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Advanced Electrolyser for Hydrogen Production with Renewable Energy Sources

FCH

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Specification and preliminary design of demonstrator

WP 3 – H2 plant flow sheeting and case studies

Deliverable 3.6

Authors: DLR

Reviewer: HyGear

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Glossary

ADEL	ADvanced ELectrolyser for hydrogen production with renewable energy sources
BoP	Balance of Plant
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
HPP	Hydrogen Production Plant
PID	Piping and instrumentation diagram
ITSE	Intermediate Temperature Steam Electrolyser
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
TES	Thermal Energy Storage
WP	Work Package

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1 Introduction

The objective of this deliverable is to provide recommendations for the development of a hydrogen production plant coupled to renewable energy. The verification of the top-down scalability of the technology was achieved in the deliverable D3.4.

Thus, one demonstration case will be set up. One of the recommendations from D3.4 concerned the coupling of a demonstrator to a solar-thermal power source, and this is taken as the starting point. The demonstration plant has an electrical capacity of 20 kWe. A concrete site will be selected and the energy source will be specified. For this purpose existing testing facilities will be considered and checked.

Chapter 2 will provide the preliminary design of the demonstration case. The key components will be preliminarily designed and sized. Finally in chapter 3, an estimation of the development costs will be given.

2 Preliminary Design

2.1 Intermediate Temperature Steam Electrolysis Stack

The demonstrator will be representative of an actual application and hence include the major balance of plant components. Based on this demonstrator, a full-scale system could be designed. The design of the demonstrator consists of the definition of the electrolysis stack and the energy source by taking into account existing test facilities. The ITSE stack as shown in figure 1 was defined in the deliverable D3.4.

Figure 1: ITSE stack

Regarding the size of ITSE, defined as the electrical power of the stack, SOEC are currently developed in power range of 10 to 40 kW. The size of the ITSE demonstrator stack was defined within a meeting in February 2013 with the partners involved in WT 3.3 (DLR, HYG, EIFER and EA). The stack modelled by the project partner HTceramix has a power of 3.9 kW. It is decided to consider a demonstration unit of 16 kW, which consists of two 8 kW subsystems. Each of the 8 kW units consists of 2 of these 3.9 kW stacks. This 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. Balance of plant components for this scale size is expected to be readily available on the market. The next table summarizes the technical specifications of the ITSE unit.

Table 1: Technical specifications of the ITSE stack

Technical Data	
Operation mode	Thermo-neutral
Stack inlet/outlet temperature	700°C
Operating pressure	1.5 bar
Pressure drop	0.5 bar
Sweep gas	Air
Sweep gas/steam ration	1:1
Steam to hydrogen conversion	60%
Stack composition	60 cells
Area specific resistance (ASR)	0.5 Ω cm^2
Stack power	3.9 kWe
ITSE unit of the demonstrator	16 kWe

2.2 *Solar tower with Air as a Heat Transfer Fluid*

Electric power for the electrolyser is provided by the steam turbine of the solar power plant. The hot air is not only acting as a heat transfer fluid for the Rankine cycle, but is also used for the evaporation of the ITSE feed water. To operate the plant under full load, the volumetric receiver has to be illuminated with sufficient solar radiative power.

2.2.1 Existing testing facilities

The high-flux solar furnace and the xenon high-flux solar simulator at DLR are used for exploration and testing new technologies with concentrated sunlight and artificial light, whereas temperatures of above 2000 °C are possible to achieve.

DLR solar furnace

In the solar furnace the energy of the concentrated solar light can be utilized to induce thermal effects on irradiated materials. The sunlight is reflected by a flat mirror (heliostat) onto a concentrator. The irradiation is turned out of the optical main axis and is focused in an experimental area of the solar furnace laboratory building. The total radiant power of up to 25 kW suns up to a flux density of 5 MW/m². The flux of the incoming, concentrated irradiation is adjusted by a shutter, thus the irradiation reaching the target can be controlled very accurately. This alignment is called off-axis and has the advantage that the focal point does not shadow the experimental set-up as it would be with on-axis geometry. The heliostat of the solar furnace is a plane mirror with an area of 57 m² that was originally used as one of 30 test series heliostats in a solar power tower in Almeria, Spain. It was modified for the DLR solar furnace, now tracking the sun, thus reflecting the incident solar radiation on the concentrator. The mirrors are made of float glass with a reflective layer of silver that is fixed on the back side because of the unavoidable weather conditions. In addition, the front side is coated with titanium oxide to guarantee the reflection of the UV spectrum of the solar radiation.

The concentrator consists of a Fresnel array of 159 hexagonal spherical mirrors which concentrates the sun radiation into the laboratory building, where it can be directed to a test object. The total area of the concentrator is 42 m², its average focal length is 7.3 m and the individual mirrors have an edge length of 32 cm. The concentrator mirrors are coated with aluminium on the front side and are protected by a vapour-deposited silicon oxide layer against weather impact. Figure 2 shows the solar furnace.

Figure 2: DLR solar furnace concentrator

The shutter at the entrance to the laboratory building 3 is used for adjusting the concentrated solar radiation. Within 0.02s, the incident radiation can be varied from 0 to 100 %. Despite the position of the shutter of about 1 m before the focal point it is exposed to considerable thermal stress. The irradiance here is already about 55-times higher than the plain solar radiation. The shutter may achieve temperatures of up to 300°C and is therefore coated with a heat resistant paint.

Figure 3: Shutter of the solar furnace

Since the start-up of the solar furnace operation in 1994 about 160 experimental campaigns have been carried out, reaching from the production of hydrogen to the implementation of tests under space-like conditions. The solar furnace laboratory building is constructed to the low energy architectural rules. The following table summarizes the technical specifications of the solar furnace.

Table 2: Technical specifications of the DLR solar furnace

Technical Data	
Solar Furnace	
Concentration	5,200
Maximum power	22 kW @ 850W/m² DNI
Radiation flux density	4.5 MW/m² @ 850W/m² DNI
Heliostat	
Dimensions, W x H	8.2 m x 7.4 m
Weight	3,000 kg
Mirror area	57 m²
Reflektivity of the mirrors in new condition	87% @ AM2
Gear ratio	88,000
Concentrator	
Dimensions, W x H	7.3 m x 6.3 m
Mean focal lenght	7.3 m
Weight	6,000 kg
Mirror area	42 m²
Reflectivity of the mirrors in new condition	89% @ AM 2

Xenon-High-Flux solar simulator

The xenon-high-flux emitter (Figure 4) is considered to be a solar simulator and delivers quite similar radiant conditions as the solar furnace. 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 100cm² at a distance of 3m with irradiance greater than 4.1 MW/m². Beyond the means of the solar furnace, it is possible to carry out experiments of several days duration under very stable radiant conditions and component tests on certification level.

Figure 4: DLR High Flux Solar Simulator

The laboratory building of the solar furnace includes a test room to perform the experiments, a control room for the management and operation of the experiment, and a workshop to prepare the works and the test set-ups. In addition, the experiments have access to chemical and material laboratories. The experimental set-ups are installed in the test room on a positioning table in order to place them in the focus of the concentrated solar radiation. An extensive data acquisition system allows the control and analysis of the experiments; for example temperatures, voltage, cooling water flows and other signals can be visualized and recorded. For the non-contact measurement of high temperatures pyrometers and infrared camera systems are used. In addition, radiation flux density measurement systems provide information on the incident power that is exposed on the experiment. The next table summarizes the technical specifications of the DLR solar simulator.

Table 3: Technical specifications of the Xenon-High-Flux solar simulator

Technical Data	
10 Xenon short-arc lamps with elliptical reflectors	Thorium-doped tungsten electrodes
Electrical power per lamp 6 kW(U=37 V, I= 160 A)	Operating pressure of lamp: 80 bar
Ignition voltage Ui=40kV	Luminance 10,500 cd/m²
Arc Length: 9 mm (cold), 7.5 mm (hot)	Magnetically stabilized arcs
Optional: UV-A/B/C Emission	Spectra similar to sunlight
Concentration	4,500
Maximum power	20 kW
Radiation flux density	4.2 MW/m² @ 165 A rated current
Dimension, W x H	4.5 m x 3 m
Weight	800 kg
Aperture	6 m²
Reflectivity of the mirrors in new condition	89 %

Thus, the solar simulator of DLR gives a good possibility to perform preliminary test of a 4kWe single stack.

<u>Solar Tower Jülich</u>

The project partners of industry and research (Kraftanlagen München GmbH, Stadtwerke Jülich GmbH, Solar-Institut Jülich der FH Aachen, Deutsches Zentrum für Luft- und Raumfahrt e. V.) have installed a dedicated research platform at half level of the 1.5 MWe solar thermal test and demonstration power plant Jülich (STJ). In parallel to the operation of the power plant about 20% of the heliostats of STJ may be appointed to experiments needing highly concentrated solar radiation. They may be designed for a power of up to 500 kW. The laboratory of the research platform has an area of 80m², a height of 3m and has a 7m x 3m opening to the heliostat field. Figure 5 shows the solar tower of Jülich.

Figure 5: Solar Tower of Jülich

Table 4 summarizes the technical specifications of the DLR solar simulator.

Table 4: Technical specifications of the solar tower of Jülich

Technical Data	
Receiver	Open volumetric receiver
Receiver thermal energy	7.5 MWth
Electricity generation	1.5 MWel
Heat transfer fluid	Air (680°C, 1 bar)
Steam generation parameters	480 bar, 26 bar
Heliostat number	2,000
Tower height	60 m

Thus, the STJ facilities provide an excellent opportunity for coupling of the ITSE demonstrator unit to a power source, with the possibility to provide both electric power and hot air for heating the steam generator.

SoHTEK receiver

To provide the electrolyser with superheated steam at temperature level of 600 to 700°C a solar tube-type receiver with a cylindric configuration has been developed as depicted in figure 6. Saturated steam of 100 °C enters the absorber pipes from behind and is superheated up to 700°C by concentrated solar radiation. This receiver has been developed by DLR within the internal project SoHTEk (Solar High Temperature Elektrolysis).

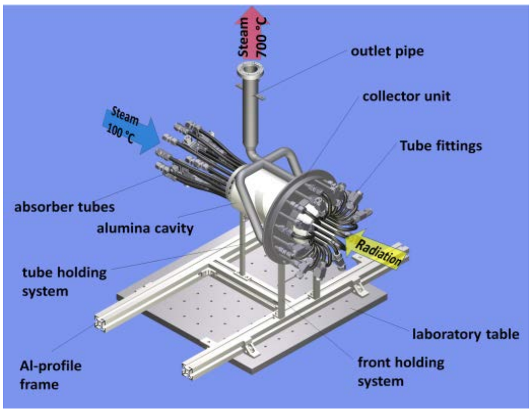

Figure 6: CAD design of the SoHTEk receiver

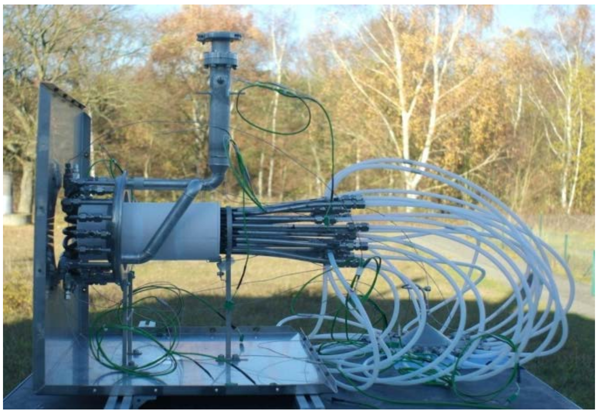

Figure 7: Mounting of the SoHTEk receiver

The aperture diameter is fixed by the nominal diameter of DLR's solar simulator focal point of 90mm. Steel tubes with 10 mm outer diameter were chosen because of their good availability off the shelf. Therefore, the amount of tubes was set to 20 in order to shape the required aperture. The remaining degrees of freedom for the geometry were calculated by applying an integral heat balance of the system. This has been done by assuming a tube wall temperature of 900°C. On the steam side the heat flux is given by the energy amount for superheating steam from 100°C up to 700°C.

2.2.2 Flowsheet of the demonstrator in the laboratory

The following figure shows the flowsheet of the demonstration plant in the laboratory. The test set-up is designed to investigate the water splitting using the ITSE stack modelled by HTceramix. It is decided to carry out preliminary tests for a single stack of 4 kW to study the behaviour of the ITSE. The feed water of the ITSE is vaporised in the steam generator developed by the ADEL project partner HyGear, which uses low pressure steam as a heat transfer fluid but could also be designed to work with other heating media such as hot air. LP steam may be generated by an electrical heater or by using the SoHTEk receiver already presented. Another possibility of generating LP steam consists of using hot air from the solar receiver as a heat transfer fluid. The water vapour can be mixed with preheated hydrogen in order to keep the composition of the inlet steam/hydrogen gas at 90 mol. % H_2O and 10 mol. % H_2 as already specified in the project. Analysis of the composition of the H_2O/H_2 stream is realised by a gas chromatography with mass spectrometry The temperature of the streams is measured with a type K thermocouple. The flow rates of the streams are controlled by volumetric flow controllers and can be adjusted. Ambient air is used as a sweep gas and is heated up to 680°C by the solar receiver. A further heating will be performed by an electrical heater, in order to rich the operating temperature of 700°C.. The flow rate of the sweep gas is adjusted by the flow control FC1 in order to maintain a sweep gas/steam molar ratio of 1. The water splitting reaction takes place in the ITSE stack at 700°C and 1.5 bar. The electrical power of the ITSE can be introduced from the grid or generated by the solar tower of Jülich.

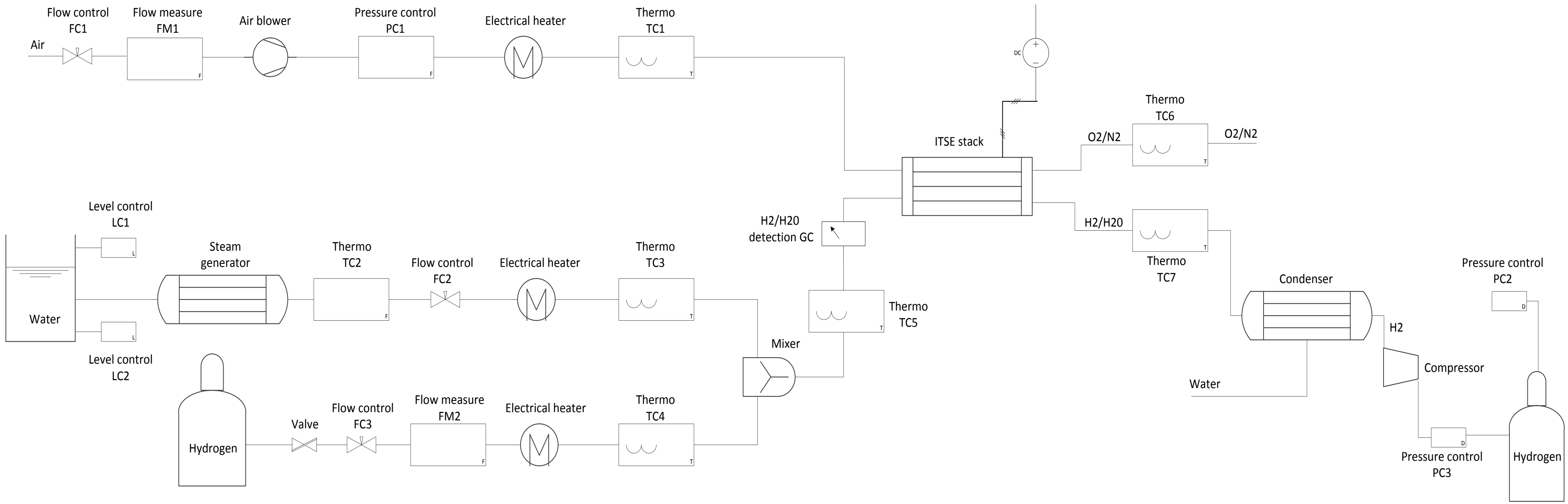

Figure 8: Flow sheet of the demonstrator in the laboratory

The next table shows the results of the simulation of the demonstration plant.

Table 5: Results of the demonstration plant

Air blower [kW]	0.15
Air electrical heater [kW]	2.01
Steam generator [kW]	4.87
Steam electrical heater [kW]	2.28
ITSE electrical power [kW]	16
Condenser heat duty [kW]	4.2
Hydrogen compressor power [kW]	1.52
ITSE feed water mole flow [kmol/h]	0.375
Sweep gas mole flow [kmol/h]	0.375
Hydrogen product mole flow [kmol/h]	0.262

2.2.3 Preliminary sizing of BoP component

2.2.3.1 Air blower

Each of the parallel units will have its own blower for sweeping air; in this way the air supply to both units can be controlled by means of the blower speed, and there is no need to include control valves (that would cause extra pressure drop). In the required size range (about 50-100 slm, pressure increase below 100 mbar) many blowers are available on the market. The airflow can usually be controlled by direct control of the blower speed, by means of frequency controllers. No specific challenges are foreseen.

Figure 9: Brushless radial turbo air blower (Domel)

2.2.3.2 Electrical heaters

Both the air and steam feeds to the stacks need to be heated to the desired inlet temperature (downstream of the recuperators). Each subsystem will have its own electric heaters. The heating power will be of the order of a few hundred Watts (expected: 0.15-0.30 kW). Many heaters are available for these duties and temperatures. Use could be made of rod-heaters that are placed in the gas pipes. Care should be taken that the Watt density of the heaters is not too high, so the heater surface should be of a minimum size. This guarantees sufficiently long lifetimes.

Figure 10: Electric rod heaters (Watlow)

2.2.3.3 Boiler for steam generation

The steam generator will most likely be a custom design. Each subsystem may either have it its own steam generator, or a single steam generator may be shared between them. Sharing poses high demands to the turn-down of the steam generator, but for a big plant it could be a means to bring down capital costs (although beyond a certain size scale parallel steam generators may have to be used anyway, because of capacity limitations). Moreover, a shared steam generator may make a fast start up of a subsystem from idle mode possible, if the other subsystem was still producing. Hence it is recommended to investigate this option in the demonstration units. Since the steam can easily be produced at (somewhat) increased pressure there is no energy penalty for using control valves to direct the steam from a single steam generator to the two subsystems. The prerequisite for sharing a single steam generator between the subsystems is that it should be well possible to control the flow rate of the heating media to the steam generator. In case hot air from the receiver is used this requires some consideration, since the air is very hot (~600°C. In case LP-steam is used for heating of the steam generator, control should be straightforward by means of flow control valves.

The capacity of the steam generator will be typically 5-10 kg/h (thermal power 3-6 kW). HyGear has extensive experience with the design of steam generators in this size range. The heating media may be passed through finned heat exchange tubes that stand in a pool of boiling water. An example is shown in figure 12.

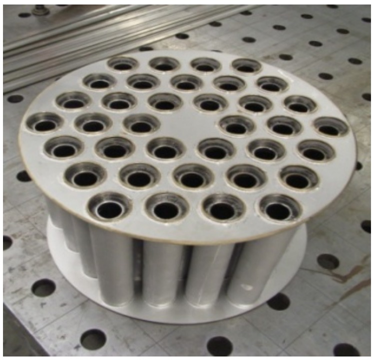

Figure 11: Steam generator (HyGear)

2.2.3.4 Feed water pump

Pumps in the required size range (5-10 l/h) are readily available on the market. The required delivery pressure will most likely have to be about 20 bar, depending on the boiler feed water treatment (application of RO requires elevated pressure).

The flow rate can be controlled by direct control of the pump itself. If a reciprocating pump is selected then flow pulsations should be taken into account.

2.2.3.5 Feed water treatment

The feed water that is sent to the steam generator should be free from contaminants. The treatment steps depend heavily on the quality of the available water. Both suspended and dissolved contaminants may be present.

Usually the first step in water treatment is filtration. Next, important contaminants to take into account concerns dissolved salts (hardness) which can cause fouling and scaling of the heating surfaces. Requirements for conductivity are severe, and should be less than 5 µS/cm. The conductivity should be continuously monitored. Most often the treatment includes Reverse Osmosis (RO) in combination with Mixed-Bed Ion Exchange (IX). The latter requires (in a full scale plant) regular regeneration of the sorbent by means of strong acids and bases; in a small plant (like the demonstration unit) replacement of the sorbent may be considered instead.

Other types of dissolved compounds (e.g. organic compounds) may be removed by applying an additional active carbon filter.

Treatment units of this scale are readily available on the market; examples are shown in following figure.

Figure 12: Left: RO system (Pure Pro), Right: Mixed-bed filter (Culligan)

2.2.3.6 Cooler for the hydrogen product

The final product cooling and condensation will be performed by means of air-cooling. It is preferred to do this in a direct manner (i.e. not by using an intermediate cooling loop) in order to guarantee a low temperature, and thus water content, at all times.

Each subsystem will have its own cooler. The cooling duty is quite low at only 0.5-1 kW per unit. The design will consist of finned heat exchange tubes, like the one shown in figure 14. The design may have to be customized (number of tubes, passes) but should be available from market parties.

Figure 13: Finned heat exchanger

2.2.3.7 Product compressor

For the case of use of hydrogen as a transportation fuel the hydrogen will have to be compressed to a few hundred bars. The total product flow is about 5 Nm^3/h. A piston compressor may be applied like the one shown in the following figure.

Figure 14: Piston compressor (HydroPac)

2.2.3.8 Product dryer

In case the hydrogen is compressed and stored, a product dryer may be added to the system as well. Drying is preferentially performed at some elevated pressure, i.e. in between compressor stages. Usually adsorption is the technology of choice, applying a twin-bed system with one bed in adsorption mode and the other in regeneration mode. Regeneration takes place by heating; possibly a heat stream from the solar plant or biogas unit can be applied.

2.2.4 Design of a ITSE demonstrator coupled to the air solar tower

The next figure shows the lay out of the demonstration plant, which will be installed in Jülich (Germany). This consists of the heliostat field, storage tanks and the solar tower. The heliostat field of the solar tower of Jülich consists of 2000 heliostats.

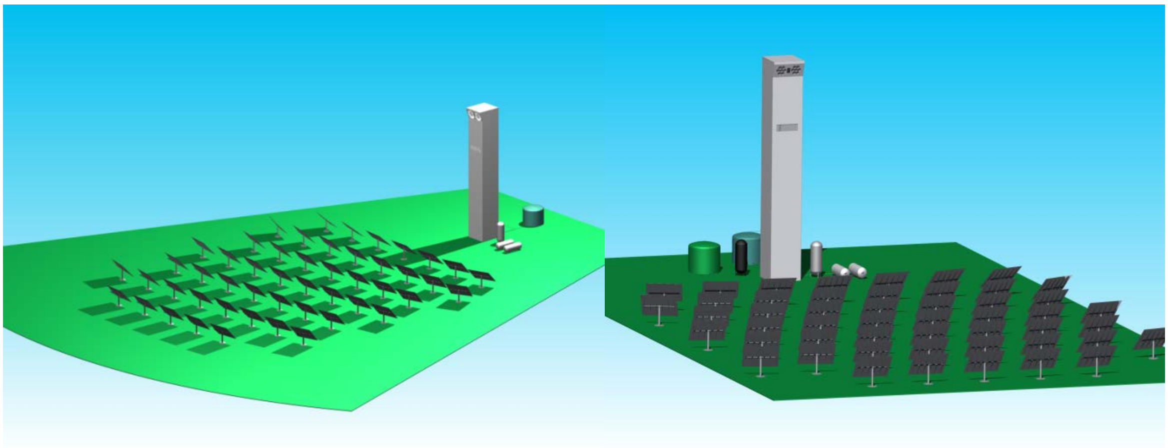

Figure 8: lay out of the heliostat field

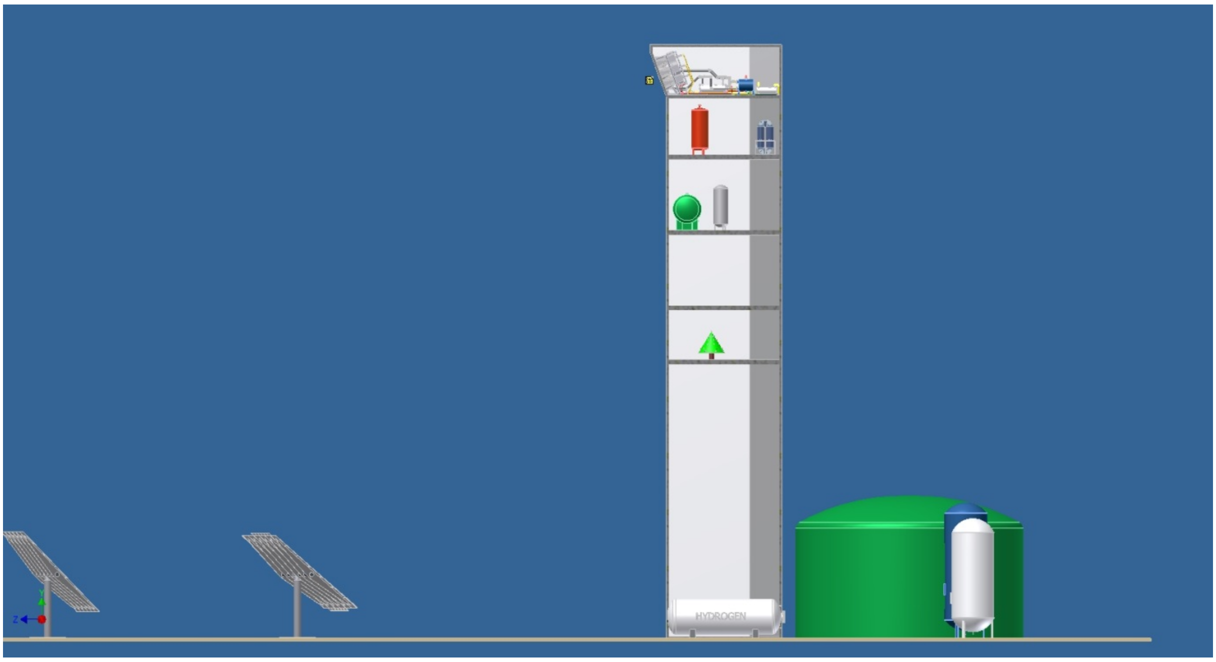

Figure 9: design of the demonstration plant

The following figures show the design of the demonstration plant. The main components of the demonstration plant will be mounted on the top of the tower. Two solar receivers will be installed. The first receiver is the open volumetric receiver which aims to heat ambient air up to 700°C. This will act as a sweep gas in the ITSE stack. The second receiver is the SoHTEk receiver, where the ITSE feed water is evaporated. The overheating of the ITSE water up to 700°C is carried out by the heat recovery system and an electrical heater. The storage tanks for hydrogen and water are located below the demonstration plant as shown in figure 18b.

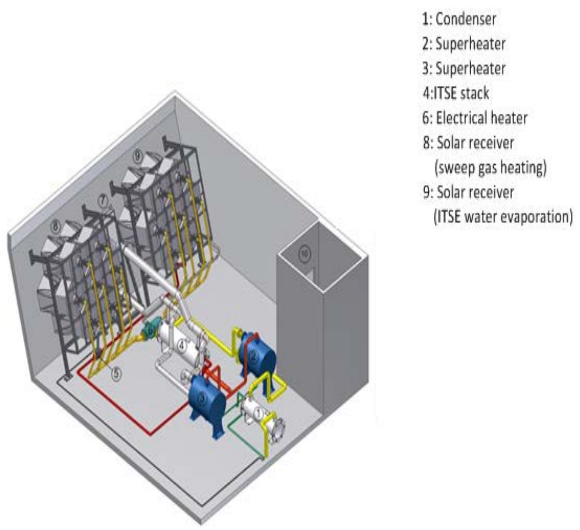

Figure 10a: design of the demonstration plant

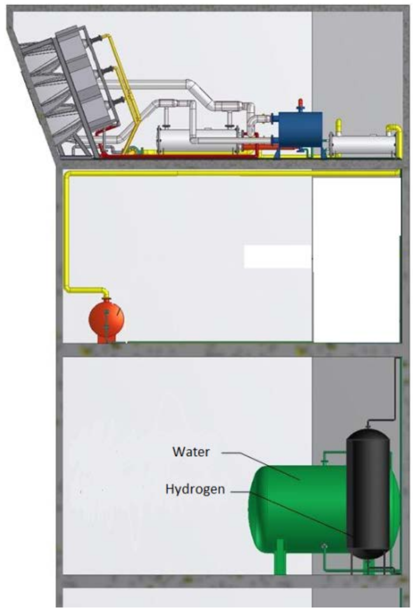

Figure 18b: side view of the solar tower

2.2.5 Estimation of the investment cost of the demonstration plant

The BoP components of the demonstration plant have been specified by the ADEL project partner HyGear. A first cost estimation of the main BoP components has been done by HyGear by taking into account the specifications summarized in section 2.2.3. This cost estimation only concerns the expenses of the main components of the demonstration plant in the solar Tower of Jülich. The real cost of the demonstration plant by taking into account direct and indirect costs e.g. valves, controllers, power supply, engineering etc. may be higher by a factor 2-3 than the costs of the main components. The following table shows the cost of the demonstration plant. It is assumed that existing testing facilities in Jülich will be used in order to perform the demonstration of the hydrogen production via ITSE.

Table 6: Cost of the components of the demonstration plant

Component	Cost [€]
Air blowers	700
H2 recycle blowers	500
HT recuperators	5000

Electric heaters	200
Feed water pumps	400
Feed water treatment	2800
Product compressor	30000
SoHTek receiver	25000
Coolers/condensers	2400
Product dryer	7000
Storage tanks	16000
ITSE stacks	12800

The total bare equipment costs of the demonstrator is estimated to be at 102,800 €. This does not include piping, sensors, insulation, engineering and system construction costs, hence the total costs may be considerably more than a factor 2 higher than the shown bare equipment costs.

3 Conclusion

This deliverable provides the basis for the definition, specification and estimation of bare equipment costs (main components only) of a demonstration unit for the ITSE technology coupled to air cooled solar tower of Jülich. The demonstrator represents a complete system, including all relevant balance of plant and is directly coupled to the air cooled solar tower of Jülich. A scale of 15-20 kW was defined for the demonstrator. The demonstrator is built 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 first simulation of the demonstration plant was performed and leads to a hydrogen production of 0.262 kmol/h. A first design of an ITSE stack coupled to the air solar tower of Jülich was carried out. The design consists of the use of the air solar receiver for the generation of hot air, which will act as sweep gas. Additionally, the SoHTek receiver is installed on the solar tower in order to evaporate the ITSE feed water.

A cost estimation of the demonstration plant was carried out. HyGear has defined the BoP components of the plant and its costs. Based on the costs provided by HyGear, the main equipment for the demonstration plant designed in this deliverable will cost 102,800 €. It needs to be mentioned that this only represents equipment cost. Additional cost contributions are expected to raise the cost for a demonstration plant significantly. If piping, control, instrumentation, wiring, adaptation/building of infrastructure, development costs etc. are considered in addition the overall cost will raise to an amount several times higher than only the equipment.