



SEVENTH FRAMEWORK PROGRAMME
Joint Technology Initiatives - Collaborative Project (FCH)
Water decomposition with solar heat sources

Deliverable D6.2
Calculation of demonstration plant cost

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CONTRACT N°: 2425224

ACRONYM: HYDROSOL-3D

TITLE: Scale Up of Thermochemical HYDROgen Production in a SOLar Monolithic Reactor: a 3rd Generation Design Study (*HYDROSOL-3D*)

PROJECT START DATE: 01-01-2010
Date of issue of this report: 28-02-2013

TO December 31st 2012
DURATION: 36 months

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1. Introduction

The successful completion of a thermal design [1] consists of the calculation of the major costs involved in the project. This deliverable will focus on the cost calculation of the demonstration plant after a flow sheet has been developed.

The cost of the demonstration plant can be calculated through the following steps:

- i. Size the units of plant
- ii. Calculate the cost of the equipment
- iii. Determine the direct and the indirect cost related to the installation and the operation of the plant

The main inputs for the cost calculation of the demonstration plant are the results of the steady-state simulation. The steady-state simulation of the demonstration plant has been carried out and its results have been summarized in the deliverable 5.2 [2].

2. Component sizing

2.1 Solar part of the plant

The demonstration plant has a rated thermal capacity of 1 MW defined as the heat absorbed by the reactors/receivers.

To operate the plant under full load, the volumetric receiver and the secondary concentrators have to be illuminated with sufficient solar radiative power. In addition to the energy required to fuel the metal oxide reduction reaction, the reactors need enough thermal energy to cover other consumptions and losses:

- The reactor thermal losses.
- The energy consumed for vaporizing and overheating the water.
- The losses of the secondary concentrators and the quartz glass window (radiative and convective losses).

For this reason, an incoming thermal power requirement of 1.8 MW has been calculated [3].

The solar field was laid out with heliostats of the type Inabensa Colon 70. This heliostat type has already been installed and tested on the Plataforma Solar de Almeria (PSA). With a reflective surface of about 70 m², they belong to the “large heliostats” category. This has the advantage to reduce the number of heliostats and tracking units needed. The reflectivity of the (clean) mirror surface is 93 %.

In the simulation, the heliostats are arranged in rows on a flat plane. Because incident rays forming great angles to the receiver normal direction have a smaller chance to pass the outlet aperture of the secondary concentrators, the rows are limited in their width. Because of the growing distance between the heliostats and the tower, the risk of blocking and shading increases. To avoid this matter, the spacing between the heliostats widens too. With a suitable field arrangement, the blocking and shading losses can be reduced by a few per cent. An expanded field leads to an increased path length between the heliostat and the receiver. However, the atmospheric attenuation represents only a small part of the total losses for the Hydrosol pilot plant and gains in importance only for much bigger plants.

During the design process, it has to be considered that the solar irradiation depends on daily and seasonal fluctuations. For this reason, it is necessary to oversize the solar field with regards to the required nominal power. The ratio of the thermal power provided by the heliostat field to the peak thermal power required by the receivers is called the solar multiple. The fixing of the solar multiple is defined by economical dimensions. This plant should operate under full loads over the period from March to October between 9 am to 16 pm under good weather conditions (a full load operation out of this time is only possible with a dramatic expansion of the heliostat field). For this purpose, a solar field power was determined about 2.2 MW. The following table shows the results of the simulation performed with the simulation tool HFLCAL.

Table 1: Results of the simulation of the heliostat field and solar tower

Parameter	Value [Unit]
Dimensions of the tower (W x L x H)	8 x 12 x 53 [m]
Receiver height	50m
Declination of the receiver	20°
Location	Southern Spain
Field power	2.2 MW
Number of heliostats	50
Entire mirror surface	3465 m ²
Annual efficiency	61.39%
Full load hours	2040 h/a

2.2 Pressure swing absorber

For a given feed with a defined pressure and composition, the main design variables of the PSA are the following:

- Vessel volume
- Cycle time
- Equalization pressure
- Offgas pressure

The dimensions of the PSA have been calculated by HYGEAR and the results are available in the deliverable 4.2 [4]. The physical dimension of the PSA vessel for the demonstration plant was set to an inner diameter of **76.1 mm** and a bed height of **478 mm**.

2.3 Compressors and pumps

The design of the compressors and the pumps consists of the calculation of its electricity consumption. The following table shows the simulation results of the compressors and pumps of the process obtained by the simulation tool ASPEN plus within the analysis made in the deliverable 5.2.

Table 2: Simulation results of the compressors and pumps

		Mass flow [kg/hr]	Mole flow [kmol/hr]	T _{in} [°C]	T _{out} [°C]	P _{in} [bar]	P _{out} [bar]	P _{el} [kW]
PSA compression								
	COMP1	9.8	4.25	40	255	1	3.89	7.39
	COMP2	9.8	4.25	45	263	3.89	15.1	7.51
Hydrogen compression								
	COMP3	8.63	4.2	45	109	12	19	2.19
	COMP4	8.63	4.2	70	139	19	30	2.36
Water Pump	PUMP	216	12	25	25	1	1.066	0.00044

2.4 Heat exchangers

The simulation results of the heat exchangers have been summarized in the deliverable 5.2. The design of the heat exchangers aims to the specification of the construction material and the calculation of the heat transfer area. This has been carried out with the simulation tool "ASPEN Exchanger Design and Rating 7.0". The next table shows the calculation results of the heat exchangers of the process.

The heat exchangers, which have been used for the HYDROSOL 3D process, are shell and tube heat exchangers, which are the most common type of heat exchangers in chemical processes. It consists of a shell with a bundle of tubes inside it. The basic design equation of the heat exchanger becomes:

$$Q=U.A.MTD \quad \text{Eq.1}$$

where Q is the total heat to be transferred, U is the overall heat transfer coefficient, A the heat transfer area, MTD the mean temperature difference, which is related to the logarithmic mean temperature $LMTD$ difference by the following equation:

$$MTD=F.LMTD \quad \text{Eq.2}$$

F denotes the configuration correction factor for tube-side and shell-side passes.

Once the temperatures of both streams (hot and cold stream) of a heat exchanger are specified, $LMTD$ can be calculated. By the specification of the material of the heat exchanger, the overall heat transfer coefficient U can be calculated and the heat transfer area A can be determined from Eq.1. This has been done by the simulation tool "ASPEN Exchanger Design and Rating". The next table shows the design of the heat exchangers. Based on the calculated heat transfer area A , the cost of the heat exchanger can be determined.

Table 3: Simulation and design results of the heat exchangers

		<i>PREHX</i>	<i>EVAPORA1</i>	<i>EVAPORA2/EVAPOR A3</i>	<i>SUPERHX1/SUPER HX2</i>	<i>CONDENS</i>
<i>Material of construction</i>		Stainless steel 304	Stainless steel 316	Stainless steel 316	Stainless steel 316	Stainless steel 304
<i>Mean temperature difference [K]</i>		337	570	218	418	80.67
<i>Overall heat transfer coefficient [W/(Km²)]</i>	Shell side	170.8	208	198	135	1507
	Tube wall	11556.4	11015	10881	13712	28463
	Tube side	800.3	938	2192	79	543
	Overall	139.1	167.9	179.1	50	394
<i>Heat transfer [kW]</i>		16	58	86	54	125
<i>Heat transfer area [m²]</i>		0.34	1.3	2.2	1.7	3.73

3. Cost calculation of the plant components

Estimating the cost of equipment is the first step in detailed cost estimation. The type of equipment and its range of operation have been determined during the flow sheeting and the simulation of the process.

The best sources of cost estimation are cost values from finished projects, quotations from experienced cost estimators. In addition to that, some commercial software packages offer the possibility to estimate the cost of the components. The cost estimation methods which have been used for this analysis are presented in the next section.

Cost indices.

Since cost data are available at different time, a correction of the cost of equipment with regards to the date of the estimate (reference year) is necessary. This can be carried out by using *cost index (CI)*. The reference data C_{ref} can be updated to the present today's cost C_{new} according to the following equation:

$$C_{new} = C_{ref} \left(\frac{I_{new}}{I_{ref}} \right) \quad \text{Eq.3}$$

Here, I_{new} and I_{ref} are the values of the cost index today and in the reference year. Cost indices for the chemical industry are published in several journals such as *Chemical Engineering, The Oil and Gas Journal etc.*

The next table shows an overview of the *Marshall and Swift (M&S) Equipment* cost indices of the last years. The M&S equipment cost indices has been used in this analysis since it is recommended for single equipment cost estimation.

Table 4: Cost index 2006-2012

Year	2006	2007	2008	2009	2010	2011	2012
Cost index	499	525	575	521	550	585	593

Size effect on equipment Cost.

For thermal process equipment, the percentage increase in equipment is smaller than the percentage increase in equipment size. This issue is described by the scaling exponent α as shown by the following equation:

$$C_{PE,Y} = C_{PE,W} \left(\frac{X_Y}{X_W} \right)^\alpha \quad \text{Eq.4}$$

where $C_{PE,Y}$ is the cost of the equipment with the size or capacity X_Y and $C_{PE,W}$ is the cost of the same unit but with a different size of capacity X_W .

The cost estimation of the solar part (Heliostat field, reactor and tower), the heat exchangers, the compressors and the pumps of the plant has been carried out by DLR. The project partner HYGEAR was responsible for the cost estimation of the pressure swing absorber (PSA)

3.1 Cost of the solar part

The solar part of the plant includes heliostats, receiver and tower as well as the equipment and supporting systems. The cost of solar tower has been calculated according to

the next equation, which has been generated by DLR for the cost calculation of solar tower system:

$$C_{Tower} = K_1 + H_1 \cdot TVER^{ALPHA} \quad \text{Eq.5}$$

where $K_1=250000\text{€}$, $H_1=14.77\text{€/m}$, $ALPHA=2.392$ and $TVER$ denotes the tower height. According to this equation, the solar tower costs **446,719€**.

The ABENGOA heliostats have been selected as the most suitable ones, which costs 120€/m^2 . The total cost of the heliostat field is calculated at **720,000 €**.

The following table shows the main components of the solar reactors and its cost calculation carried out by DLR.

Table 5: Cost calculation of the solar reactors

Component	Number of units	Cost per unit [€]	Total Cost [€]
Quartz plates	14	600	8400
Reactor modules	14	3000	42000
Secondary concentrator	14	12000	168000

The next table shows the summary of the total cost of the honeycombs, the redox material and the coating process. Each reactor unit consists of 16 honeycombs. The cost of the honeycombs has been calculated by APTL to be at 50€/monolith . The redox material costs 30€/monolith .

Table 6: Total cost of the honeycombs, the redox material and the coating process

Component	Total Cost [€]
Honeycombs [€]	11200
Redox material [€]	6720
Coating process [€]	3808

The total cost of the solar reactors including receiver, secondary concentrator and material is calculated to be at **240,128 €**. The solar part of the plant including the heliostat and the tower costs **1.406 Mio. €**.

3.2 Cost of the pressure swing absorber

Two cases have been considered regarding the hydrogen separation in the pressure swing absorber (PSA): a base case and a high purity case (See deliverable D4.2 for more information). The cost for the two cases are almost equal since the difference of the vessel sizes of two cases is small (the main difference between the cases is related to the way of operation i.e. by the adsorption cycle time).

For the demonstration plant, the total cost of the PSA has been calculated by the project partner HYGEAR to be at **250,000€**. This includes all equipment, engineering, installation and transport. The calculated cost of the PSA does not include the cost of the compressors since a compression to the PSA operating pressure of 15 bars is required. A buffer is necessary in order to control the N_2 content of the product gas after leaving the

solar reactor and before entering in the PSA. The cost of the buffer has been also calculated by HYGEAR to be at **15,000€**. This will lead to a total cost of the PSA about **265,000€**.

3.3 Cost of the compressors and pumps

The compressors used for the compression of the product gas to the operating pressure of the PSA and the compression of the hydrogen product to the storage pressure are centrifugal compressors since they are the most common compressors, which are characterized by high capacities and low compression ratios. The costs of the compressors have been calculated by using cost equations from 2007 [5]. By using the cost index of the years 2007 and 2012 (It is assumed that the plant will be built over night and the start-up of the operation will be at the end of 2012), the cost of the compressors in 2012 have been determined as given by Eq.3.

The following table shows the cost calculation of the compressors of the demonstration plant.

Table 7: Cost calculation of the compressors

Cost calculation of the compressors	PSA compression		Hydrogen compression	
	COMP1	COMP2	COMP3	COMP4
<i>Cost of the compressor in 2007, CC_{2007} [Mio. €]</i>	0.0806	0.081	0.058	0.059
<i>Cost of the compressor in 2012, CC_{2012} [Mio. €]</i>	0.093	0.093	0.067	0.068
<i>Installation cost of the compressor IC [Mio.€]</i>	0.074	0.075	0.054	0.054
<i>Total cost of the compressor TC_{2012} [Mio. €]</i>	0.167	0.168	0.121	0.123

According to Table 7, the costs of the compressors of the plant are calculated to be at **581,988 €** for the reference year 2012.

The same procedure has been used for the cost calculation of the pumps. Table 8 shows the costs of the pumps.

Table 8: Cost calculation of the pumps

Cost calculation of the pump	PUMP
<i>Cost of the pump in 2007, CC_{2007} [€]</i>	743
<i>Cost of the pump in 2012, CC_{2012} [€]</i>	861
<i>Installation cost of the pump IC [€]</i>	1205
<i>Total cost of the pump, TC_{2012} [€]</i>	2066

As shown in the Table 8, the total cost of the pumps is about **2066 €**.

3.4 Cost of the heat exchangers

After the calculation of the heat transfer area and the specification of the heat exchanger material, the first step of the cost calculation of the heat exchangers consists of the determination of the base price. This does not include the costs related to the impact of the pressure and temperature on the equipment cost. Other costs are also not included such as the construction and the installation cost. Those mentioned aspects are generally considered with correction factor in order to obtain the total cost of the module.

The cost of the construction C_c of the heat exchangers is calculated according to the following equation:

$$C_c = 0.44C_p \quad \text{Eq.6}$$

where C_p denotes the base price of the heat exchangers. The pressure and temperature influence have been already taken into account. The costs of the installation material C_M are given by the next equation:

$$C_M = 0.71C_p \quad \text{Eq.7}$$

The other indirect costs related to the heat exchangers such as fee, contingency, installation and transport costs will be considered in the economic analysis.

Table 9: Cost calculation of the heat exchangers

	<i>PREHX</i>	<i>EVAPORA1</i>	<i>EVAPORA2 / EVAPORA3</i>	<i>SUPERHX1 / SUPERHX2</i>	<i>CONDENS</i>
<i>Material</i>	Carbon steel	Carbon steel	Carbon steel	Stainless steel 316	Stainless steel 304
<i>Heat transfer area [m²]</i>	0.34	1.3	2.2	1.7	3.73
<i>Cost of the heat exchanger in 2004, C_p [\$]</i>	4500	6000	8000	16500	15300
<i>Cost of the material for installation C_M [\$]</i>	3195	4260	5680	11715	10863
<i>Cost of construction C_o [\$]</i>	1980	2640	3520	7260	6732
<i>Total cost of the heat exchanger in 2004, C_{T2004} [€]</i>	7442	9923	13230	27288	25303
<i>Total cost of the heat exchanger in 2012, C_{T2012} [€]</i>	9885	13180	17573	36245	33609

As seen in Table 9, the total costs of the heat exchangers are about **110,493 €**.

3.5 Cost of the purchased equipment of the plant

The following table shows the equipment cost of the demonstration plant.

Table 10: Equipment cost of the demonstration plant

Solar part incl. receiver-reactor[€]	1,406,847
Pressure swing absorber [€]	265,000
Compressors and pumps [€]	584,054
Heat exchangers [€]	110,493
Total cost [Mio. €]	2.366

More than half the process unit investment results from the solar system, more precisely the tower and the heliostat field are the main cost factor of this part (Figure 1). The costs of the heat exchangers represent the lowest process unit investment.

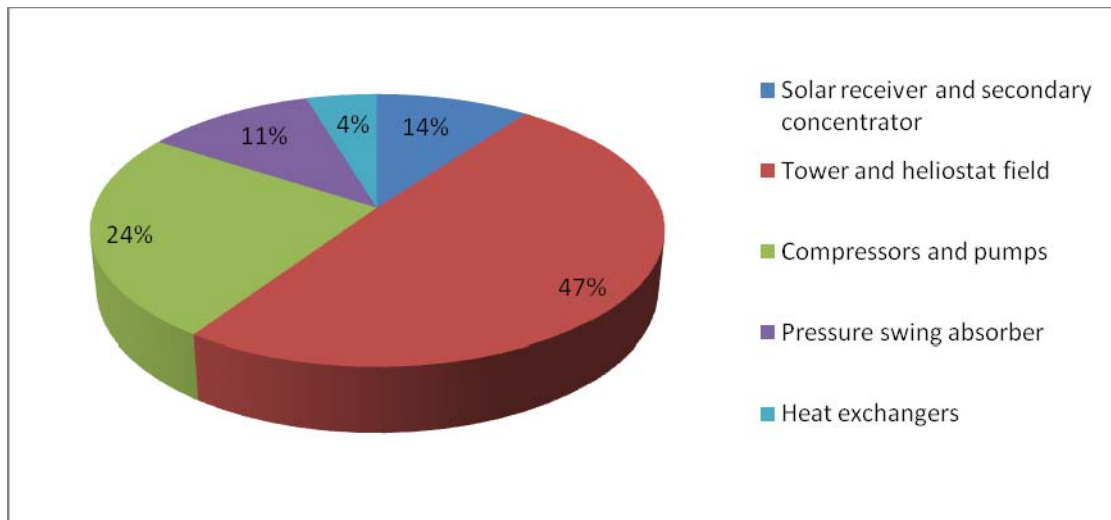


Figure 1: Distribution of the process unit investment of the demonstration plant

4. Calculation of the total investment requirement

The purchased equipment costs have been calculated (see table 10). In this analysis, the factor method is used to calculate the total capital investment *TCI* in terms of percentage of the purchased equipment cost *PEC*. The percentage given in the next table are average values based on experience from various projects in the chemical process industry. This includes direct and indirect costs:

- i. Direct costs: involves the expenses for installation, instrumentation and controls, electrical equipment and materials, civil and architectural work.
- ii. Indirect costs: involves the expenses for engineering, supervision and contingencies.

The calculation of the demonstration plant considers both the general case of a new system design and the expansion of an existing system e.g. the solar tower of Jülich(Germany), which is used and operated by DLR.

The following table shows an overview of the direct and the indirect costs related to the installation and operation of a new demonstration plant given as factors of the purchased equipment cost *PEC*.

Table 11: Calculation of the direct and the indirect costs of the new demonstration plant

<i>Purchased equipment cost</i>	PEC
<i>Direct cost(x*PEC)</i>	
Piping	0.15PEC
Instrumentation and control	0.25PEC
electrical equipment	0.15PEC
Civil, structural and architectural work	0.15PEC
Auxiliaries and service facilities	0.15PEC
<i>Indirect cost (x*PEC)</i>	
Engineering and supervision	0.25PEC
Site installation	0.15PEC
<i>Other cost (x*PEC)</i>	
Start-up expenses	0.2PEC

The next table shows the direct and indirect costs, and the total capital investment of the new demonstration plant.

Table 12: Direct, indirect costs and total capital investment of the new demonstration plant

<i>Purchased equipment cost [Mio. €]</i>	2.366
<i>Direct cost [Mio. €]</i>	
Piping	0.354
Instrumentation and control	0.591
electrical equipment	0.354
Civil, structural and architectural work	0.354
Auxiliaries and service facilities	0.354
<i>Indirect cost [Mio. €]</i>	
Engineering and supervision	0.591
Site installation	0.354
<i>Other cost [Mio. €]</i>	
Start-up expenses	0.4732
<i>Total capital investment [Mio. €]</i>	5.791

As shown in the table 12, the total capital investment of the demonstration plant is estimated to be at **5.791 Mio. €**.

The second case consists of the adaptation of an existing solar facility to the HYDROSOL 3D process. Due to the fact that some components are already available, the costs of the solar part include only the cost of the solar receiver and the secondary concentrator. In

addition to that, some direct and indirect costs related to the installation of the plant will be avoided. The following table shows the equipment cost of the adapted solar plant.

Table 13: Equipment cost of the adapted solar facility

Solar receiver and secondary concentrator [€]	240,128
Pressure swing absorber [€]	265,000
Compressors and pumps [€]	584,054
Heat exchangers [€]	110,493
Total cost [Mio. €]	1.199

The following table shows an overview of the direct and the indirect costs related to the expansion of an existing solar plant given as factors of the purchased equipment cost *PEC*.

Table 14: Calculation of the direct and the indirect costs of the adapted solar facility

Purchased equipment cost	PEC
Direct cost ($x \cdot PEC$)	
Piping	0.15PEC
Instrumentation and control	0.1PEC
electrical equipment	0.1PEC
Indirect cost ($x \cdot PEC$)	
Engineering and supervision	0.15PEC
Other cost ($x \cdot PEC$)	
Start-up expenses	0.1PEC

The expenses related to the civil and architectural work, site installation and the auxiliary facilities are not included. It was assumed that the expenses of the instrumentation, control and electrical equipment are lower as compared to the new demonstration plant.

The next table shows the direct and indirect costs, and the total capital investment of the adapted plant.

Table 15: Direct, indirect costs and total capital investment of the adapted solar facility

Purchased equipment cost [Mio. €]	1.199
Direct cost [Mio. €]	
Piping	0.179
Instrumentation and control	0.119
electrical equipment	0.119
Indirect cost [Mio. €]	
Engineering and supervision	0.179
Other cost [Mio. €]	
Start-up expenses	0.119
Total capital investment [Mio. €]	1.914

The total investment requirement of the adapted solar plant is calculated to be about **1.914 Mio. €**. This represents about 50% of the total investment requirement of the new demonstration plant.

5. Conclusion

In this analysis, the plant's components have been sized based on the simulation results achieved in the deliverable 5.2. The costs of the equipment have been calculated.

The cases have been analysed regarding the equipment cost calculation and the total investment requirement: the general case of a new plant, which includes new design of the tower and the heliostat field, and the expansion of an existing solar plant. In the last case, which refers to the solar tower of Jülich (Germany), the tower and the heliostat field does not need to be re-designed.

The total cost of the equipment of the new demonstration plant has been calculated to be at **2.366 Mio. €**. Among this, the solar part of the plant represents about 63 % of the total equipment cost due to the higher costs of the heliostats. The total investment requirement of the new demonstration plant has been estimated at **5.791 Mio. €** by taking into account the direct and the indirect costs related to the installation and operation of the plant.

The second case consists of the adaptation of an existing solar plant to the HYDROSOL 3D process. Some components do not need to be installed such as the tower and the heliostats. This will not only lead to a decrease of the equipment cost, but also to a decrease of the direct and the indirect costs related to the site installation and plant's operation. The analysis of this case has shown that the equipment of the adapted plant costs about **1.119 Mio.€**. The total investment requirement of the adapted plant has been estimated at **1.914 Mio. €**.

6. References

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