling ramps

2G components integration

In ADEL, the most promising components were integrated in SRUs and short stacks as far as possible. Then, 2G contact (LNF) and protective (Co-oxide) layers were tested in a 2G SRU and 2G cells from SP with LSC oxygen electrode being integrated in 2G short stacks for the 2G testing campaign **at SRUs and short stacks level**. Additionally, short stacks from SP were improved through the optimisation of the sealing design and protective coatings.

With 2G cells, **performance** similar to single cells was obtained with an improved SP stack (optimisation of the sealing design and protective coatings). Average ASR achieved 0.59 and 0.74 Ω.cm² at 750 and 700°C respectively. Therefore, this 2G stack could be operated with reasonable current density (-0.6 A/cm² at TNV) at ca. 700°C as shown in Figure 1-11.

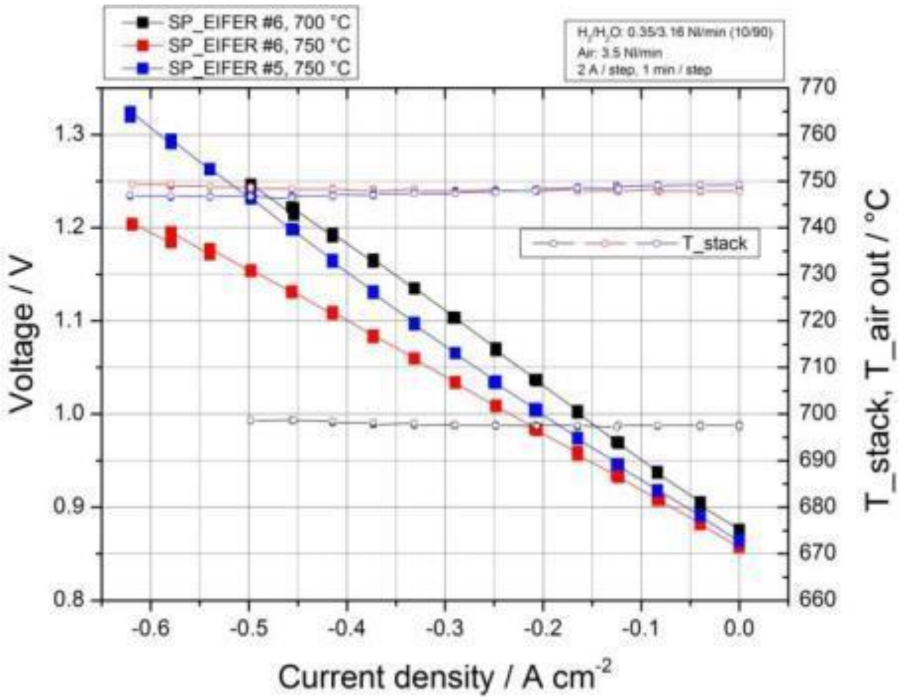


Figure 1-11: Comparison of average iV curves of a 2G SP stack with 2G SP cells (LSC oxygen electrode) and a SoA SP stack with SoA SP cells (GDC-LSCF oxygen electrode)

SRUs and short stacks testing

Concerning the **evaluation of durability under transient conditions**, the good tolerance obtained with the SoA SRU was confirmed with the **2G SRU**: no significant degradation was observed under load cycling with a high speed of current change between OCV and thermoneutral or exothermal voltage respectively. Furthermore, this behavior is maintained under load cycling with a slow speed of current change, resulting in a higher thermal effect (see Figure 1-12).

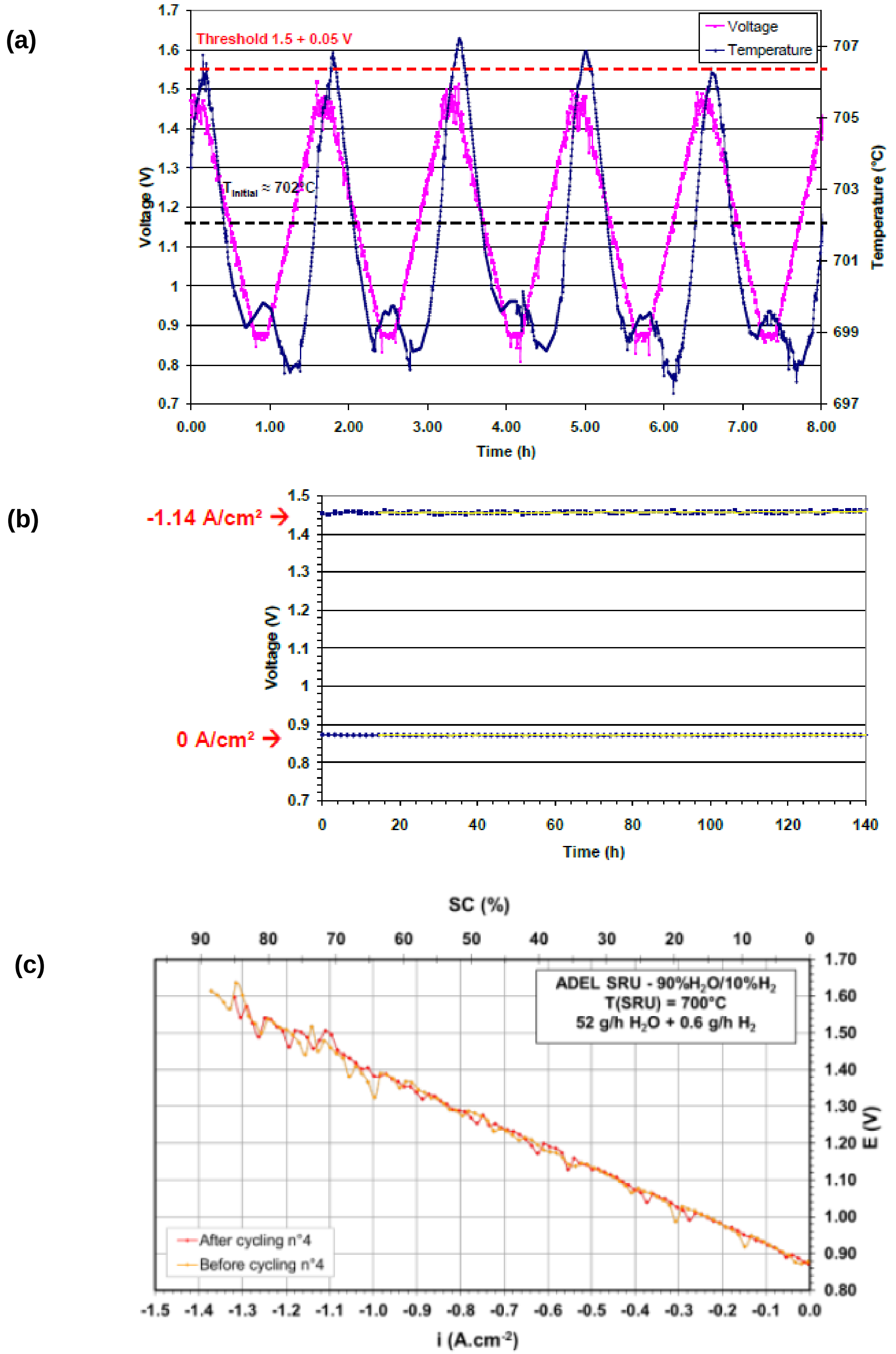


Figure 1-12: Durability under transient operation of a 2G SRU. (a) Thermal effect when cycling between OCV and exothermal voltage (-1.14 A/cm²) with a slow speed of current change (0.5 mA/cm²/s), (b) voltage evolution as a function of time and (c) iV curves before

At short stack level, it seemed that transient operating conditions were more critical probably due to the higher thermal effect in comparison to SRUs. Indeed, three TOFC stacks survived cycling operations with a current density of -0.6 A/cm² (see Figure 1-13 and Figure 1-14) but for two of them, when increasing current density to -0.9 A/cm², increased thermal fluctuation and excessive degradation were observed (see Figure 1-14).

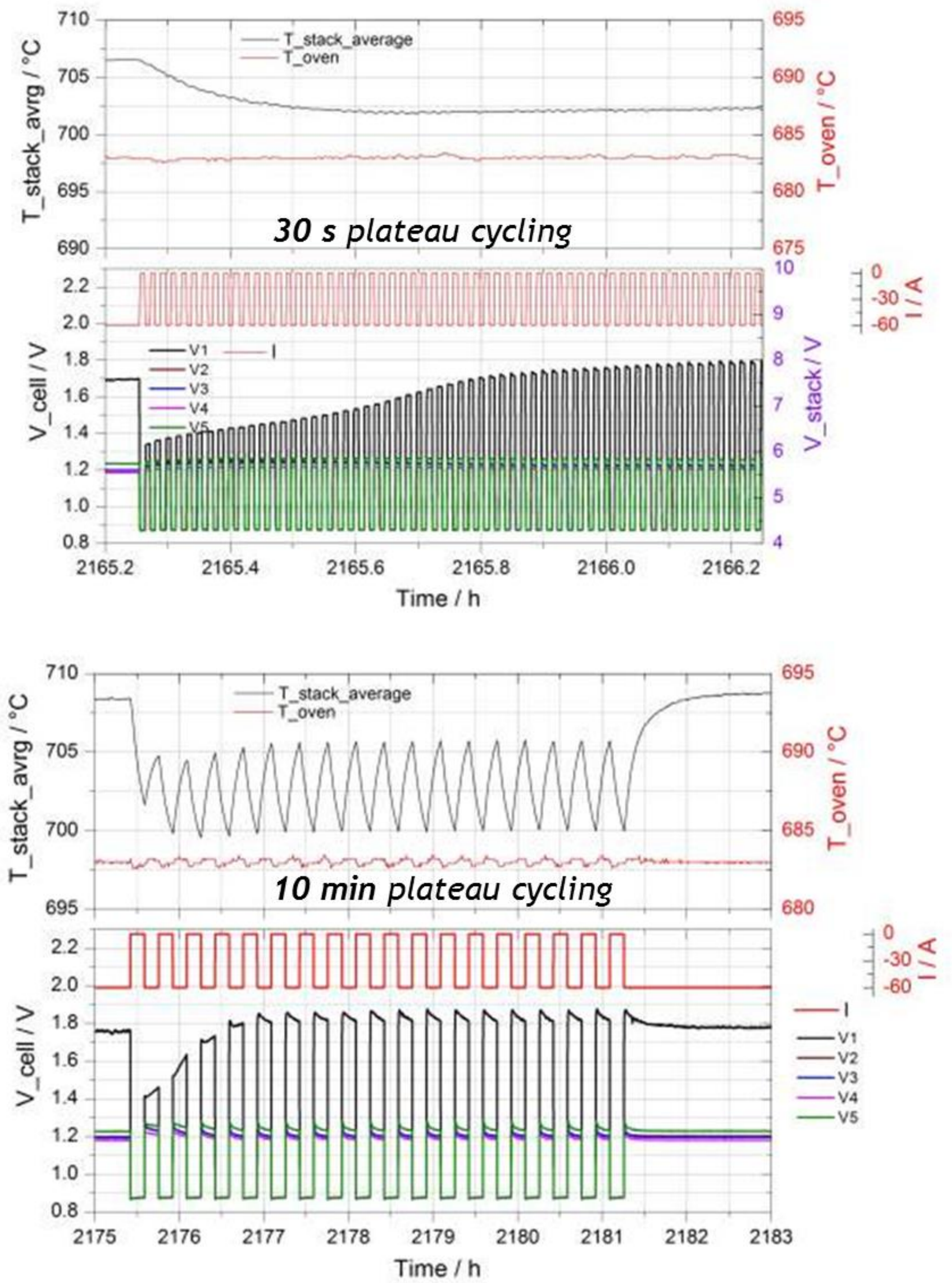


Figure 1-13: Durability under transient operation of a SoA TOFC short stack with FP6-SOFC600 cells.

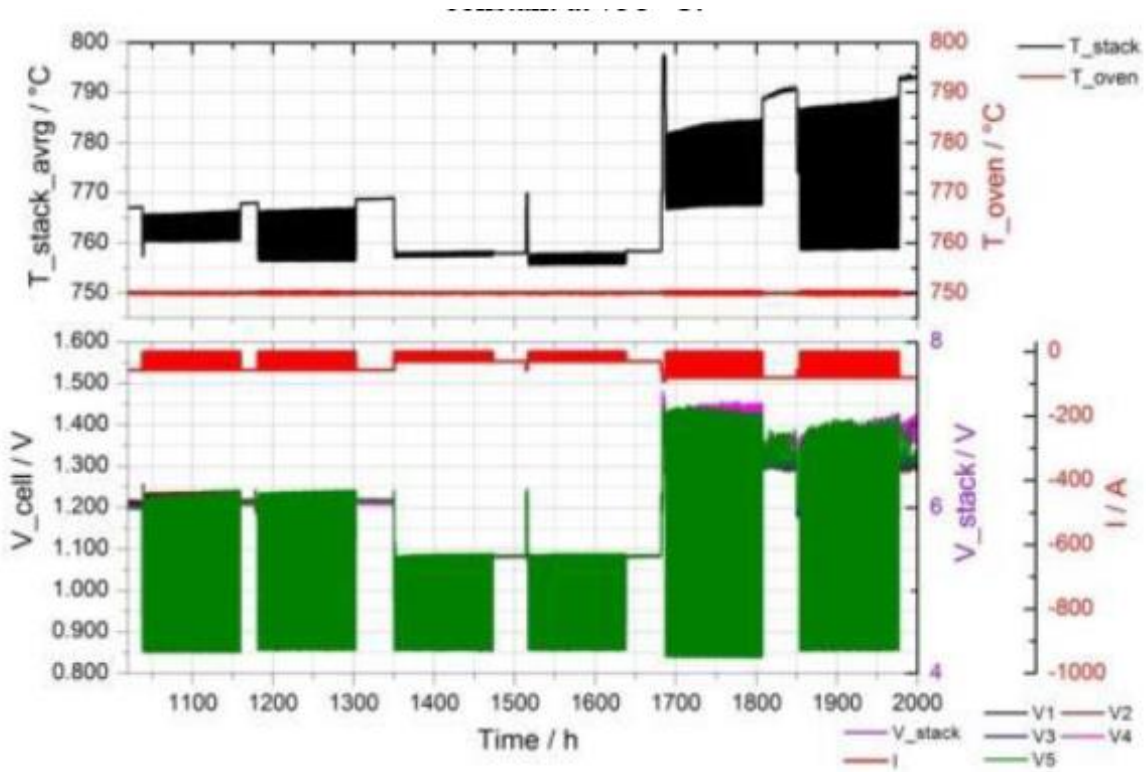


Figure 1-14: Durability under transient operation of a SoA TOFC short stack with SoA SP cells (GDC-LSCF oxygen electrode).

Concerning **evaluation of durability in steady state conditions**, this point still remains the major issue even at intermediate temperature (700°C) and wasn't improved in the second part of the project with 2G components, especially at high current densities. Voltage degradation rate as high as 7%/kh and ASR variation of 70 mΩ.cm²/kh were achieved (see Figure 1-15) at 700°C and -1 A cm^{-2} for a 64% steam conversion rate with a **2G SRU** including 2G contact and protective layers (FP6-SOFC600 cell). Voltage degradation rates of 1-5%/kh were achieved under less severe operating conditions (700°C, about -0.5 A.cm^{-2} and about 30-50% steam conversion rate) for the best cells of **SoA and 2G short stacks** (see Figure 1-16, Figure 1-17 and Figure 1-18).

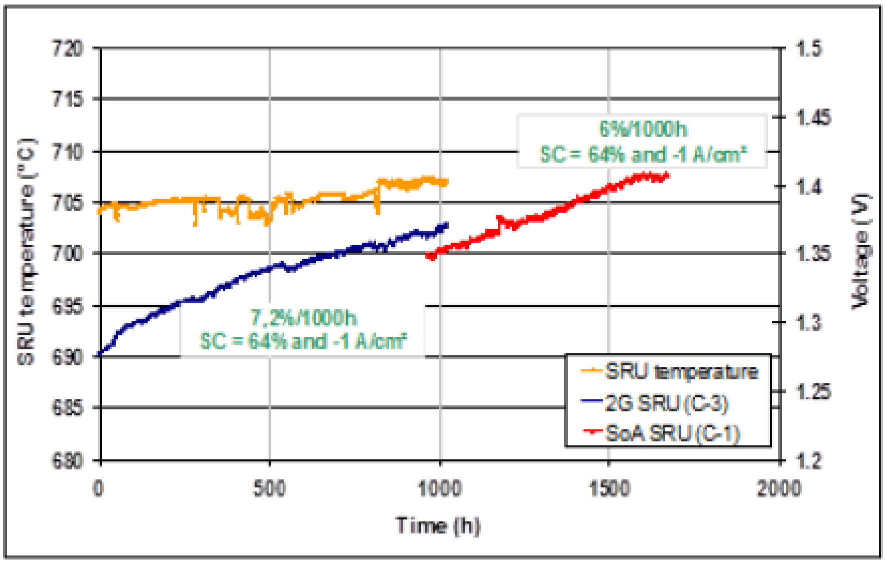


Figure 1-15: Durability measurement of a 2G SRU with 90% H_2O/10% H_2 cathodic gas flow

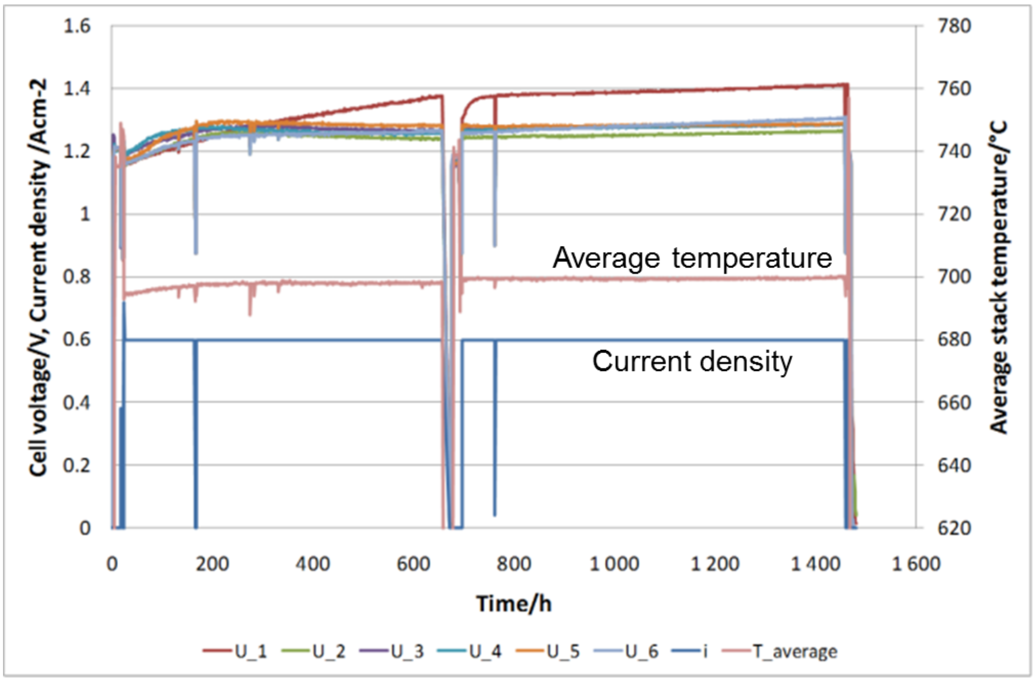


Figure 1-16: Durability measurement of a SoA SP short stack with FP6-SOFC600 cells and 90%H_2O/10%H_2 cathodic gas flow at 700°C, -0.6 A/cm² and SC = 50%.

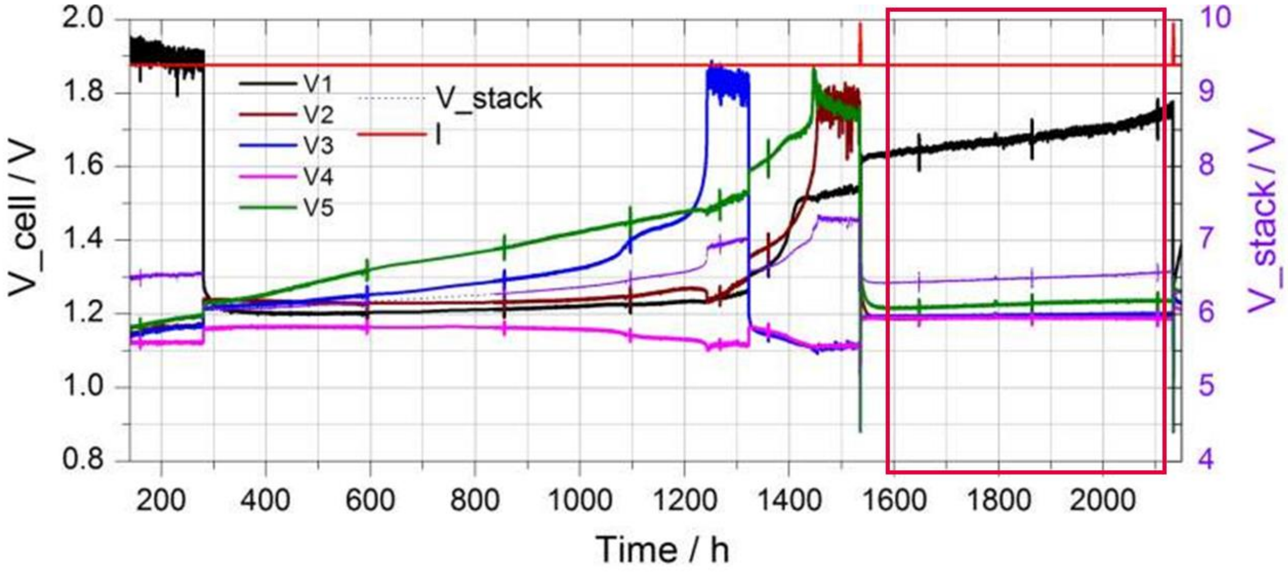


Figure 1-17: Durability measurement of a SoA TOFC short stack with FP6-SOFC600 cells and 90%H_2O/10%H_2 cathodic gas flow at 700°C, -0.6 A/cm² and SC = 50%.

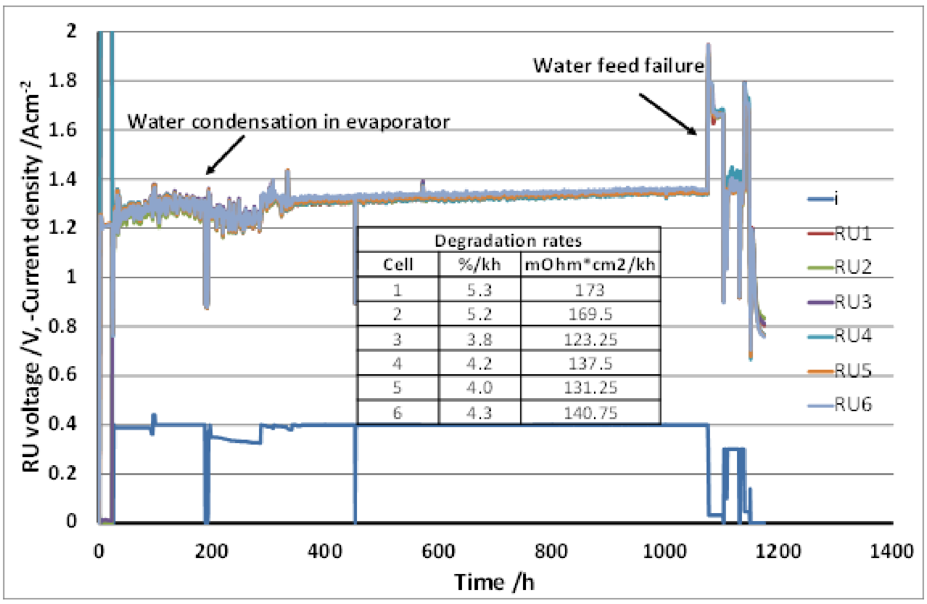


Figure 1-18: Durability measurement of a 2G SP short stack with 2G SP cells (LSC oxygen electrode) and 90% H_2O/10% H_2 cathodic gas flow at 700°C, -0.4 A/cm² and SC = 33%

Post-test SEM examination

Initial and post-test **microstructural characterization** of the cells selected in the ADEL project highlighted the main following phenomena responsible of SOECs degradation (see Figure 1-19):

- a weakening of the electrolyte/Ni-YSZ interfaces,
- an increase of porosity,

both indicating material transport in the Ni-YSZ hydrogen electrode close to the electrolyte.

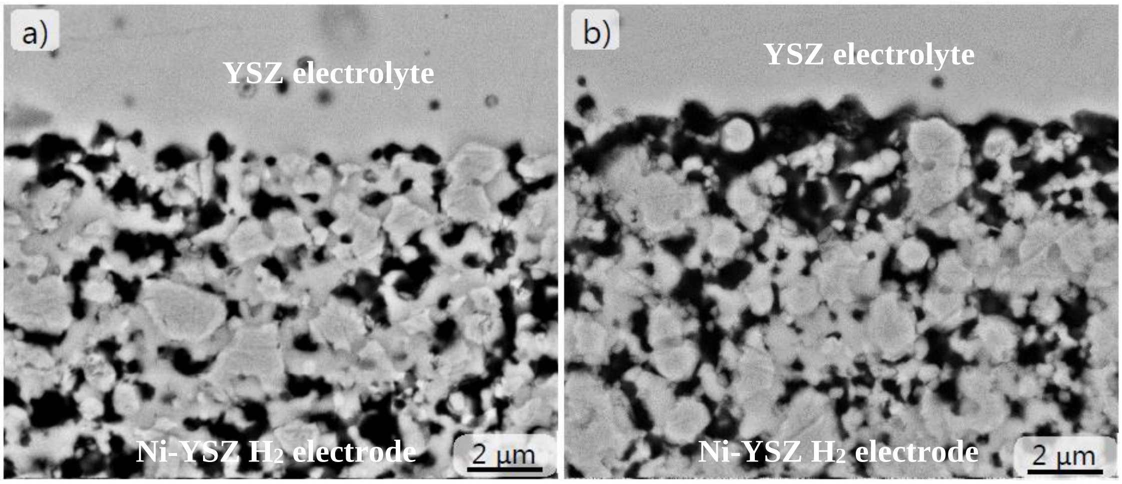


Figure 1-19: YSZ/Ni-YSZ interface of (a) reduced but otherwise fresh SoA SP cell compared to (b) a SoA SP cell tested in a short stack.

This hypothesis is in part corroborated by the smearing of interfaces observed by cross-sectional synchrotron radiation X-ray diffraction.

To conclude on the main S&T results of ADEL WP1 regarding stack component optimisation, electrochemical testing campaigns showed that further stacks development is necessary. Indeed abnormal voltage fluctuations indicating unstable electrical contact in the stacks and particularly at the endplate contact were observed.
Results of the 2G testing campaign completed and confirmed results of the SoA testing and the achievement of the major evaluation criteria defined for the project.
High electrochemical performance was achieved in ITSE operation with an electrode supported cell Ni-YSZ/YSZ/GDC/LSCo from FP6-SOFC600 at single cell, SRU and short stack level as well, using efficient contact coatings of interconnects and efficient sealant. Microstructural characterisation allowed to identify some leads for improvement of 2G cells developed in the project.
Good tolerance to transient operating conditions (load cycling) was demonstrated at both SRU and short stack levels. Though high current densities lead to excessive degradation with short stack due to the higher thermal effect occurring compared to SRU (more difficult dissipation of heat generated by exothermal stack operation), results are very promising for coupling electrolysers with varying renewable energy sources. Longer transient operation has to be tested to validate those results.
The steady-state degradation improved with respect to earlier results but is above the objectives, also in ITSE operation at 700°C, for single cell, SRU and short stack. Also under thermal cycling, when using efficient interconnect protective coatings and efficient sealant, similar results were achieved.
Two main degradation phenomena were proposed at hydrogen electrode, based on microstructural post-test characterisation. Further statistical analyses have to be systematically performed to better understand degradation mechanisms in ITSE operation.

1.3.2 WP2 - ITSE integration and operability

Work Package 2 is a link between the stack technology developers (WP1) and system integrators (WP3). It aims to prospect integration possibilities of the solid oxide electrolysis cell technology into a carbon-free (or carbon neutral) energy system providing heat and electricity. Work Package 2 is divided into three main tasks:

- Task 2.1 Stack integration: ITSE Unit (definition & design)
- Task 2.2 Energy sources
- Task 2.3 Integration schemes of ITSE Unit and Energy Sources

1.3.2.1 WT2.1

The objectives of Task 2.1 were to define the essential components of an ITSE system ensuring safe and stable operation with optimised overall efficiency. Focus was put on the heat and hydrogen recovery and the stability of the operation temperature.

Therefore, a **rigorous solid oxide electrolyser stack model** describing the performance of the stack was developed under the modelling environment gProms and validated using experimental data from WP1. The stack model was then integrated in the **complete ITSE system model** that also included heat exchangers, blowers, pumps, electrical heaters and an evaporator. As stated in the project description, the operating temperature objective for ITSE was initially 600°C to allow direct coupling with C-free heat sources, but it appeared that this temperature was too low according to electrolysis thermodynamics. Therefore, the ITSE operation temperature was finally changed to 700°C. Eight different system variants were compared in the simulations, considering a higher operating temperature (800°C, HTSE), the use or not of air sweep on the anode side of the SOE and the operating cell voltage, either thermoneutral (~1.3V) or exothermal (<1.3V).

It was shown that HTSE provided a higher H_2 yield due to the better performance of the stack at 800°C, but that the efficiencies of ITSE and HTSE were comparable. Operating in thermoneutral mode requires marginally higher specific electric power input than the exothermal mode. The specific heat input is also higher in the thermoneutral mode, most obviously for the ITSE. This is related to the lower steam conversions. Finally, air sweep increases the heat and power consumption.

Based on these results and on the recommendations from WP1, the final reference ITSE system design considered operating the SOE around the thermoneutral voltage, with a steam-to-hydrogen conversion limited to 60% to prevent accelerated degradation and the use of a sweeping air flow but limited to a minimum, to avoid dealing with pure oxygen at high temperature.

The system modelling results were also used for an **economic evaluation**. The figure below (Figure 1-20) shows the decrease of the price per unit at increased overall power showing that economics is more favourable at larger scale with a cost of the electrolyser drastically lower when increased power (above 500 kW). The unit price of the SOE was compared to present alkaline and high-temperature electrolysers. As it can be seen, the unit price of the HTSE/ITSE is comparable to the HYDROGENICS and Statoil alkaline systems.

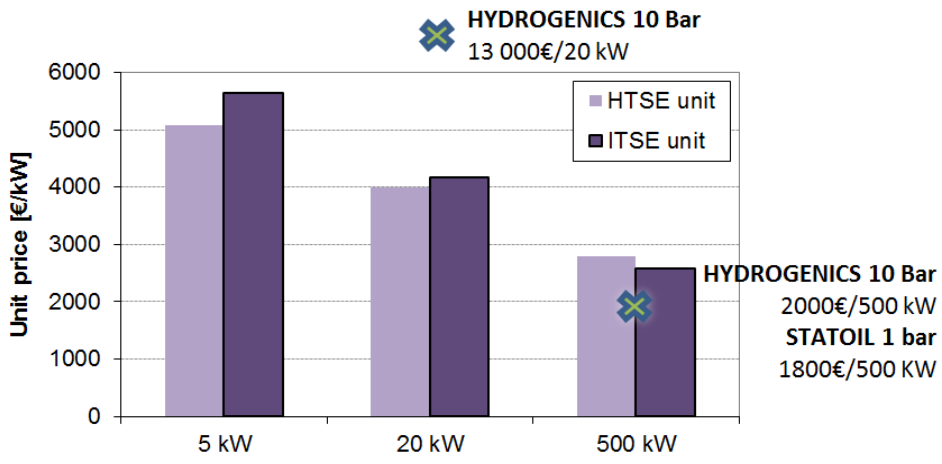


Figure 1-20: Impact of unit size on the price of a unit

Table 1-2 gives a comparison between the efficiencies (expressed in kWh/Nm^3 of produced hydrogen) calculated by the system model and that of concurring low temperature electrolysis technologies. The electrical consumption per cubic meter of hydrogen is remarkably lower (3.5 kWh/Nm^3) than competing technologies (4.5-5.8 kWh/Nm^3 for Alkaline and 5.4-6.7 kWh/Nm^3 for PEM).

Table 1-2: Comparison of the efficiency of different electrolysis systems (source: website of companies)

Company	Technology	kWhe/Nm3(H_2)	Pressure
AccaGen SA	Alkaline	5	20 bar
AccaGen SA	Alkaline	5.2	30 bar
IHT	Alkaline	4.65	32 bar
PIEL	Alkaline	5.25	4 bar
PIEL	Alkaline	5.86	18 bar
Hydrogenics	Alkaline	4.9	10 bar
Hydrogenics	PEM	6.7	8 bar
Proton	PEM	5.8	30 bar
Giner	PEM	5.4	85 bar
ADEL	SOEC	3.4	atm.
ADEL	SOEC	3.5	30 bar

The **coupling of the ITSE system with intermittent energy conversion systems (solar, wind)** requires to study its dynamic behaviour under variables load, in particular for peak shaving and distributed applications. Therefore, a test protocol with operation at partial load, voltage variations and current density ramps/switches/plateaus was first written and implemented in the SOE testing (WP1). Based on the feedback of the preliminary cycling tests and on the prior performance and economic simulations, the ITSE system model was adapted (as displayed in Figure 1-21) and used for the development of basic control algorithms.

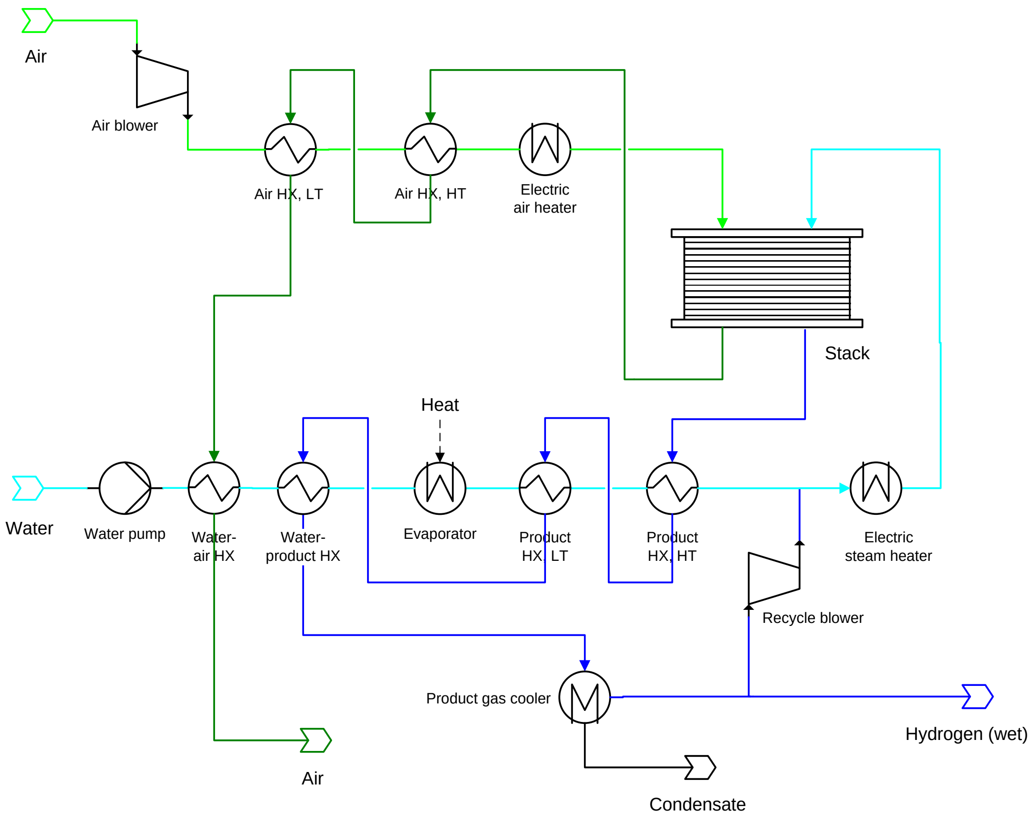


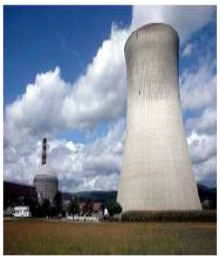
Figure 1-21: Process flow diagram of the ITSE unit model used the development of the control algorithms.

It was shown that control action to maintain the stack temperature in the appropriate range is solely required when the power load goes below 60% of the nominal power input. In this case, the steam conversion (thus the steam flow rate) provides a possible means to control the stack outlet temperature when the power varies. Depending on the specific application, the steam/air ratio (thus the air flow rate) may be varied simultaneously; this may be optimised depending on the relation between heat and power availability for each specific application.
Regarding an “Idle Mode”, it has to be noted that a full-scale electrolyser system will probably consist of several parallel sub-systems. Turning up/down power is then realized by switching on and off several of these sub-systems. This significantly reduces the turn-down of each individual stack, potentially to a range of 60-120% of nominal power for a very large system. Finally, for the switching-off of stacks, it is preferred to maintain the stacks in a hot stand-by mode rather than performing thermo-cycling. This requires passing hot steam through the stacks and, to prevent re-oxidation of the cathode, drawing a minimal current.

1.3.2.2 WT2.2

This task, **Energy sources**, was dedicated to the identification of available energy conversion technologies able to deliver heat and electricity to the ITSE. In a first step, the analysis of the available energy sources in order to assess their compatibility with the ITSE unit was done while in a second step, options for hybridisation of the energy sources were inspected and the possible technologies for flow diagrams development were selected.
The selected energy conversion technologies for coupling with an Intermediate Temperature Steam Electrolyser were solar, nuclear, wind and geothermal technologies (cf. Figure 1-22).

Solar energy



Nuclear energy

Wind energy

Geothermal energy

Figure 1-22: Available energy conversion technologies analyzed.

Options for hybridization of the energy sources for managing the heat and electricity fluctuations were analyzed for three scenarios of applications treated in WP3:

- Scenario 1: full dedicated production of H_2 from ITSE with a stable (continuous) energy source for industrial applications
- Scenario 2: grid management with peak shaving
- Scenario 3: production of H_2 from ITSE for smart management of distributed generation systems

The different options selected for each scenario are listed in Table 1-3 and have been analyzed in detail in WP3.

Table 1-3: Summary of scenarios and technologies for simulation in WP3

Scenario	Technology	Hybrid options	Code	Partner
Firm capacity	Nuclear PWR Generator	No or through grid	EcosimPro	EA
Dispatchability and management of demand	Air Volumetric Solar Central Receiver Systems with medium size TES	No or through grid	Aspen	DLR
	Solar Thermal Direct Steam Generation with and without TES	No or through grid	Trnsys	IMDEA
Distributed Generation and micro-grids	Wind	Wind+Biomass	Aspen	DLR
	Photovoltaics and/or Wind	PV/Wind+Biomass	Ebsilon	IMDEA

1.3.2.3 WT2.3

This task has covered the identification of potential schemes of integration of the selected energy sources with the ITSE systems. It was carried out in close coordination with the activities and outcomes obtained in Task 2.2, where the energy conversion technologies were selected, and Task 3.1, where flow sheeting of appropriate systems has been elaborated. The main objective of this task was the review of technology-related issues associated to the formulation of realistic schemes of integration of the different energy sources with the electrolyser.

Energy conversion technologies defined in Task 2.2 were treated with their respective heat transfer fluids for elaborating a conceptual definition of the components involved in the different processes. A sizing and the assessment of processes components was carried out taking into account technical datasheets. The scope of the work was limited to the main components of the processes, in particular the heat exchangers, since a more concrete component sizing has been performed in WP3 for the demonstration cases. The main conclusions for the integration schemes are listed in the following table (Table 1-4) for each energy technology.

Table 1-4: Energy technologies with their specific heat transfer fluids and main conclusions for the integration schemes

Energy source	Heat transfer fluid	Partner responsible /Energy Technology	Main observations/conclusions
Nuclear	Helium,S-CO_2,liq. lead, steam	EA (different types of nuclear reactors)	PWR defines a specific steam pressure and temperature conditions from which the thermal energy is obtained and determines the energy process from the nuclear power plant to the electrolyser.
Solar thermal	Molten salt Steam	IMDEA (solar tower) Abengoa Hidrógeno (parabolic trough) IMDEA (Solar tower, linear Fresnel)	Direct steam generation in central receiver system uses water as hot temperature fluid. This generates steam directly into the receiver later sent to steam turbine to produce electricity. Two different solar plant scales were studied: 10 and 50 MWe solar power plants. Two SOEC units of 2.5 MWe into the 10 MWe solar plant and three SOEC units of 10 MWe into the 50 MWe DSG-CRS plant were integrated.
Solar thermal	Air /gaseous media	DLR (solar tower, dish)	The solar tower technology with air as heat transfer fluid was analysed by elaborating a flow sheet of the air cooled solar tower coupled to the ITSE unit.
Biomass /Solar	Steam	IMDEA (PV + biomass combustion with steam cycle)	The integration of the electrolyser into a hybrid power plant, combining biomass combustion and photovoltaic panels was described. A directory of steam raising boilers was presented. It was shown that an appropriate boiler should be low pressure fluidized bed gasifiers. Due to the required steam conditions, a fluidized bed boiler should be selected and it has to be aquotubular (pipes-walls). Current state-of-the art technologies can be used but a specific design by the manufacturer of the steam boiler might be better.
Biomass /Wind	Steam	DLR (Wind turbine + biomass combustion with steam cycle)	This process of coupling ITSE unit with wind and biogas energy has been analysed for producing methane as green fuel. Biogas obtained from solid biomass gasification was used in the boiler. Biogas combustion was done through a hot gas generator. The gas stream might be split in three hot currents. The heat coming from the highly exothermic methanation reaction was used for the production of steam fed to the electrolyser.

1.3.3 WP3 - H_2 plant flow sheeting and case studies

One of the main goals of WP3 was the analysis of the performance under nominal conditions of selected carbon-free energy technologies defined in WP2 (cf Table 1-4). This also included the design of the ITSE Unit, coupling the electrolyser with suitable balance-of-the-plant units. The evaluation was done to identify realistic cases to be studied in more detail in the last part of the project. The performance of the ITSE Unit has been analysed and the layout optimized. It was concluded that the following components should be integrated in the balance-of-the-plant: water treatment/conditioning facilities, drying units to remove water from the hydrogen product and hydrogen compressor, required for storage and for transport of hydrogen.

Further analysis was carried out to investigate the energy conversion technologies coupled to the ITSE unit regarding the site selection, the definition of the boundary conditions and the possible applications of the generated hydrogen. The following table summarizes the energy technologies and its specifications, the defined scenario for each technology, and the selected site of the proposed Hydrogen Production Plant.

Table 1-5: Site and specifications for the selected technologies

Scenario	Technology	Hybrid options	Specifications	Electricity generation	Heat generation	Site	Hydrogen applications
Firm capacity	Nuclear PWR Generator	No	- PWR: 800 MWth, 790.6 MWth for electricity production, 9.4 MWth for heating purposes	PWR reactor	PWR reactor	Vandellós / Tarragona (Catalonia, north-east of Spain)	Chemical and petrochemical industry
Dispatchability and management of demand	Solar tower with Air, with TES	No	-Electricity generation: 10-40 MW_{el} Reflective area of each heliostat: 120 m^2	Volumetric air receiver	Volumetric air receiver	Almeria (Andalusia, south of Spain)	Hydrogen refuelling station (e.g. fuel cell driven vehicles)
	Solar tower with Steam, with and without TES	No	-53.11 MWth and 246 MWth -Reflective area of each heliostat: 120 m^2	DSG receiver	DSG receiver	Seville (Andalusia, south of Spain)	-During peak hours: Storage of surplus energy or Hydrogen refuelling station - During demand peak hours: Use in a fuel cell
Distributed Generation and micro-grids	Photovoltaic	Biomass	-Electricity generation: 4.5 MWel	PV and biomass	Biomass	Huelva (Andalusia, south of Spain)	Hydrotratment e.g. Hydrodesulfurization
	Wind	Biogas	Electricity generation: 10 MW_{el}	Wind and biogas	Biogas	Niedersachen /Schleswig-Holstein (North of Germany)	Methane and Methanol production

Detailed flow-sheeting and systems analysis for selected schemes of integration of ITSE in different CO_2-free energy plants have been performed. The following power levels and cases have been considered for the individual technologies:

- Nuclear power → 200 MW, using an ITSE of 20 MW
- Solar Tower Plants → 10 and 50 MW (ITSE Unit of 1/3 to full power, which corresponds to 3-15 and 10-50 MW respectively)
- Biomass + PV → 4.5 MW, using an ITSE Unit of 2.5 MW

- Biomass + Wind → 10 MW power plant

The completion of the analysis included an economic assessment of the energy conversion technologies analysed. The numbers obtained are highly dependent on the following concepts:

- Price of the bulk hydrogen: 5.0 €/kg
- Cost of the electric energy taken from the grid: 89.03 €/MWh, taxes included.
- Price of the electric energy injected in the grid: 80.13 €/MWh. The value considered is slightly higher with respect to the current prices from conventional sources. One more real figure could be 50 €/MWh. This value has been considered to be consistent with the purchase price.

The economic assessment of the air cooled solar tower, the direct steam generation plant and the nuclear power plant lead to an average hydrogen production cost of 9.8 €/kg. But the analysis of the investigated technologies also revealed the potential to further reduce the hydrogen production cost and to achieve sales prices of less than 5 €/kg.

In the cases considering a solar energy source, the optical and thermal losses of CSP systems can still be reduced. E.g. the air cooled solar tower investigated in the ADEL project is a fail-safe concept that has proven operation in Jülich (Germany). The solar to electric efficiency as well as the solar to fuel efficiency calculated in the ADEL project is considered quite low for CRS systems – thereby providing a conservative efficiency calculation. This is due to the relative low receiver performance of the current state-of-the-art volumetric receiver systems, which are operates at lower temperature and pressure. Efficiency improvements should first concentrate on the receiver and the air circuit. This can be achieved by using pressurized air receiver, which is operated at higher temperature and pressure that the open volumetric receiver and accordingly the efficiency will be significantly improved. Besides the receiver, thermal storage is a key component for the performance and economic profitability of the CSP plants. The reliability of the components employed in the thermal energy can be increased as well. Within the economic analysis performed for the solar cases, it is concluded that the heliostats costs represent about 30-40% of the initial capital investment of the solar part of the plant by taking into account a price of 120-140 €/m² according to the state of the art. The development of low cost heliostats fields for less than 100 €/m² is the focus of many industrial companies so that total investment capital of CSP plants could be significantly reduced. Concerning the electrolysis process, the economic analysis has shown that the ITSE stacks are currently still expensive, but it is expected that costs will go down significantly when the technology matures and production volumes increase. Moreover, the durability of the ITSE stack is targeted to be increased by reducing the degradation rate. Finally, it is concluded that the pressurization of the ITSE stack (15-30 bar) will be very advantageous since it will reduce the cost of the ITSE stack and avoid the use of compressors for the compression of the hydrogen product. By taking into consideration the aforementioned aspects, it appears feasible and possible to decrease the hydrogen production cost down to less than 5 €/kg.

The following table gives an estimation of the hydrogen production cost from the different technologies, assuming NPV=0€:

Table 1-6: Estimation of the hydrogen production cost for different technologies (NPV=0€): nuclear power plant (NPP), solar tower with air-cooled volumetric reciever (VRS) or direct steam generation (DSG-CRS), and hybrid biomass and photo-voltaic (bio+PV) plant

Case	H_2 cost (NPV=0)/€kg^{-1}
NPP	6.05
VRS	7.67
DSG-CRS	16.01
Bio+PV	6.69 (15229 m^2 panels) 6.67 (33333 m^2 panels)

Finally recommendations for a demonstrator plant were elaborated. This provides the basis for the definition and specifications of the main components for a demonstration unit. The case selected was an ITSE system coupled to the air cooled solar tower in Jülich, Germany. The demonstrator represents a complete system, including all relevant balance-of-plant components and is considered to be integrated in the research platform of the solar tower of Jülich working with air as heat transfer fluid.
A scale of 15-20 kW was defined for the demonstrator which represents a compromise with respect to the status of the electrolyser development and the state-of- the-art size of the energy source and BoP components. The demonstrator is made up of two parallel subsystems, each containing two stacks. Each of the two subsystems has its own Balance of Plant. At the proposed scale size, it is possible to realistically investigate the turn-down ratio and the system dynamics. Having two parallel subsystems enables switching between operation and idle mode, as well as testing part load and full load operation, and exploring different operational strategies. Moreover, start-up and shut-down scenarios can be simulated. A simulation of the demonstration plant was carried out and lead to a hydrogen production of 0.524 kg/h. Also a design study of an ITSE stack coupled to the air solar tower of Jülich was done. The design consists of the use of the air solar receiver for the generation of hot air, which acts as sweep gas. A tubular receiver was considered to be installed on the solar tower in order to evaporate the ITSE feed water.

The results of this project build a solid base for targeted continuation of high temperature electrolysis. The very high energy transformation efficiency and the cycling tolerance of the stack open opportunities for integration in the new emerging energy scene. The challenges to be overcome are the insufficient durability and still too high cost. The realisation of a demonstration site as described would be meaningful as practical experience in view of technology scaling and integrated operation in the energy field.

1.4 Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results.

1.4.1 Potential impact

The ADEL project has progressed in the development and analysis of Intermediate Temperature Steam Electrolysers (ITSE) as a particular case of High Temperature Electrolysis. This section highlights the potential impact of this technology in general, taking into account the specific insights gained during ADEL.

The **main achievements** of the ADEL project are:

- The demonstration of **high performance** SOE technology, **compatible with intermittent power sources**, with a reasonable durability.
- Detailed modelling of an intermediate temperature electrolyser system (ITSE) and development of control strategies for coupling with intermittent renewable power and heat sources.
- Detailed flow-sheeting of complete H_2 production plants coupling ITSE with renewable heat and power sources, and cost analysis of the most promising combinations.
- The specifications of a demonstrator coupling an ADvanced ELectrolyser with a solar tower.

A better understanding of the technical and energetic strengths and weaknesses of High Temperature Electrolysis was gained during the project. Valuable application opportunities were identified. In particular, the following **features** of High Temepratture Electrolysis were put forth:

- Very efficient H_2 production technology compared to conventional electrolyser technologies and steam reforming of natural gas; this is particularly the case when a (waste) heat source is available for steam generation.
- A good compatibility with intermittent power sources: the electrolyser stacks tolerate rapid load cycling without additional degradation.
- High capital costs, mainly due to the limited life-time of the SOE, resulting H_2 production cost not yet fully competitive.

An important conclusion of the ADEL project is that the allothermal heat source is mainly required for steam generation; a high temperature coupling provides only marginal efficiency gains, against much increased complexity and cost for such an Electrolyser. Operating the High Temperature Electrolyser simply from steam earns most benefits already. Eliminating the need for very high temperature sources to achieve very high efficiencies results in a wide choice of compatible (waste) heat sources that can be considered for the thermal coupling. Therefore the geographical distribution of suitable locations for High Temperature Electrolysis is beyond the original expectations.

According to the specific features listed above, the selection criteria for the **early niche applications** will favour cases with a high load factor, as the capital cost are still high and need to be amortised.
On-site hydrogen production for industrial applications (e.g. chemical, petrochemical and glass industry) is particularly interesting, especially when waste heat can be valued for steam generation. On-site production of hydrogen at the point of use is expected to reduce the CO_2 emissions up to 70% compared to conventional large scale centralized steam reforming.
On-site hydrogen production for **vehicle fuelling-station** (either battery driven vehicles with fuel cell range extenders, or directly by fuel cells or internal combustion engines) is another promising

application. Different scenarios predict a transition period from carbon based automotive fuels to hydrogen with small tank stations. Those tank stations will be best supplied with hydrogen by local production (either at the tank station itself, or close by where the natural resources allow optimal production), preferably using renewable sources. Decentralised High Temperature Electrolysis can build an intermediate step during the build-up of a hydrogen distribution infrastructure, avoiding the construction of heavy infrastructure of hydrogen distribution in a transition phase.

Grid balancing within the daily time-scale might not be the most appropriate application for High Temperature Electrolysis since Smart Grids present a strong alternative. Though the electrolyser stacks as such cope well with very short time constants of change, the associated systems for steam provision and gas separation have a higher inertia of response.

High Temperature Electrolyser can, temperature-wise, be coupled advantageously with methanation, in which the hydrogen reacts with CO_2 to form methane and steam. This process is particularly suitable for **power-to-gas** and **biogas upgrading** (increase of the methane content and decrease of CO_2 by methanation) and contributes to the mitigation of CO_2 emissions. This basically corresponds to a change in paradigm from carbon capture and storage (CCS) to carbon capture and cycling (CCC). Thereby, excess electricity produced by intermittent renewable power sources can either be used for fuelling vehicles (intermode energy switch from electricity to mobility) or stored (seasonal electricity storage). Power-to-gas is expected to reduce the load on the electrical grid, in particular for seasonal balancing. Though this option today is economically not viable on its own, it clearly offers a solution to circumvent the political barriers for building new electrical highways over long distances. In Germany, though economically and technically viable, it seems politically impossible to connect areas with very high share of renewable power in the grid to the actual areas of electricity consumption, i.e. from the shores of the North Sea to the industrial centres in the South. However the gas grid does not see any capacity limitation and offers still large reserves for energy transportation. The building of large scale High Temperature Electrolysis plants close to the production centres of renewable power would strengthen the complete energy system and thereby also enable a larger overall share of renewable power in the grid. Whether High Temperature Electrolysis can contribute to this is strongly dependent on external elements such as legislation and the will of increasing autonomy than pure economics and technical features.

In the light of the above considerations, it can be stated that the ADEL project enters fully in the **Europe energy and environment policy**. European energy dependence is steadily rising with perspectives of reaching around 70 % of the Union's energy requirements in the next 20 to 30 years, compared to 50% today. Moreover, imported products come from regions threatened by political instability, with prices liable to large and frequent variations. In addition to this energy dependency, major environmental threats hang over our climate[1]. Europe, along with other industrialised continents or countries in the world, has already set the example by adopting an ambitious policy for a lean and ideally a CO_2 free energy production and use. Therefore, the European policy has defined a series of strategic goals summarised as follow:

- 20% reduction in greenhouse gas emissions compared with 1990 levels.
- 20% share of renewable energy sources in the energy mix.
- 20% reduction in primary energy use.

High Temperature Electrolysis would contribute to the first goal by **partial substitution of fossil fuels** by hydrogen or synthetic NG produced from renewable power sources, in particular by replacing steam reforming from NG or coal. However, in terms of cost-competitiveness, H_2

[1] Green Paper and Annex to the Green Paper of 08 March 2006 « a European Strategy for sustainable, Competitive and secure Energy »

production from High Temperature Electrolsis strongly depends on regulation, especially if the C-tax is low. If CO_2 cost is high, H_2 or synthetic NG could become competitive with conventional NG, thereby reducing strategic dependencies towards foreign regions.

High Temperature Electrolyser can be seen as an **electrical energy storage** process since it enables to convert electricity into a chemical product, either hydrogen or methane through methanation, or liquid fuels through Fisher-Tropsch synthesis. Chemical storage of electricity is particularly suited for seasonal storage because of slow discharge time-scale, large storage capacity and high energy density. Seasonal storage enables, for instance, the utilisation in winter of the excess PV electrical power produced during summer, thereby enabling an increase of the renewable energy share in the energy mix. This also holds true for the biogas upgrading.

Finally, seasonal electricity storage also permits a reduction in primary energy use by reducing the need for power production from fossil fuels in the winter season.

The development of an industry around large scale electrolysis process will provide jobs and create a new industrial value chain within the EU. Cost reduction synergies are expected from the emerging SOFC industry; with the establishment of several high temperature membrane reactor technologies, a spill-over effect for such applications to the refining industry is also expected. The main effect for the up-stream petrol industry will be to increase the energy efficiency (replacing thermal separation processes with selective membrane processes) and a broadening of the range of suitable raw materials that can enter refining process due to the highly selective process provided by the membranes. Overall, High Temperature Electrolyser as membrane reactor technology contributes to Europe's overall competitive position in the global race for resources, by increasing its autonomy and flexibility.

1.4.2 Dissemination activities

The activities on dissemination are concentrated onto three main areas:

- Set-up of a **public website** and an identification kit, composed by the project logo, flyer, posters and a general presentation of the project.
- Elaboration of a **Dissemination and Exploitation Plan**.
- Scientific and technical dissemination via communications to **conferences, workshops and symposia**.

Development of the project website and elaboration on the Dissemination and Exploitation Plan were accomplished during first reporting period. Therefore, during this second period, most of the effort was concentrated on the dissemination in conferences and journals.

The **public website** was developed according to the programme schedule and already by Month 2 it was fully operational at www.adel-energy.eu. During the project the website has been maintained by ACCEL and several improvements have been implemented. The website has been a dynamic and efficient tool for public dissemination of the project and related events. The welcome page provided visual information on the project and highlighted events. The contents included the technology to be developed; application areas for the novel ITSE technology; the ADEL consortium including an individual profile for each organization; the latest news about the project; relevant events in the field of hydrogen and sustainability; media information such as press releases or images and all possibilities to contact the representatives of the ADEL project.
Main improvements during this period have been the implementation of an Event Management Tool and the improvement of the collaborative working space at the extranet (members zone). The EMT allowed easy recording & tracking of ADEL-related participation in conferences and other advocacy events, and the access for individual editing by partners after logging on to the ADEL

extranet, as well as easy & intuitive use (very similar to Excel) through smartsheet-technology with the option to attach applicable documents (e.g. abstracts, flyers). Detailed documentation on how to use the Event Manager Tool and how working in the collaborative working space was compiled in a Member Area Manual. All these improvement facilitated the direct upload of contents and information of events directly from partners.
The website was enriched with information about the ADEL declared participation in the Generation IV International Forum - Very High Temperature Reactor system - Hydrogen Production and links to New Energy World Industry Grouping (NEW-IG), esp. regarding Hydrogen Transport and refuelling infrastructure.

Figure 1-23:Promotional video of ADEL project sent to JU FCH for dissemination.

The download area contains a specific folder with project logos, ppt templates for presentations and several posters and leaflets describing the work programme and outcomes of the project. Thus a corporate identity as formed as outlined in the Dissemination and Exploitation plan. The Plan identifies target groups among industry, politics, science and general public, and defines specific communication goals, benefits and risks. Dissemination towards the FCH JU has been also planned. During this period ADEL project results were presented at the JU FCH Programme Review Days in November 2013. A project video entitled “ADEL: application scenario N°1: hydrogen re-fuelling station” was elaborated and projected during the 2nd International ADEL Workshop in Ajaccio in 2013 and sent to JU FCH for dissemination.

Regarding dissemination in **journals**, the following list compiles some relevant publications from ADEL project:

- ✓ J.Mougin, A.Chatroux, K.Couturier, M.Petitjean, M.Reytier, G.Gousseau, F.Lefebvre-Joud. High temperature steam electrolysis stack with enhanced performance and durability. Energy procedia, 29 (2012), p.445-454.
- ✓ F. Petipas, A. Brisse, Ch. Bouallou. Model-based behaviour of a high temperature electrolyser system operated at various loads. Journal of Power Sources, Volume 239, 1 October 2013, Pages 584–595.

- ✓ F. Petipas, Q. Fu, A. Brisse, Ch. Bouallou. Transient operation of a solid oxide electrolysis cell. Int J Hydrogen Energy 2013, 38: 2957-64.
- ✓ Roeb M., Monnerie N., Houaijia A., Sattler C., Sanz-Bermejo J., Romero M., Canadas I., Drisaldi Castro A., Lucero C., Palomino R., Petipas F., Brisse A. (2013) "Coupling Heat and Electricity Sources to Intermediate Temperature Steam Electrolysis". Journal of Energy and Power Engineering, 7 (11) 2068-2077.
- ✓ S. Diethelm, J. Van herle, D. Montinaro, O. Bucheli (2013) "Electrolysis and Co-Electrolysis Performance of SOE Short Stacks". Fuel Cell, vol 13, iss. 4, pp 631-637.
- ✓ Sanz-Bermejo J., Gallardo-Natividad V., Gonzalez-Aguilar J., Romero M. (2014). "Comparative System Performance Analysis of Direct Steam Generation Central Receiver Solar Thermal". Journal of Solar Energy Engineering. Vol. 136 / 010908-1
- ✓ Sanz-Bermejo J., Gonzalez-Aguilar J., Gallardo-Natividad V., Romero M. (2014). "Coupling of a Solid-Oxide cell unit and a linear Fresnel reflector field for grid management". Energy Procedia (Elsevier). Accepted.
- ✓ Sanz-Bermejo J., Muñoz-Antón J., Gonzalez-Aguilar J., Romero M. (2014). Optimal Integration of a Solid-Oxide Electrolyser Cell into a direct steam generation solar tower plant for hydrogen production. Applied Energy (Submitted)
- ✓ Roeb M., Monnerie N., Houaijia A., Sattler C. (2014) "Coupling of wind turbine and biogas energy with an Intermediate Temperature Steam Electrolyser for Methane Production“ Journal Green and Sustainable Chemistry. Submitted.

Dissemination in **conferences and symposia** from ADEL project:

- ✓ O. Bucheli, F. Lefebvre-Joud, A. Brisse, M. Roeb, M. Romero (2011) "Advanced electrolysers for hydrogen production with renewable energy sources" Europen Fuel Cell Forum 2011, 28 June-1 July 2011, Lucerne, Switzerland.
- ✓ K. Couturier (2012) "ADEL-Advanced Electrolysers for Hydrogen Production with Renewable Energy Sources. European FCH projects meeting: materials issues for fuel cells and hydrogen technologies, 26 – 27 March 2012, Grenoble, France.
- ✓ J. Sanz-Bermejo, J. Gonzalez-Aguilar, M. Romero (2012) "Performance analysis of direct steam generation central receiver systems" Proceedings of ASME Turbo Expo 2010: Solar Brayton & Rankine Cycle GT2012 June 12-15, 2012, Copenhagen, Denmark.
- ✓ O. Bucheli, F. Lefebvre-Joud, F. Petitpas, M. Roeb, M. Romero (2012) "Advanced Electrolysers for Hydrogen Production with Renewable Energy Sources" 10th European SOFC Forum, 26–29 June 2012, Lucerne, Switzerland.
- ✓ N. Monnerie, A. Houaijia, M. Roeb, C. Sattler, J. Sanz, M. Romero, I. Canadas, A. Drisaldi, C. Lucero, R. Palomino, F. Petipas (2012) "Coupling heat and electricity sources to intermediate temperature steam electrolysis" SolarPACES 2012 Conference, September 11 – 14, 2012, Marrakech, Morocco.
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1.4.3 Task 4.2 Networking

This task is essentially dedicated to the organisation of two international workshops aiming at communication and data exchange between invited speakers and selected audience from the scientific community and industry with experience in plants integrating non-fossil energy sources. The 1st International ADEL workshop "Electrolysis concept and RES integration, system modelling and components development", with over 60 experts in hydrogen production and electrolysis from Europe and overseas, took place in Seville, Spain, the days 20 – 21 October 2011 and was organized by the partner Hynergreen Technologies (now Abengoa Hidrógeno).
During this second period, the main outcome within Task 4.2 was the organization of the 2nd ADEL International Workshop that took place on the 8th – 9th of May 2013 at the Palais des Congrès of Ajaccio, Corsica (France). The host of the Workshop was CEA-Grenoble / LITEN in association with the University of Corsica. The theme of the Workshop was "Hydrogen Production Systems with Non-Fossil Energy Sources: From Components and Process Design to Large Scale Systems" and it was was organized in six different technical sessions covering the whole chain of development (materials, energy sources, design, scaling up and outlook):

Session 1: Hydrogen production systems with non-fossil energy sources
Session 2: Demonstration feedback
Session 3: High temperature electrolysis materials and components
Session 4: Process design
Session 5: Scaling-up and BOP
Session 6: Outlook, panel discussion

The programme of the sessions included a number of keynotes and guest talks, and in addition several poster sessions presented by project partners and external participants. Following keynotes and guest talks were presented:

Keynotes:
- ✓ Overview of the ADEL project. Olivier Bucheli, HTceramix SA, CH
- ✓ Analysis of hydrogen from electrolysis and competing technologies for utility-scale energy storage. Kevin Harrison, NREL, USA
- ✓ Thermo-economic analysis of hydrogen as a renewable energy carrier. François Maréchal, École Polytechnique Fédérale de Lausanne, CH
- ✓ Plateforme MYRTE - Project development and operational experience. Philippe Poggi, Université de Corse, FR
- ✓ General overview on material requirements based on the ADEL experience. Karine Couturier,
- ✓ CEA-Grenoble / LITEN, FR
- ✓ Development of a wind-wave power open-sea platform equipped for hydrogen generation with support for multiple users of energy. Armando Palomar, AWS Truepower SLU, ES
- ✓ FCH JU point of view on green hydrogen production. Dr. Jean-Luc Delplancke, Programme Head of Unit

Guest talks:

- ✓ The role of Solid Oxide Electrolysis in the context of future energy scenarios in Denmark. John Bøgild Hansen, Haldor Topsøe A/S, DK
- ✓ The activity of CNR in energy storage. Vincenzo Antonucci, CNR Institute for Advanced Energy Technologies, IT
- ✓ Materials for load cycling and reverse SOFC operation at intermediate temperature. Dario Montinaro, SOFCPOWER SpA, IT
- ✓ Analysis of aging phenomenas and corrosion behaviour of steel interconnects in SOEC cells. Ulrich Vogt, EMPA / Swiss Federal Laboratories for Materials Science and Technology Laboratory for Hydrogen and Energy, CH
- ✓ Synthetic natural gas via integrated SOEC - methanation plants: a thermodynamic and economic assessment. A. Lanzini, Polito Torino, IT
- ✓ Simulation tools to optimize hybrid renewable systems, HOGA Software. Ismael Aso Aguarta, McPhy Energy S.A., FR
- ✓ Optimal Integration of a SOEC into a solar steam tower plant for hydrogen production. Javier Sanz Bermejo, IMDEA, ES
- ✓ Design and control of high temperature electrolyser systems fed with renewable energies. Floriane Petipas, EIFER (European Institute for Energy Research), DE
- ✓ Design and engineering decisions of the Balance of Plant of the heat transfer process from the nuclear plant to ITSE. Andrés Muñoz Cervantes, Empresarios Agrupados, ES
- ✓ BOP issues in electrolyzer systems. Cristina Lucero, Abengoa Hidrógeno

The programme included a site visit to the world‘s largest hydrogen-based energy management system coupled to a photovoltaic field, the MYRTE Platform on Friday, 10 May 2013.
The event was advertised on different websites. A flyer and promotional video were prepared for the workshop, and all the presentations and posters were uploaded for dissemination on the ADEL website.
As many as 40 participants attended presentations and poster sessions with lively discussions during the two-day workshop. The participation of external experts from companies and institutions should be highlighted: University Putra (Malayisia), CNR Institute for Advanced Energy Technologies (Italy), Hochschule Esslingen (Germany), Department of Energy - Politecnico di Torino (Italy), H2life Public Interest Foundation (Belgium), National Hydrogen Centre CNH2 (Spain), NREL National Renewable Energy Lab (USA), EPFL (CH), AWS Truepower SLU (Spain), Université de Corse (France), McPhy Energy (France).

At the end of the workshop all participants contributed to the formulation of general conclusions and a joint statement on the advantages and technology development needs of high temperature electrolysis in combination with renewable energy sources.

1.4.4 Task 4.3 Market communications

Market survey and communication with platforms were the main activities in this task. Given the fact of the small amount of PM allocated in general to WP4, the activities of market survey were coordinated by DLR through WP3. Regarding the second part on communications, the partners used PM from the other tasks (4.1 and 4.2) to carry out this activity. Market survey followed the strategy planned in Deliverable D4.2 already issued in the first project period.
Analyses on market survey are therefore reported in D3.5 and mainly encompass:

- ✓ Analysis of hydrogen markets and niches.
- ✓ Analysis of current and future market of the different energy sources under consideration.
- ✓ Identification of Synergies of ITSE and individual renewable energy sources (as means to store and transport renewable energy or to perform grid management)
- ✓ Derivation of demonstration scenarios and some preliminary ideas for a market introduction

Regarding communication platforms, the main activities concentrated on the presentation of ADEL in existing networks and panels IEA-HIA (task 25 and other tasks), the IEA implementing agreement SolarPaces (presentations in SolarPACES2012 in Marrakesh and SolarPACES2013 in Las Vegas) and also at the Eurotherm community. In SolarPACES, the activities of ADEL were reported to the task working group on “Solar Fuels”. Regarding Eurotherm, Martin Roeb and Manuel Romero, provided information on ADEL at the EUROTHERM Seminar No. 98. Concentrating Solar Energy Systems. 4-5th July 2013. Vienna, Austria.

IPHE recognised project Thesis; GenIV/Archer and IAHE Nuclear Energy Division, to monitor and review the state of the art, to develop a common approach to evaluate those processes, to link the topic to further industrial representatives, and ensure a target oriented dissemination of the technology. It is important to mention that, through the intermediation of Empresarios Agrupados, ADEL has participated in the Generation IV International Forum (GIF), a co-operative international endeavour organised to carry out the research and development (R&D) needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems. Martin Roeb presented ADEL at the semi-annual meeting of GIF governing body held on 16-17 May 2013 in Beijing, China.

1.5 Please provide the public website address, as well as relevant contact details.

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