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1. EXECUTIVE SUMMARY (3 pages max. all points)

1.1 Description of the deliverable content and purpose

Within the EU-funded project Sophia, improved high-temperature electrolysis and co-electrolysis technology for coupling to solar power sources is developed. A 3 kWe prototype electrolyser unit will be designed, constructed and operated and combined with a Concentrated Solar Power system receiving its energy from the solar simulator at DLR. The prototype unit will contain newly developed stack technology with balance of plant, and operate under elevated pressure (up to 15 bar).

Within WP2, the industrial specifications for high-temperature electrolysis and co-electrolysis are defined, and different scenarios for complete process chains are identified. In Deliverable 2.1, a description is provided of the end-user requirements for this technology as well as the system requirements for the prototype that will be developed. These requirements have been developed within Task 2.1. Eventually, similar requirements for co-electrolysis will be developed. The current Public document summarizes Deliverable 2.1, which is confidential.

Requirements depend on the application of the hydrogen: three applications are considered, i.e. injection into the natural gas grid, transportation and production of chemicals by methanation of CO_2. Purity requirements are comparable, setting limits mainly to H_2O levels in the product. No major other contaminants are expected from the SOEC unit. The required product pressures differ but are all above atmospheric. For large scale applications it will be required to deliver the hydrogen continuously (i.e. 24/7); for transportation discontinuous production might be feasible if storage capacity is high enough.

General requirements for the prototype have been derived (steam supply and power input).

1.2 Brief description of the state of the art and the innovation brought

The Sophia project aims to couple high-temperature electrolysers to thermal solar energy sources, which is unprecedented. It will require innovations in design and control to match production and demand, as well as to night-time operation.

1.3 Deviation from objectives

None

1.4 If relevant: corrective actions

None

1.5 If relevant: Intellectual property rights

Not applicable.

2 SOEC development

2.1 Project aims

The central objective of Sophia is to further develop solid-oxide electrolyser and co-electrolyser technology for coupling to solar energy sources. The technology may be applied for the production of gas or liquid fuels from renewable power; this may include the storage of energy at times of overproduction of power. Key aspects that are covered within the project include the optimization of cells with optimized microstructure and composition and/or increased sizes compared to the state-of-the-art, the development of pressurized electrolyser stacks, the conception and investigation of scenario's for power-to-gas, and building and testing of a prototype electrolysis system.

With regards to the prototype, the aim is to develop and test a 3 kWe high-temperature electrolyser unit, which will be coupled to a solar simulator for extensive testing. The prototype should be representative of an actual application; hence it should consist of a complete system, including the major balance of plant components that will also be present in a full-scale system. This includes amongst others high-temperature recuperative heat exchangers and a steam generator. The performance of the integrated system will be determined; amongst others, attention will be given to the dynamic behaviour of the system.

Regarding the end-user requirements, different end-products may be considered: the hydrogen may be applied directly as an end-product (for example, for direct addition to natural gas, or for transportation applications) or as an intermediate product that is used in further synthesis, e.g. the production of hydrocarbons. In that case the hydrocarbons can be regarded as the end-product for the end-user. Within the scope of Sophia the end-users will typically be gas and electricity companies, with an aim to eventually produce hydrocarbons (possibly including liquid fuels). The requirements are formulated with such typical end-users in mind.

2.2 Operating conditions of solid oxide electrolysers

Crucial operating parameters for SOEC are the following:

- Temperature.
- Operation mode (exothermal, thermo-neutral or endothermal).
- Steam conversion.
- Pressure
- Use of sweep gas

These are further discussed in the sections below.

2.2.1 Temperature

Typically operating temperatures for HT electrolysers range between 700-1000°C, and more specifically 700-800°C. Increasing the temperature generally leads to a decreased Area Specific Resistance (ASR) , and so to a higher electrical efficiency, as reflected by lower voltages at a certain current density.

A higher operating temperature requires a higher feed inlet temperature, and this in turn requires larger heat exchangers and/or higher heating power if electric heaters are used.

2.2.2 Operation mode

The operation mode is related to the current density; at low current density and thus low voltage the process is endothermal, whereas at high current densities and voltages it becomes exothermal. The thermo-neutral cell voltage amounts to 1.25-1.35 V in electrolysis and co-electrolysis modes.

In order to prevent rapid ageing it is often required to limit the current density and preferably operate in the endothermic mode. However, since the hydrogen production rate for a given stack size is directly related to the current density this means that a bigger stack and thus heavier investment is required to achieve a certain hydrogen production. Moreover operating in the endothermic mode requires a solution for achieving a sufficiently high steam temperature, since this cannot be achieved with recuperators only.

The Sophia prototype system will most likely be designed to operate in the thermoneutral mode, but it can still be operated slightly exothermic or endothermic, depending on the results of the durability studies. In any case, electric heaters are necessary to provide the final high temperature heating of the feed gases, amongst others during transient operation (e.g. start and stop, power changes etc.).

2.2.3 Steam conversion

Usually the steam conversion is limited to 50-60%, again to avoid rapid aging. From a system's perspective the steam conversion should be as high as possible since it determines efficiency; steam requires a substantial amount of heat for its generation. Moreover the size of balance of plant components (heat exchangers, steam generator, pumps, valves etc) obviously depends on the steam flow rate which increases when the steam conversion is limited. A report by Halder-Topsoe indicates a higher steam conversion of 80% is feasible [12].

2.2.4 Anode sweep gas

During electrolysis oxygen is produced at the anode. In principle the oxygen could be considered a useful byproduct, however pure oxygen is a very reactive gas, especially when it is produced at elevated pressure and high temperature. This means that the oxygen will quickly corrode most steel alloys, which is a serious safety risk due to the elevated pressures and high temperatures.

To prevent such safety and lifetime issues, an anode sweep gas can be used. Air is the most obvious choice. The air-flow should be such that the oxygen content in the anode gas at the outlet of the electrolyser is limited to 50% or less, to avoid heavy corrosion.

Moreover, the use of a sweep gas is also convenient for control reasons, ie. for achieving a balanced pressure between anode and cathode. The allowed pressure difference is limited for mechanical reasons. In addition, the use of sweeping air may allow improved temperature control during turn-down to low power.

Obviously the use of a sweeping gas necessitates additional balance of plant, such as a compressor and high-temperature heat exchangers. The compression energy consumption is a serious drawback for elevated pressure electrolysers. Therefore, although the use of sweeping air will be the starting point for the design of the prototype, options to avoid the use of sweep gas will be evaluated in WP5.

2.2.5 Pressure

Operating at elevated pressure may lead to somewhat increased efficiency of the SOEC. Moreover from a system's perspective, an elevated pressure may be advantageous since the product hydrogen needs to be pressurized anyway. On the other hand, if a sweep gas for dilution of the produced oxygen is used which has to be compressed then the efficiency gain is lost, and might even turn into a disadvantage.

2.2.6 Purity

The produced hydrogen will contain water; the hot hydrogen coming from the electrolyser contains all unconverted steam which may amount to 40-50% of the product stream. After cooling the hydrogen will be saturated at the cooling temperature. Further drying may be necessary, when a low dew-point is specified (which is the case for most applications).

Other expected impurities may be oxygen and nitrogen (from diffusion of air into the product lines, or from dissolved amounts in the water to the steam generator). Since the process operates at overpressure the chance that these compounds will be present is low.

It is not expected that the demineralized water contains significant amount of other contaminants.

Other potential contaminants might originate from the process equipment. Evaporation of metal salts might cause contamination with dust. With the current knowledge this is not expected to occur in practice.

2.3 Stack development at CEA for the Sophia prototype

A stack has been previously developed and tested by CEA for steam electrolysis and co-electrolysis at atmospheric pressure. Some design adjustments have recently been realized with major focus on stack gas sealing and distribution optimization and on the reproducibility and reliability for the 25 repeat units of the stack corresponding to 3 kWe size [Di Iorio et al., SOE stack activities at CEA, EFCF proceedings, 2014].

This stack design will be adapted to (co-)electrolysis operation under pressure for the SOPHIA project: thanks to its self-tightening system, the stack will be placed in a pressurized vessel; this allows an operation under pressure (up to 30 bars) without applying a differential of pressure between the inside and the outside of the stack.

The operating conditions (temperature, pressure range, steam conversion, operation mode) have been defined. Based on this, the stack current and voltage for the targeted SOPHIA prototype (3 kWe) have been estimated. All the operating conditions will be optimized according to cell performances and durability tests performed at single cell or short-stack levels during the project.

3 Concentrated solar technologies

3.1 Technology description

Concentrated-solar technology systems consist of mirrors or lenses with tracking systems to focus a large area of sunlight onto a small area. The concentrated radiation can be used then as heat or as heat source for a conventional power plant (solar thermoelectricity). The solar concentrators in CSP (Concentrated Solar Power) systems can often also be used to provide industrial process heating. Concentrating technologies are available in four common forms, namely parabolic trough, dish, linear Fresnel and solar tower. In this report, several energy conversion technologies are studied in order to analyse their capability to provide heat and electricity to the SOE (Solid Oxide Electrolysis) process as well as the integration of the CSP plants in the electrolysis process.

3.1.1 Solar Tower

A solar power tower converts sunshine into electricity for the world's electricity grids. This technology uses computer controlled sun-tracking mirrors, well known as heliostats to focus sunlight on a receiver at the top of a tower (Figure 1).

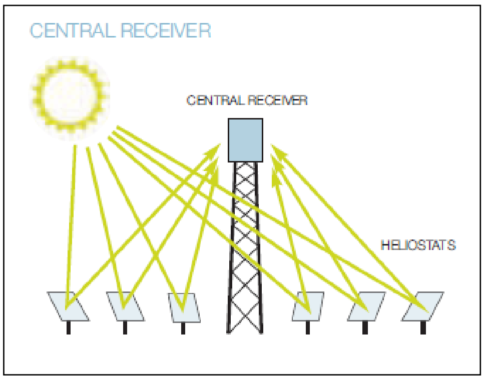

Figure 1: Central tower concept

A heliostat field can consist of multiple up to several thousands of heliostats, each individually two-axis tracked. The heliostat field reflects the irradiation to a solar receiver, which is typically mounted above the heliostat field on a tower and which is the part of the system that converts the solar radiation into heat. This is used for example to evaporate water within a Rankine cycle in order to generate electricity. Solar power tower can achieve very high operating temperatures of over 1000°C for air, enabling them to produce hot air for gas turbine operation. Gas turbine can be used in combined cycles, yielding very high conversion efficiencies of the thermal cycle of more than 50% [1]. The operational range of pressure varies between 1 and 40 bar and the provision of electricity as well as of heat is possible.

There are several heat transfer fluids (HTF), which can be used by the receiver of the solar tower, namely air, molten salt and steam. A general overview of solar tower technologies using the mentioned heat transfer fluids is given in the next sections.

3.1.1.1 Air solar Tower

Some current European designs use air as heat transfer medium for solar power tower operation because of its high reachable temperature and its good handiness [2]. Another advantage of air as heat transfer medium is its abundance without costs, its non-toxicity, and the fact that it does not require freeze protection during times of non-operation. This technology has been developed and demonstrated by DLR at the solar Tower of Jülich, which has a total receiver thermal energy input of 7 MW allowing the electricity generation of 1.5 MW [3]. Ambient air is sucked through a blackened porous ceramic structure on which the solar radiation is focused. The air cools the outer parts of the receiver and is heated up gradually to the design temperature level at the inner surface of the porous absorber. In passing through the receiver, the air is heated to around 700°C and this heat is delivered to the water-steam cycle in a heat recovery boiler. The steam generated there drives a turbine/generator and returns in form of condensate to the steam generator.

3.1.1.2 Molten Salt solar Tower

In this technology, the concentrated solar radiation heats molten salt to over 538°C. The heated molten salt flows then into a thermal storage tank where it is stored, maintaining 98% thermal efficiency, and eventually pumped to a steam generator. The steam drives a standard turbine to generate electricity within a Rankine cycle. The biggest solar Tower plant using molten salt as HTF (Heat Transfer Fluid) is the Ivanpah solar Tower power plant operated by BrightSource, which has an electricity generation of 377 MW [4].

In a solar molten-salt tower power plant, the molten nitrate salt, which is a clear liquid with properties like water at temperatures above its 240°C melting point, is pumped from a large storage tank to the receiver, where it is heated in tubes to temperatures of 565°C. The salt is pumped through a steam generator to produce the steam for the turbine to produce electricity. After the steam turbine, the salt returns at 285°C to the storage tank to be used in the cycle again.

3.1.1.3 Steam solar Tower

This technology uses water as HTF, producing steam directly into the receiver. This makes it possible to avoid the need for an intermediate steam generator, which may reduce the investment cost by 3-4%. Furthermore, the steam temperature is not limited by the degradation of the HTF, enabling the use of higher performance Rankine cycles. The two commercial CRS plants PS-10 and PS-20 are installed in Seville and connected with the grid since 2007 and 2009 respectively. They work on a saturated steam concept. The solar power tower stores heat in tanks as superheated and pressurized water at 50 bar and 285°C. The water evaporates and flashes back to steam, when pressure is lowered. The receiver produces saturated steam at 40 bar 250°C from thermal energy supplied by the concentrated solar radiation flux. The steam is sent to the turbine, where it expands, producing mechanical work and electricity.

Since 2009, Abengoa Solar and BrightSource are operating their own pilot plants producing superheated steam at temperatures above 500°C and 100 bar.

3.1.2 Solar Through

In solar parabolic troughs technology (Figure 2), the sun's radiation is concentrated via mirrors on a focal line where the heat receivers (i.e. steel tubes) are placed, with concentration factors of 60-80 and maximum operating temperatures of about 550°C. The receiver tubes are placed inside an evacuated glass envelope to avoid convection heat losses. Solar heat is removed by a heat transfer fluid (e.g. synthetic oil, molten salt) flowing in the receiver tube. It is then transferred to a steam generator to produce super-heated steam and run the turbine.

Figure 2: Parabolic through

Mirrors and receivers (i.e. the solar collectors) track the sun along a single axis (usually, East to West). Most of the solar parabolic trough plants currently in operation have capacities between 15 and 100 MWe, efficiencies of around 14-16% (ratio of net electric output to solar energy input) and a maximum operating temperature of 390°C, which is limited by the degradation of the synthetic oil that is used as the heat transfer fluid. These plants are designed to generate electricity but they can also produce high-temperature heat. It is usual for these plants for having a short thermal energy storage system to deal with the transient moments where sunlight is not available and to continue with the operation when the sun goes by. Big storage system allows the operation of the plant for more than 7 hours.

3.1.3 Solar Dish

The parabolic dish (Figure 3) concentrates the solar radiation into the thermal receiver integrated in a Stirling engine. The receiver consists of a heat exchanger designed to transfer the absorbed solar energy to the working fluid. Then the absorbed thermal energy is converted to mechanical power by expanding the working fluid in a piston-cylinder. The modern dishes have an efficiency of 31% by converting the solar radiation into electricity.

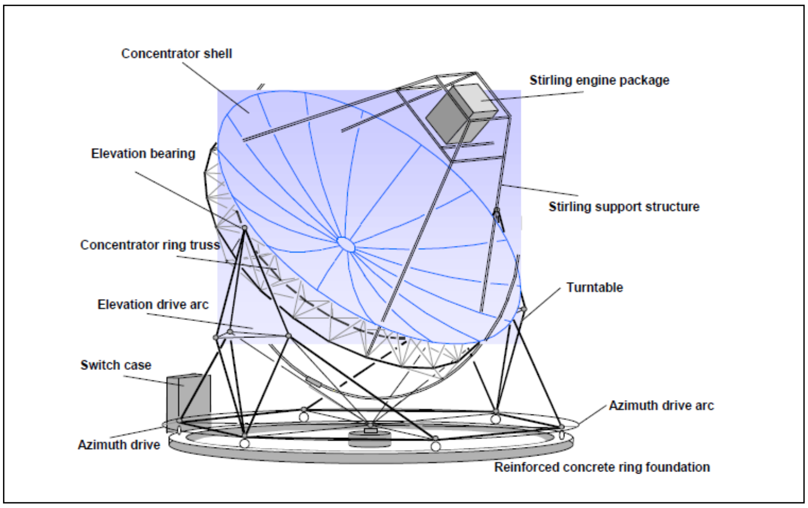

Figure 3: Dish Stirling system

Because of the parabolic shape, the dishes have concentrations ratios between 600 and 2000. The temperature that can be achieved is about 1500°C [5]. With current technologies, a 5 kW dish Stirling system requires a dish-diameter of 5.5 m and a 10 kW dish requires a dish-diameter of 7.5 m.

3.1.4 Linear Fresnel

A Linear-Fresnel Reflector (Figure 4) consists of 2-D concentrating reflectors with linear focus. In this case, the parabolic reflective surface is obtained by an array of linear mirror strips which independently move and collectively focus on absorber lines suspended from elevated towers [6]. Reflective segments are close to the ground, while absorber lines are suspended from elevated towers. The solar field is composed of several parallel rows of these collectors aligned on a north south horizontal axis, tracking the sun from east to west to ensure that solar radiation is continuously focused on the linear receiver.

Figure 4: Fresnel field of the SHP Company in Australia

Current pilot plants are producing superheated steam at 100 bar and 370°C, but it is expected to produce superheated steam at 100 bar and 450°C during following years.

3.2 Coupling of the CSP technologies to SOE process

The different concentrating solar energy technologies defined in Section 3.1 are able to provide the electrolysis process with heat and electricity, which are the main requirements of the SOE process. In addition to that, several investigations carried out in the framework of the EU-founded project ADEL have shown that the use of a sweep gas is necessary for the operation of the process in order to remove the produced oxygen and to make control of the electrolyser easier. The capability of the CSP technologies of providing the SOE process with electricity, heat for water vaporization and pre-heating of inlet gases (i.e. steam and sweep gas) will be discussed below in details.

3.2.1 Electricity generation

The electricity generation occurs within a Rankine cycle, where water is preheated, evaporated and superheated by the heat transfer fluid already heated in the solar receiver. Steam parameters depend on the heat transfer fluid. Central receiver systems can reach a solar-to-electricity conversion efficiency of up to 23% and a net annual efficiency of 7-20%, which is very much dependent of the location of power plant [5]. Currently, a next generation of solar tower systems is under development with higher process temperatures of more than 1000 °C applying new receivers with volumetric absorbers making use of porous structures or particles. These power plants have the potential to reach higher electrical efficiencies and are, moreover, applicable to processes for solar fuel production.

The size of a solar tower system is variable and thermal power inputs up to several hundred MW are feasible. Power towers can be coupled to steam cycles of 5 to 200 MW of electric capacity, with thermal cycle efficiencies of 30-40% [1].

3.2.2 Heat supply

The process of the high temperature steam electrolysis requires heat in addition to electricity. The major heat requirement of the electrolysis system concerns the heat for steam generation. This will be provided by the solar receiver. Thereby, the feed water is evaporated by a part of the heat transfer fluid generated in the solar receiver. Previous investigations carried out within the predecessor project ADEL have shown that the superheating of the steam up to 600-800°C can be performed by heat recovery from the outlet streams of the electrolyser in combination with electrical heaters [10]; the latter provide the final heating and require only a relatively small power input, compared to the power input to the electrolyser.

3.2.3 Sweep gas supply

The design of the high temperature electrolyser includes a sweep gas on the anode side. It allows removing produced oxygen from the anode and controlling the cell temperature and pressure. However, the operation of the electrolysis stack without a sweep gas would be advantageous in terms of efficiency since the sweep gas has to be compressed and heated up to the operation temperature of the electrolyser, which is energy consuming. As a result, the efficiency of the overall process without sweep gas at the anode is higher than the operation with sweep gas. Sweep gases identified for the anode side of the electrolysis stack are Oxygen, Air and Steam. When the sweep gas is pure oxygen, the oxygen can be considered as a by-product of the electrolysis process and can be either re-circulated or sold, generating economic benefits. However there are great concerns in terms of safety of using hot pure oxygen. Using air as a sweep gas is interesting regarding the integration with energy sources. Indeed, the heat transfer fluid of the air solar tower power is air, which can be directly introduced in the electrolyser without major technical effort. The main disadvantage of this sweep possibility is that oxygen can no longer be considered as a by-product. Material issues of the SOEC prevent the use of steam on the anodic side up to now.

3.3 Integration of the prototype

The 3kWe HTE prototype is too small to be tested in a solar tower unit. Therefore, it will be coupled with a solar tubular receiver developed at DLR and will be tested in the DLR's solar simulator.

3.3.1 Solar simulator

A xenon high flux solar simulator based on elliptical reflectors with xenon short-arc lamps is operated at DLR's premises in Cologne (see figure 5). These lamps offer high intensities and unfiltered spectrum which matches sensibly well to sunlight. The emitted radiation is feasible for a wide field of applications. The radiant power of 20 kW is pointed on a target area of about 100 cm² at a distance of 3 m with irradiance greater than 4.1 MW/m². The xenon high-flux solar simulator at DLR is used for exploration and testing new technologies, whereas temperatures of above 2000 °C are possible to achieve.

Figure 5: Xenon high flux solar simulator

3.3.2 Solar receiver

In solar towers as well as in the solar simulator temperatures of over 1000° C can be achieved without any problem. The solar energy can be then transferred with a solar receiver to water or other heat transfer medium. For this process a tubular solar receiver can be used and be coupled to the HTE.

With such a receiver, the radiation passes only from one side through an aperture and irradiates tubes through which a heat transfer medium is led. This minimizes heat loss even at high temperatures. A solar tube-type receiver with a cylindric configuration has been thus developed in order to provide the electrolyser with superheated steam (Figure 6). The aperture diameter of the receiver is fixed by the nominal diameter of DLR's solar simulator focal point of

90 mm. This receiver is composed of 20 absorber steel tubes inside a cavity. The tubes consist of high-alloy steel. The back of the cavity is closed; the concentrated radiation enters in the front of the cavity. The absorber tubes are loaded from behind with steam from a steam generator which can generate steam between 180°C and 240°C. The tubes are arranged in a ring and run orthogonally from the focal plane of the solar radiation towards the rear and form a cavity in which the radiation is absorbed. The tubes are at the same time the absorber of the solar energy and the heat exchanger for heating the heat transfer medium. A major challenge is the uniformity of the distribution of the vapor on the 20 individual tubes of the receiver cavity to ensure a constant heat transfer and make sure that the mass flows of the individual tubes are nearly identical. To get this under control a distribution system was developed.

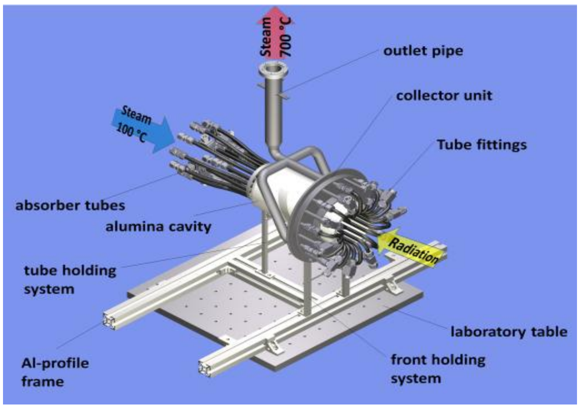

Figure 6: Tubular solar receiver

Figure 7: Tubular solar receiver tested in the DLR's solar furnace

After having been simulated, the solar receiver has been tested in the solar simulator at DLR. The solar receiver has achieved a steam production of 5 kg/h steam, which should be sufficient for a 3kWe HTE. For the moment, experiments have permitted to reach a steam temperature of 700°C with an input power level of 4 kW. Simulations show that the average steam-outlet temperature can achieve 860°C. So it is probably possible to reach a steam temperature of 800°C and some experiments will be carried out to demonstrate it.

3.3.3 Integration issues

The stack needs to be kept hot all the time, also over the night which can be an integration issue for the coupling of the HTE with the solar energy. This issue can be solved by addition of some sufficient heat storage capacity or the eventual addition of electrical heaters. Concerning the prototype of 3kWe HTE which will be tested in the solar simulator, an electrical heater may be added in order to keep the stack hot all the time.

Concerning the scale-up plant of MW range, there are different storage possibilities. In fact, a big advantage of the CSP technology is the capability to provide dispatchable power – by storing solar energy and releasing it when it's needed. Storage can thus eliminate intermittency. Storage technologies can be direct or indirect (in this case the storage medium is not heated directly by the concentrators) [6]. Solar heat can be stored in liquid or solid media such as molten salts, ceramics, concrete, phase-changing salt mixtures or in saturated water.

4 End-user requirements

4.1 Product requirements

End-user product requirements depend on the application of the produced hydrogen. The applications for hydrogen produced by an SOEC that are foreseen at the time of writing are the following:

- Injection into natural gas grid
- Transportation
- Methanation of CO_2 or WGS reactor

Requirements concerning product specification are summarized in table 2[1].

Table 2: Product requirements

	Injection into NG grid	Transportation	Methanation
Pressure	40-100 bar (transportation grid) 2-10 bar (distribution grid)	300-700 bar	5-30 bar
Temperature	ambient	ambient	~300°C
Relevant impurity levels	<50 ppm H_2O <1% O2	<5 ppm H_2O <5 ppm O_2	Maximum to H_2O content?
Typical scale	>50 Nm^3/h (demo-units)	100-1000 Nm^3/h	>50 Nm^3/h H_2 (demo-units)

As noted in Chapter 3, very few contaminants are expected to be relevant for hydrogen obtained by steam electrolysis (mainly H_2O and possibly O_2). Detrimental compounds like sulphur and CO are not expected when steam electrolysis is considered, provided that the boiler feed water used for steam generation is of adequate quality.

The specific demands per application type are discussed below

4.1.1 Injection into NG grid

The pressure requirements depend on whether injection is in the high-pressure transportation grid or in the distribution grid. The latter operates at lower pressures, so it is possibly a better

[1] Note: as mentioned in chapter 2, co-electrolysis is not a part of this deliverable; similar requirements for co-electrolysis should be defined in D2.4.

option for direct coupling to the SOEC developed within Sophia (no compressor required). Another advantage is that the distribution grid is a much finer network, so there will be more suitable locations for SOEC-plants close to the gas pipelines. On the other hand the product flow may be limited by local gas demand which may vary quite strongly.

The maximum allowed content of hydrogen in NG varies per country. Reasons why the allowed hydrogen content of natural gas is limited are the effects of hydrogen on the Wobbe index of natural gas, on the combustion behaviour of the gas mixture, and the effects on pipeline materials integrity. The allowable amount of hydrogen blending is case specific and differs between different end-user sectors.

The demand for hydrogen may vary quite strongly in time since the flow of NG in the pipelines varies.

4.1.2 Transportation

Using hydrogen in fuel cell cars requires very high pressures for storage. This requires the application of high-pressure compressors. On the other hand, compression from medium to high pressure may be done at the filling station anyway (trucked H2 from tube trailer is usually delivered at 200 bar and compressed further in one or two stages to the final pressure).

The hydrogen has to be very pure, even inert compounds like N2 and He should be below total levels of 100 ppm.

4.1.3 Methanation

The conversion into methane can be appropriate whenever injection of hydrogen in the gas grid is preferred but limited by hydrogen specifications. Typically the hydrogen (or syngas) has to be introduced into the methanation reactor at around 300°C and at an elevated pressure of up to 30 bar [13]. Depending on the reactor design and catalyst this could vary. The foreseen SOEC operation pressure of 15 bar may be sufficient for direct application.

Regarding the purity, while it is hard to give a general specification the hydrogen should preferably be as dry as possible, since H_2O is a reaction product and hence moves the equilibrium to the wrong direction.

The units will most likely operate fully continuously, ie 24/7. Hence delivery of hydrogen/syngas should be continuous as well. Hydrogen has to be cooled down, the released heat may be recuperated and used for preheating the steam in the electrolyser system.

Obviously, in case hydrogen is converted into methane or other hydrocarbons, a carbon source (e.g. CO_2) is required for synthesis.

4.2 System requirements

4.2.1 Required inputs

The electrolyzer system can be designed with recuperative heat exchangers, meaning: the feeds of the SOEC stack are pre-heated by the products. This applies to both the steam/hydrogen side and the oxygen (air) side. However, if the stack is not operating in the exothermic mode with a substantial temperature difference between inlet and outlet, the feeds cannot be completely heated to the required inlet temperature. Therefore, a small extent of the heating is done by electric heaters (this represents only a minor portion of the total electric power consumption). However, heat for the generation of steam is provided from an external source; this would be provided by the solar system (CSP). The temperature level of the external heat input can be low, i.e. slightly above the boiling temperature of water at the operation pressure. This amounts to about 200°C at 15 bar.

The system requires the following inputs:

- Electric power for
    - Electrolyser
    - Electric heaters
    - Other equipment (pumps, compressors, actuators…)
- Deionized and degassed water for steam generation
- Heat for steam generation, e.g. in the form of a hot heat transfer fluid (note: alternatively the steam is directly generated in the solar receiver)
- Air for anode sweeping. This is required for startup and for transients anyway, and probably also for nominal operation
- Cooling medium, for final cooling and condensation of the products. It may be either cooling water or cooling air. The latter may pose restrictions to the final temperature level (and coupled to that, its water content) that is achievable in hot climates. Products should be cooled below 50°C.

Depending on the application of the hydrogen the product may have to be further treated, i.e. further compressed, cooled for water knock-out and possibly further dehumidified, e.g. by means of adsorption on zeolite or activated alumina.

4.2.2 Electric power supply

The SOEC will be directly coupled to a CSP. Both electric power and heat may be derived from the solar plant, depending on the exact case. The electric power may be generated in a steam-cycle (Rankine cycle) that receives heat from the CSP. Alternatively, the CSP may deliver power to the grid whereas the SOEC takes only heat from the CSP, and power from the grid. A combination is also possible, e.g. during day-time the SOEC receives power from the CSP and during night-time from the grid.

When the electric power is provided by the CSP this direct coupling necessitates considering the operation of the SOEC during night-time. Basically there are two options:

- Put the SOEC system in stand-by mode. The SOEC system has to remain hot, so a small energy input (both heat and electric power) may be required to avoid daily cold-starts. For example, a small flow of hot steam may be fed to the cathode to compensate for heat losses. It is preferred to keep the system pressurized, to avoid time and energy consuming pressurization/depressurization steps, as well as potential negative mechanical consequences.

- Continuous operation. This means that a large energy storage has to be accounted for, since both heat and electric power are required. If electric power is derived from the CSP, then that system needs a large heat buffer to allow continuous operation of the Rankine cycle. At night-time, electric power for the SOEC might be taken from the grid though. The SOEC system may be turned down to limit the size of the energy storage.

It will depend on the economic evaluation if continuous operation is required or if a standby mode is satisfactory. The fact that an expensive system is not in production during perhaps 2/3 of the time is probably detrimental for the economics (although it should be recognized that economics are not the only factor for applying SOEC).This may depend on the scale of operation as well.

Besides the daily power and heat cycles inherent to CSP systems, the power and heat inputs may also vary quite strongly on a much smaller timescale (minutes to hours). Small variations in heat and power inputs can be tolerated but these variations should not be too strong; for instance if the power input decreases by 25% and the gas flows are not adapted the process may become quite strongly endothermic leading to too large temperature gradients of over 50K in the stacks. This is about the maximum that can be tolerated. Such power input variations may be solved by heat buffering and grid-parallel operation. The temperature may be controlled by adaptation of the sweep gas and/or steam flow.

It is foreseen that a full scale system will consist of a great number of parallel stacks, probably grouped in sets of sub-systems. Power has to be supplied at the desired voltage and current; this depends on the number of stacks that are electrically put in series, the number of plates in each stack as well as the cell performances. Power conditioning is an important part of the plant, but it is not further treated here.

4.2.3 Supply of heat for steam generation

Solar heat will be used to generate and possibly superheat steam. This can be done either directly (i.e. the steam for the SOEC process is generated within the solar receiver) or indirectly (i.e. the solar receiver heats a heat transfer fluid that in turn gives off its heat in a separate steam generator). The latter option appears to allow easier storage of heat, and hence potentially has better capabilities for handling transients. Moreover it avoids the need for pressurized operation of the receiver itself.

Considering that the working pressure of the SOEC will be 15 bar, the steam needs to be supplied at a slightly higher pressure, say 16 bar. The corresponding boiling temperature then amounts to 202°C; hence, if an indirect heating method is used the HTF should at the outlet of the steam generator have a temperature of about 20K above this. Depending on the ΔT in the HTF loop this means that the HTF has to be delivered to the steam generator at about 250°C.

As pointed out in section 6.2.1, the remainder of the feed heating can be performed by recuperation from product and electrical heaters. So in principle there is no need for transferring high-temperature heat from the solar receiver to the SOEC-system (although it might enhance the efficiency of the electrolyzer .

4.2.4 Boiler feed water

The feed water for the steam generator should be demineralized by means of either reverse osmosis or ionic exchange, or a combination of both. The conductivity after treatment should be below 5 µS/cm (see e.g. http://www.kuntze.com/en/parameter/conductivity.html). In addition, the feed water should be degassed to remove dissolved gases like O_2, CO_2 and also N_2.

4.2.5 Air for anode sweeping

The working temperature of the SOEC-system is around 800°C. Hot oxygen is released at the anode at this temperature. Since oxygen is an extremely reactive compound this poses serious challenges, especially considering the elevated pressure.

Extreme materials of construction may have to be considered to allow the production of pure oxygen. To minimize the hazards it may be opted to quench the oxygen immediately after the electrolyser, e.g. as a step in water-preheating (not shown in figure 8).

Alternatively, sweeping air may be used to dilute the oxygen to below 50%. This makes the anode product less corrosive, however the air has to be introduced at the same pressure as the steam, so this comes at the expense of high compression power, reducing the efficiency of the concept. Moreover the sweeping air also has to be preheated in high-temperature heat exchangers, adding to the costs of the plant.

4.3 Controls

Pressure balancing of the stack is extremely important. Pressure gradients should not exceed 50 mbar. This not only means that anode and cathode sides have the same pressure, but also the atmosphere in the pressure vessel surrounding the stack.

For safety it may be recommended to use an inert atmosphere in the pressure vessel.

Special attention should be given to the system controls during transients (turn-down) – temperature gradients should at all times remain limited to some 50K overall (note: 20 K is validated, 50 K is expected but not experimentally checked).

5 Requirements for the prototype

The prototype will be a 3 kWe electrolyser; the actual power may vary between 3.0-4.8 kWe, depending on amongst others the operation temperature. For a 25 cell stack operating at a cell voltage of 1.30 V the following basic requirements can be deduced:

Stack voltage=32.5 V (DC) (in autothermal mode)

Stack Current=100-150 A

H_2 production = 1.0 Nm^3/h

Temperature 750-800°C

Steam fed (at 50% conversion) = 1.7 kg/h (range: 1.3-2.6 kg/h=1.6-3.2 Nm^3/h)

Sweeping air input = 20 slm (=1.2 Nm^3/h)

Cooling water requirement = 30 l/h

Above numbers are for nominal operation. Considering minimum and maximum operation levels, all flows may vary between 50-125% of the nominal levels.

Sweeping air shall be provided to the SOEC; in a later phase of the testing may be switched off, but this depends on the progress of engineering. The system will comprise an air compressor that will suck in the air. The air needs to be clean and free from explosive compounds (i.e. originate from a non-Ex zone).

Electricity will be taken from the grid. The system will include a power conditioner to deliver DC power at the required voltage. Dynamic power variations may be invoked on purpose as part of the test program, to simulate the dynamic behavior of large-scale CSP systems.

Product storage is not necessary; the products (H_2 and O_2) shall be vented into the atmosphere. Sample lines shall be included to enable chemical analysis. Flow meters shall be installed to determine production capacity at given power input.

Due to the safety regulations at the testing location (DLR), operation shall cease at night, meaning that the system shall be put in a stand-by mode. Provisions have to be included to keep the system hot, such as electric heaters for continued generation of hot steam that is to be fed to the system. Most likely the pressure has to be released for stand-by operation, due to the safety regulations at DLR.

The system shall be controlled automatically by means of a microprocessor, but with a proper human-machine interface; platform to be decided.

Start-up and shut-down procedures should aim at slow heating/cooling avoiding temperature shocks (heating/cooling rates yet to be determined but probably of the order of ~3 K/min). The system shall include all required mechanical safety devices to avoid over-pressurization and unwanted back-flow of hazardous gases. Moreover, an emergency shut-down procedure shall be devised to cover amongst others any of the following situations:

- Over-pressure
- Loss of pressure

- Over-temperature
- Fire

If any of the situations occurs the system needs to immediately cease operation, i.e. power input shall be cut. An automatic N_2-purge may be included.

The system produces an explosive gas (hydrogen) and hence consideration has to be given to potential formation of explosive atmospheres.

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