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

Deliverable D 6.1
Analysis of hydrogen production and supply cost

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CONTRACT N°: 245224

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 TO: 31-12-2012

Date of issue of this report: 28-02/2013 **DURATION:** 36 months

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1 Introduction

This document reports on the economical evaluation of the Hydrosol technology for the generation of green hydrogen.

It first summarizes the main features of the design of a “first of a kind” industrial-size hydrogen generation unit and explains the methodology used for the hydrogen production cost estimate. The cost calculations for current economical conditions are then presented and the results commented. In particular, the impact on the hydrogen production cost of other possible scenarios is discussed (scale of the plant, location,…) and the range of production costs covering all these scenarios is presented. Perspectives for future reduction of the production costs are exposed. Eventually, the cost of transportation is evaluated and a range of hydrogen supply cost is presented.

2 Design of an industrial-size Hydrosol plant

2.1 Plant specifications

Plant location

The production cost of any product from a solar process varies to a significant extent with the quality of the solar resource at the plant location. The selection of the location for a case study can create bias on the results if the chosen location corresponds to extreme resource values.

The location of the Hydrosol industrial case study had to be selected to correspond to a “fair but not outstanding” solar location, so as to reflect an average price of the technology. Considering this and the quality of the solar data available for various sites, the plant location has been set to Almeria, Spain.

Capacity

Whereas the demonstration plant designed under Work Package 5 is sized to accommodate a 1 MW net heat input at the reactor level, the “first case” industrial size plant is designed for 21 MW net thermal input.

Hydrogen production under nominal solar conditions is then derived from this main design specification as follows:

- The heliostat field is designed to insure 21 MW_{th} net thermal input under nominal solar conditions (see Appendix A)
- The solar reactors and downstream process are sized accordingly
- The yearly production is estimated from the nominal production, using the yearly load factor (or “capacity factor”) corresponding to the insolation data at the selected location (load factor accounts for the daily and yearly variations of the solar resource which impact plant production). A capacity factor of 20% is representative of the operation of solar concentrated technologies in the South of Spain.

Note: the 21 MW_{th} capacity chosen for plant design can be considered as the low border of the industrial range of capacities. The largest solar fields currently under construction in the world are about 12 times bigger than the one considered here [1]. This leaves room for cost reduction through scale effect in a phase of large deployment of the technology.

Hydrogen specifications

The hydrogen produced by the plant will be suitable for external sale.

Quality will be compliant with the requirements of the ISO 14687 Type I Grade A.

Hydrogen will be delivered at plant outlet at 350 bar to be suitable for export under gaseous form by tube trailers.

Other specifications

Other plant specifications are provided in Appendix A, together with details about the main specifications summarized in the previous paragraphs.

2.2 Industrial plant design - Methodology

Simulation and CAD tools used for the industrial plant design are similar to the ones used for the demonstration plant design. They are detailed in Deliverable 5.1, part 3.

HFLCAL is a software for designing and optimizing solar tower systems. It has been developed by the company Interatom in the beginning of the eighties. In 1994, HFLCAL was acquired by the DLR and continuously advanced.

Aspen Plus has been chosen as the software tool for the simulation of the HYDROSOL 3D process. The behaviour of the system and its components can be modelled and analysed from a thermodynamic point of view. Aspen Plus uses the sequential modular approach concerning the flow sheet elaboration. The various components are available in a library and can be linked by connections, which can be flow of mass or energy. The equations of the different components of the flow sheet will be called and solved sequentially.

The process heat for the thermochemical cycles can be provided by solar concentrating systems. The considered redox system is Fe_3O_4/FeO. The water decomposition occurs at a low temperature in the range of 500 to 900°C by reacting with the reduced form of the oxide FeO and leads to the formation of the oxide Fe_3O_4 and H_2. The reduction of the oxidized form of the oxide Fe_3O_4, which is highly endothermic, proceeds at temperatures above 1100°C. In this study, the water splitting reaction takes place at 896°C, while the reduction occurs at 1150°C. The Plant of the solar thermochemical hydrogen production from water, which has been simulated within this study, has a thermal input of 21MW**.**

2.3 Industrial plant design - Results

2.3.1 Solar part

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 %. The solar reactor has been designed by DLR for the 1 MW_{th} demonstration plant. The reactor for the 21 MW_{th} plant is scaled up based on the reactor of the demonstration plant. The reactor of the industrial plant consists of 294 receivers. Each receiver module is interconnected to a secondary concentrator.

The choice of the most suitable heliostat type is very important for the field layout. Heliostats with a high mirror surface enable operating with a relatively low number of heliostats. Though large surface areas lead to stronger impacts of wind effects, it is more useful to use fewer large-surface heliostats instead of lots of smaller. This is, because the main error that occurs is caused by the tracking unit. Thus, a significant part of the plant’s energy losses result from imperfect tracking. In this study the Inabensa Colon 70 was chosen, because it is well known from its use at the PSA. Furthermore, it has a large surface area of almost 70 m² and exhibits only a small deviation of 3.5 mrad. In order to achieve the 21 MW intercepted solar radiation, 1050 mirrors are required. The industrial plant has a tower of 160 m high.

2.3.2 Process part

The plant process flowsheet is provided in Appendix B (Aspen flowsheet). The characteristics of the process main equipment items are provided below.

Rotating machinery								
	Number of units (including spare)	Fluid	Mass flow [kg/hr]	P_in [bar]	P_out [bar]	Weight (tons)	Power [kW]	Comments
PSA compression (COMP 1/COMP2)	2	Hydrogen + nitrogen	476,7	1	15		743,0	2 stages with interstage water coolers - Reciprocating
Hydrogen compressor (*COMP3/4/5*)	2	Hydrogen	431	15	350		956,3	3 stages with interstage water coolers
Feed water Pump	2	Demin water	10809	atm	2	0,4	0,8	
Air separation inlet compressor (*COMP6*)	2	Air	5584,5	1	6	425,9		
Cooling Water pumps	2	Cooling water	172595	atm	2	0,8	13,4	

Figure 1 - Rotating equipment characteristics

Heat exchangers							
	Number of units (including spare if any)	*Material*	Fluids (tubes / shell)	Weight (empty) [ton]	P_{design} [barg] (tubes / shell)	*Heat transfer per unit [MW]*	*Heat transfer area [m^2]*
PREHX A/B	*2*	Carbon steel	Steam with H2 / Evaporating steam	0,9	3,5/3,5	0,23	25
EVAPORA1 A/B/C	*3*	Stainless steel 316	Dry steam with high H2 content / Evaporating steam	1,8	3,5/3,5	1,3	40
EVAPORA2/EVAPORA3	*2*	Stainless steel 304	Dry air / Evaporating steam	0,7	3,5/3,5	0,86	17
CONDENS A/B/C	*3*	Stainless steel 316	Cooling water / Condensing steam	9,25	3,5/3,5	1,63	572

Figure 2 - Process exchangers characteristics

Special units				
	Number of units (including spare if any)	*Product flow*	Product specification	*Comment*
O_2/N_2 separation - Cryogenic unit	*1*	5500kg/h of nitrogen	99,99% nitrogen purity	*Inlet compressor not included*
Pressure Swing Absorption unit	*1*	Hydrogen + nitrogen inlet: 476,7kg/h	99% hydrogen purity	*Operating pressure: 15 bar*

Figure 3 - Special process unit characteristics

2.3.3 Balance of plant

The following utility units and common facilities are considered within the boundary limits of the plant:

Utilities				
	Number of units (including spare if any)	*Weight (tons)*	Specification	*Comment*
Feed water treatment	1	*3*	Q=11 m3/h of demin water	*Ion-exchange technology*
Feed water storage	*1*	*10*	1 demineralized water tank - CS with liner - 150 m3	
Service & instrument air	*1*	4	50 m3/h - 7 barg dry air	*1+1 compressors packaged in one unit, 2 buffer vessels*
Potable & service water	*Distribution only*	n.a.	From external network	
Electricity	*Step-down transformer and distribution only*	n.a.	Power from grid - MV connection	

Figure 4 - Utility units

Buildings			
	Surface (m2)	*Height of floors*	*Comment*
Administration & social	*150*	standard	*single floor*
Control room	*60*	standard	*Out of hazardous zone - Not blastprrof - single floor*
Workshop & warehouse	*200*	5m	*single floor*
Gate house	*20*	standard	*single floor*

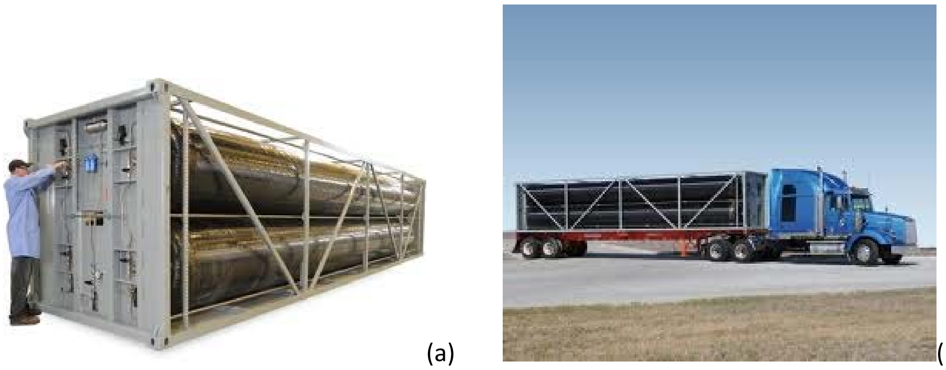
Figure 5 - Buildings characteristics

2.3.4 Considerations about Hydrogen storage for export

Considering on one hand that the location assumed for this first industrial plant isn't close to any existing hydrogen pipeline and, on the other hand, that the daily production will be rather limited (20,000 to 25,000 Nm^3/day), the plant production will be exported by trucks.

Downstream final compression to 350 bar, the hydrogen product will be bottled into special transport containers such as those proposed by the company Lincoln Composites (see illustrations below). Current containers can store hydrogen up to 250 bar. Units adapted to 350 bar are under development [2; 3] and are assumed to be available by the Hydrosol unit start-up.

The cost of this moveable containers is considered part of the logistic cost of hydrogen distribution (see chapter 6) and isn't included in this estimate.


(a) (b)

Figures 6a & 6b - Hydrogen storage & transport technology

3 Hydrogen production cost estimate - Methodology

3.1 General

The cost of the hydrogen generated by the Hydrosol plant is calculated considering the plant output and costs along its full lifetime. It is expressed in equivalent cost per unit of production at year 0.

Calculation takes into account the plant investment costs (CAPEX) as well as the operating costs (OPEX).

Depending on the time T at which a given cost CT is incurred, it is de-rated to take into account cost actualisation and so reflect its equivalent value at year zero (i.e. the amount of money C0 that would have generated the given amount CT at year T if invested at year 0 considering the remuneration of money and risk factors linked to immobilization).

$$C_0 = \frac{C_T}{(1+\alpha)^T}$$

where α is the discount rate, which reflects the remuneration of immobilized money and the level of risk.

The sum of the costs incurred by the plant during its complete lifetime expressed in equivalent value at year 0 is then divided by the discounted cumulated plant production to reach an equivalent cost per unit of production.

Considering a 25 year lifetime plant with an investment split over 2 years (CAPEX0 at year 0 and CAPEX1 at year 1), spending OPEX on operating expenses every year and producing P_{H2} hydrogen along its lifetime, the cost of hydrogen is given by

$$c_{H_2} = \left(CAPEX_0 + \frac{CAPEX_1}{(1+\alpha)^{\square}} + \sum_{t=2}^{t=26} \frac{OPEX}{(1+\alpha)^t} \right) / \sum_{t=2}^{t=26} \frac{P_{H_2}}{(1+\alpha)^t}$$

Note: Effects of financing, taxes and money erosion are not taken into account.

3.2 Capital cost estimate (CAPEX)

3.2.1 General

Plant CAPEX is composed of the cost of conception and construction of the plant (“EPC cost”) and of the costs incurred by the plant owner to manage and insure the project, acquire the land, follow permitting process etc (“Owner costs”).

At project stage, a plant cost estimate also includes provisions for contingencies that are meant to cover all cost sources not yet identified (e.g. bad soil quality impacting foundations, supplementary equipment, requests for design adaptation from permitting process etc). The level of contingencies included in a cost estimate depends on the level of definition of the project (the highest the definition level, the lowest the contingencies).

3.2.2 EPC cost estimate

The EPC cost estimate of the industrial plant has been jointly performed by TOTAL, HYGEAR and DLR with a split of work corresponding to their core field of competencies.

3.2.2.1 Solar part

The EPC cost corresponding to the solar field and the reactors has been estimated by DLR using the semi-detailed methodology presented in Deliverable D6.2.

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:

CTower=K1+H1.TVERALPHA

Where K1=250000€, H1=14.77€/m, ALPHA=2.392 and TVER denotes the tower height. The industrial plant has a tower of 160 m high. According to the tower cost equation, the tower costs 3.014 Mio.€. The cost calculation of the heliostat field is summarized in the following table.

Table 1: Costs of the heliostat field

Mirror surface [m^2]	70
Number of mirrors	1050
Reflective area [m^2]	73500
Mirror costs [€/m^2]	140
Heliostats costs [€]	10290000
Heliostats costs [€Mio]	**10.29**

The following table shows the main components of the solar reactors and its cost calculation, which have been estimated by DLR.

Table 2: Cost calculation of the solar receivers

Component	**Number of units**	**Cost per unit [€]**	**Total Cost [€]**
Reactor modules	294	3,000	882,000
Secondary concentrator	294	12,000	3,528,000

Each reactor module consists of 16 monoliths. The cost of the honeycombs has been calculated by APTL to be at 50€/monolith. The redox material costs 30€/monolith and it has been estimated that the cost of the coating process is about 17€/monolith. The next table shows the summary of the total cost of the honeycombs, the redox material and the coating process.

Table 3: Total cost of the honeycombs, the redox material and the coating process

Component	**Total Cost [€]**
Honeycombs [€]	235,200
Redox material [€]	141,120
Coating process [€]	79,968

Then, other contributors to the investment were calculated using the following cost factors:

Table 4: Total cost of the honeycombs, the redox material and the coating process

Purchased equipment cost	PEC
Direct cost(x*PEC)	
Piping	0.15PEC
Instrumentation and control	0.15PEC
electrical equipment	0.15PEC
Civil, structural and architectural work	0.15PEC
Auxiliaries and service facilities	0(1)
Indirect cost (x*PEC)	
Engineering and supervision	0.15PEC
Site installation	0.15PEC
Start-up expenses	0.1PEC

Note 1: auxiliaries & services facilities are specifically quoted in the "Balance of Plant".

3.2.2.2 Process part & Balance of Plant

The “conventional part” of the plant has been estimated by TOTAL E&P Estimation Department, with the exception of the Pressure Swing Absorption unit (static equipment) which has been quoted by Hygear.

The methodology applied corresponds to the first level of semi-detailed estimate. It proceeds with the successive calculation of 4 types of EPC cost contributors:

- Main equipment items
- Bulk material (covering structures, civil, piping, instrumentation & control, electricity, painting, insulation…)
- Erection / construction
- Engineering

The estimation proceeded as follows:

- Using the equipment list with weights, the costs of the main equipment items were first estimated.
- Bulk materials quantities and costs were then estimated using weight ratio against the weight of main equipment items (specific ratio per type of item).
- The cost estimation of construction was performed using hr/t ratio of material and hourly rates (specific ratio per discipline involved in the construction activities).

Engineering EPC cost was then added (15% of the sum of the above costs).

The Oxygen / Nitrogen separation unit was estimated as a package unit using a budgetary quotation from a supplier.The estimation report delivered by TOTAL E&P Estimation Department is provided in appendix 3 and gives further information about the estimation hypothesis.

3.2.2.3 Pressure Swing Absorption

The EPC cost of the PSA package unit was estimated by HYGEAR on the basis of their internal experience of smaller units and using cost engineering sources for extrapolation to the larger capacity required.

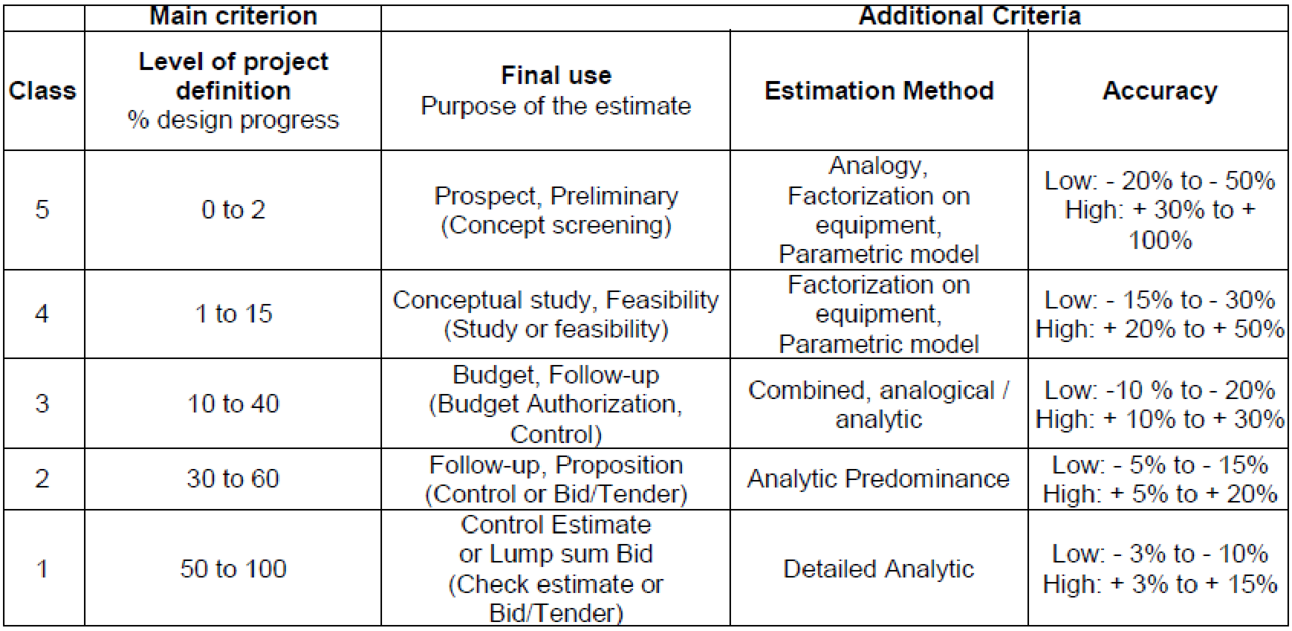
3.2.3 Project cost estimate

As stated in paragraph 3.2.1, the estimation of the cost of an industrial project is the sum of the EPC costs, of the other costs incurred by the investor (Owner costs) and of a provision for contingencies which depends of the level of definition of the project.

According to TOTAL estimation procedure, when no specific detail about the owner costs structure of a given project is available, the owner costs are considered to be 15% of the EPC cost.

Considering the stage of development of the design, contingencies up to 25% of the project costs are considered (TOTAL standard practice for an onshore project at preliminary design stage).

The estimate performed as described above can be considered “high range Class 5” as defined by the Association for the Advancement of Cost Engineering International (AACE). Characteristics of estimate classes defined by the AACE are provided in the Figure 7 below.



	Main criterion	**Additional Criteria**		
Class	**Level of project definition** % design progress	**Final use** Purpose of the estimate	**Estimation Method**	**Accuracy**
5	0 to 2	Prospect, Preliminary (Concept screening)	Analogy, Factorization on equipment, Parametric model	Low: - 20% to - 50% High: + 30% to + 100%
4	1 to 15	Conceptual study, Feasibility (Study or feasibility)	Factorization on equipment, Parametric model	Low: - 15% to - 30% High: + 20% to + 50%
3	10 to 40	Budget, Follow-up (Budget Authorization, Control)	Combined, analogical / analytic	Low: -10 % to - 20% High: + 10% to + 30%
2	30 to 60	Follow-up, Proposition (Control or Bid/Tender)	Analytic Predominance	Low: - 5% to - 15% High: + 5% to + 20%
1	50 to 100	Control Estimate or Lump sum Bid (Check estimate or Bid/Tender)	Detailed Analytic	Low: - 3% to - 10% High: + 3% to + 15%

Figure 7 - AACE estimate classes

Considering that a preliminary equipment sizing had been performed to support the equipment cost estimate, the accuracy associated to the Hydrosol estimate is +40%/-30%, in the high range of a class 5 estimate.

4 Hydrogen production cost estimate – Application

4.1 Capital Cost Estimate (CAPEX)

4.1.1 Estimate of the equipment items

4.1.1.1 Solar field

The estimated Purchased Equipment Costs are as follows:

Table 5: Solar items-Purchase Equipment Costs

Equipment / Item	**Cost (M€)**
Heliostats	10.29
Tower	3.014
Solar reactors including honeycombs, redox material and coating process	4.866
Total	*18.17*

4.1.1.2 PSA estimate

HYGEAR estimates the full cost of the static equipment of the PSA to 1,9M€ (EPC cost - including engineering, equipment, transport, instrumentation and installation).

4.1.1.3 "Conventional" part estimate

General

The "conventional" part of the plant corresponds to the process (with the exception of the PSA static equipment), the utility units and the buildings, as described in paragraph 2.3.

This "conventional" part has been estimated using the detailed equipment list and Total internal cost databases. The estimated cost of the process equipment, with the exception of the PSA static part and the O_2/N_2 separation unit is 10,736M€.

Specific case of the O_2/N_2 separation unit

The full cost of the separation unit package is estimated to 3 M€ (EPC cost - including engineering, equipment, transport, instrumentation and installation).

4.1.2 Overall CAPEX estimate

The table below summarizes the project cost contributors and the CAPEX estimate.

Table 6: Overall CAPEX estimate

		Solar Part (M€)	**Process (M€)**	**O2/N2 separation unit (M€)**	**PSA (M€)**
EPC	**Main equipment**	18,2	8,3		
	Bulk material	13,6	2,8		
	Erection / Construction		5,6		
	Engineering	2,7	2,5		
	Total EPC	*34,5*	*19,2*	3	*1,9*
	Total EPC	*58,6*			
Owner costs	**Company Cost**	6,6			
	Associated expenses (Insurance, com,...)	2,4			
	Provisions	16,9			
	Total CAPEX	***84,6***			

4.2 Operation cost estimate (OPEX)

The following main contributors to the OPEX are taken into account for the estimate:

1) Power consumption

The yearly electrical consumption is estimated from the nominal power consumption per item and the yearly load factor associated to each piece of equipment:

Table 7: Power consumptions for OPEX estimate

Power consumers			
	Power [kW]	Estimated yearly average load factor	Yearly power consumption (MWh)
PSA compression (COMP 1/COMP2)	743,0	20%	1302
Hydrogen compressor (*COMP3/4/5)*	956,3	20%	1675
Feed water Pump	0,8	20%	1
Air separation inlet compressor (*COMP6)*	983,0	20%	1722
Cooling Water pumps	13,4	20%	23,5
Service & instument air compressors	0,4	10%	0,3
Provision for other utilities & buildings	10,0	35%	31
Total			***4755***

Electricity price used for the estimation is 10.7€c/kWh (Year 2011 electricity price for industry in Spain according to [4]).

Electricity power cost is estimated to 509 k€/year.

2) Manpower

It is estimated that the site will employ about 20 people for operation and administration. All-in manhour rate considered is 49 €/h, corresponding to an equivalent annual cost per employee of about 83.3 k€/y.

All-in manpower cost is estimated to 1670 k€/year.

3) Maintenance

Annual charges for maintenance are set to 2% of the investment (including consumables).

Maintenance charges are estimated to 1542 k€/year.

4) Insurance

Annual fixed charges for insurance are set to 1% of the investment.

Insurance charges are estimated to 771 k€/year.

5) Total OPEX

Considering the above, Total OPEX are estimated to 4492 k€/year.

4.3 Plant yearly production estimate

The Heat & Mass balances produced with Aspen have shown that the plant production under nominal solar conditions was 431kg_{H2}/h.

As explained in paragraph 2.1 this production varies with solar conditions and a capacity factor has to be taken into account for evaluating the yearly production. A capacity factor of 20% is considered representative of the operation of solar concentrated technologies in the South of Spain.

In addition, an availability factor is used to reflect plant planed shut-down for maintenance purposes and loss of availability due to unplanned failure of equipment. 95% availability is considered.

Considering the above, the yearly production of the plant is estimated to 717 t/y.

4.4 Production cost estimate (Levelized Cost of Hydrogen)

For the production cost calculation the following hypothesis are made:

- The plant construction duration is 24 months and starts upon project Final Investment Decision (FID)
- 60% of the CAPEX are supposed to be spent during the first year of construction and the remaining 40% during year 2
- The discount factor is 4%
- The expected lifetime of the plant is 25 years (from start-up)
- Plant production is considered constant along its lifetime (no degradation).

The table presented hereafter displays the cost calculation performed, according to the methodology explained in paragraph 3.1. The estimated cost of production is 14.0 €/kg.

Table 8: Calculation of production cost

Selected Case	**Andalucia**		
Date Assumptions			
Commencement date (FID)	2013	on Quarter	Q1
Construction duration	24	months	
COD	2015	on Quarter	Q1
Economical Assumptions			
Reference	01/01/2013		
Inflation	0,0%		
LCOH2 @	4%	in real	
Production	717,0	t/y	

			2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2038	2039
Discount Factor	4%		1,00	1,04	1,08	1,12	1,17	1,22	1,27	1,32	1,37	1,42	1,48	1,54	1,60	2,67	2,77
Inflation	0,0%		1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Net Production	tons	17 925,0	0,0	0,0	717,0	717,00	717,00	717,00	717,00	717,00	717,00	717,00	717,00	717,00	717,00	717,00	717,00
Calcul du LEC par les coûts																	
Capex (project after FID)	M€	84,6	50,8	33,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Capex - total	M€	84,6	50,8	33,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Opex	M€	112,5			4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
Capex (unflated)	M€12	84,6	50,8	33,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Opex	M€12	112,5	0,0	0,0	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
NPV of Capex	M€12	83,3	50,8	32,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NPV of Opex	M€12	67,6	0,0	0,0	4,2	4,0	3,8	3,7	3,6	3,4	3,3	3,2	3,0	2,9	2,8	1,7	1,6
Net discounted production of Hydroge	t	10 770,2	0,0	0,0	662,9	637,4	612,9	589,3	566,7	544,9	523,9	503,8	484,4	465,7	447,8	269,0	258,6

Levelized Cost Of Production	€12/t	14 010
Capex	€12/t	7 734
Opex	€12/t	6 276

5 Discussion on production costs

5.1 Contributors to estimate variations – Current economical conditions

In paragraph 4.4, a levelized production cost has been estimated for the hydrogen produced with the Hydrosol technology. This cost represents the best estimate that can be derived from the current level of definition of a specific plant defined as “first industrial application case” of the technology. Real production costs vary with many factors and, rather than using a fixed value, a range of costs should preferably be defined to evaluate the economical perspectives of the technology.

The following parameters have to be considered to derive a range of production costs from the estimate made for a specific case:

a) Impact of an increase of the solar resource
b) Range of scale of the industrial plants
c) Range of accuracy of the CAPEX & OPEX estimate

a) Solar resource

Best solar locations in the world have annual DNI resources exceeding 2600 $kW/m^2/y$ (South West of United States, parts of South Africa, of Sahara,…). This corresponds to more than 120% of the solar resource considered in the case studied. In addition, lower latitudes can also slightly increase the efficiency of the solar field (less cosine losses). For a given solar field and downstream process design, it is estimated that the load factor of the plant (capacity factor) can increase up to 25% instead of the 20% considered in the case studied.

In the field of power production, 2000 $kWh/m^2/y$ is currently considered as the minimum solar resource required for economically viable concentrated solar plants. It is also chosen as the lowest range of the solar resource at locations envisaged for the Hydrosol process.

b) Scale of the industrial plant

As outlined in paragraph 2.1, for unchanged solar conditions, the solar field capacity of the largest solar towers under construction in the world are about 12 times bigger than the one considered. Assuming a moderate cost scale-up factor of 0.8 applicable both to the solar field and the downstream process, this represents a CAPEX decrease per unit of capacity of about 40%:

$CAPEX_{largest\ unit} = CAPEX_{base\ case} *(12/1)^{0.8} = 7.3\ CAPEX_{base\ case}$

$CAPEX_{largest\ unit} / P_{largest\ unit} = 7.3\ CAPEX_{base\ case}/ P_{largest\ unit}$

Considering that the plant production P is proportional to its capacity ($P_{largest\ unit} = 12\ P_{base\ case}$):

$CAPEX_{largest\ unit} / P_{largest\ unit} = 7.3/12\ CAPEX_{base\ case}/ P_{base\ case} \approx 60\%\ CAPEX_{base\ case}/ P_{base\ case}$

Similarly, a cost factor of 0.9 is considered applicable to the Opex extrapolation.

As stated in paragraph 2.1, the capacity considered in the study is the low boundary of industrial plants capacities.

c) Range of accuracy of the Opex / Capex estimate

The CAPEX estimated in paragraph 2.3 corresponds to the P50 cost probability. This means that the actual cost of the plant has 50% chance to be higher than the estimate and 50% chance to be lower (see also appendix C).

On the basis of the accuracy defined for the “conventional part” of the cost estimate, the range of CAPEX is estimated to be +40%/-30% of the P50 cost estimate. OPEX range is assumed to be +30%/-30% of the estimate presented.

5.2 Resulting range of the production cost estimate

Applying the cost increase & decrease factors listed above to the initial estimate leads to the following range of hydrogen production cost with the current economical conditions:

"Base case" estimate:	14 €/kg
Low boundary of production costs:	5.4 €/kg
High boundary of production costs:	20.3 €/kg

The production cost calculation sheets corresponding to the low and high cost estimate boundaries are presented in Appendix D.

5.3 Cost reduction perspectives

As described in paragraph 3.2.1, the main components of the solar reactors are the reactor modules and the secondary concentrators. Each reactor module consists of 16 honeycombs. The total cost of the redox material coated honeycombs is derived by taking into account prices of industrial grade raw materials and is calculated to be 0.456 M€. This value represents only the 2.5% of the total cost that is estimated for the solar part of the plant (i.e. heliostats, tower and solar reactors) and a 0.5% of the overall CAPEX. This indicates that further reduction of the cost of the redox material coated honeycombs would not cause any significant reduction in the total cost of the solar part of the plant. However, there is still a margin for lower raw material prices, such as use of recycled iron oxide and purchasing of large quantities of raw materials (in the scale of tons) that would cause another 20% reduction of the cost of the coated honeycombs.

Also, several improvements are expected for the solar tower technology across its main components. Large heliostats have aperture areas of 62 to 120m² and multiple mirror facets. Sizes for large heliostats are expected to increase up to 150 m². With this size increase, the total number of tracking system drives would decrease, reducing the tracking system costs per m². The heliostats are the most relevant cost factors for tower's solar field. Improvement in these dimensions for heliostats can yield a cost reduction of 7% per solar field area. Another improvement potential concerns the tracking system. Current tracking system is based on the use of one drive per heliostat. However, small heliostat developers are developing a system based on a common row tracking with micro-robotic drives that couple at each heliostat individually. Such a system can effect in a total tracking system cost reduction by 40 %.

The optimization of the solar field leads to a cost reduction. The solar field layouts can be tailored in order to optimize sun shading and blocking produced by heliostats. This can be achieved by different heliostat designs according to their location on the solar field. The mix of different heliostat types in a given solar field might contribute to the reduction of the total cost of the field up to 10% and an efficiency improvement of 3% when compared with currently employed designs [7].

6 Hydrogen supply costs

Hydrogen is a used and stored industrial gas with a well-developed set of codes and standards governing its use. Hydrogen is typically stored in steel ASME.certified vessels, ir in composite vessels that currently are DOT certified, but nor yet fully ASME certified. The applicable codes are the ASME Boiler and Pressure Vessel Code, Section VIII for stationary uses, and 49 Code if Federal Regulations for transportation uses. Additional applicable codes and standards include CGA G-5.4 (piping) and G-5.5 (hydrogen vent systems), CGA H-5 (storage) and NFPA 55 [5].

Hydrogen can be transported as a compressed gas, a cryogenic liquid or as a solid metal hybrid. There are many considerations, which have to be taken into account while analysing the cost of the hydrogen transportation. The cheapest method of transportation depends on the quantity of hydrogen and the distance. For large quantities of hydrogen, hydrogen delivery via pipelines is cheaper than all other methods except in the case of transport over an ocean, in which liquid hydrogen transport would be cheapest. Pipeline delivery has the advantage of a low operating cost, which mainly consists of compressor power costs but a high capital investment. Pipelines have been used to transport H_2 for more than 70 years. Several thousand kilometres of H_2 pipelines are currently in operation world wide. The energy required to compress H_2 is 4.5 times higher than for natural gas per unit of delivered energy. As a consequence, long distances H_2 transportation for energy use may not be economically competitive. Transportation costs to deliver gaseous H_2 to refuelling stations are in the range of \$1-\$2/GJ [6].

Hydrogen can be transported by truck, rail or ship. This transportation pathway is more expensive than gas piping. In current plants, the electricity required for H_2 liquefaction at -253°C is about 35-43MJel/kgH_2 with potential reduction to 25 MJel/kg [6]. The cost of liquefaction in large system is about \$7-\$9/GJ, 75% of which comes from the cost of electricity. Transportation of liquid H_2 by ship over long distances is also more expensive than for natural gas (LNG) since very low-temperature cryogenic technology is needed.

Over than 140 H_2 refuelling stations are in operation world wide. Most stations deliver hydrogen at 350 bar. Costs of refuelling stations are estimated between \$3/GJH_2 and \$10/GJ with centralised H_2 production and on-site production respectively. These costs include investment and H_2 compression. Transportation, distribution and refuelling stations may add some \$5-\$12/GJ to H_2 production costs. On-board hydrogen storage for fuel cell vehicles is challenging regarding the operating pressure. Storage requires energy intensive compression at higher pressure in the range of 350-700 bar. The electrical power required for the compression represents 12% of the hydrogen energy content based on the lower heating value (LHV). The tank costs more than \$4,000 per vehicle [6].

7 References

[1] – Data on SolarReserve Crescent Dunes project – Available at
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[2] – *L'hydrogène, carburant de l'aprés-pétrole?* – Editions Technip - 2012– Chapter 6 – *Technologies de distribution de l'hydrogène* – F. Barbier – Air Liquide

[3] - http://lincolncomposites.com/

[4] - *Spain energy report* – Enerdata - November 2012)

[5] – *An overview of hydrogen production and storage systems with renewable hydrogen case studies*-Timothy Lipman, PhD- 2011.
[6] - *Hydrogen production and distribution*- IEA report- 2007
[7]- *Solar thermal electricity 2025*- ESTELA report, 2011

Appendix A

MAIN BASIS OF DESIGN FOR THE HYDROSOL INDUSTRIAL PLANT

1. Introduction to Appendix A

This appendix gathers the main basis of design applicable to the HYDROSOL 3D industrial case study.

It first describes the purpose and the boundary limit of the industrial hydrogen production plant to be designed under the Hydrosol 3D project, as part of WP6. It gathers the process design basis and provides the criteria others than process data that have to be taken into account for plant design and cost study.

2. Hydrosol 3D industrial plant – Purpose & General Description

The plant to be designed is a solar hydrogen production plant based on the 2 step metal-oxide process demonstrated at pilot stage during the Hydrosol 2 project and that will be further proven by the construction of a 1MW demo plant.

It is assumed that the industrial case study plant will not be integrated into an industrial complex. Therefore,

- it will have to deliver purified hydrogen at specifications suitable for its storage, transport and use by external consumers as defined hereafter.
- heat recovery scheme will be optimised within the boundary limits of the plant.
- except for power delivered from grid, the plant will have to produce its own utilities when required and provides for storage of the consumables delivered by others.

The plant will be fed by pipe with raw fresh water.

Oxygen released during the metal oxide regeneration is not considered as a plant product and its valorisation isn't considered.

3. Process design basis

Plant Capacity

Considering that the unit size of the solar field will further define the maximum capacity of a Hydrosol industrial plant, the plant thermal power input is set as the parameter defining the plant capacity.

The capacity of the "first generation of industrial plants" will be 21MW$_{th}$, defined as the solar heat effectively absorbed by the reactors. The corresponding solar field capacity will be calculated during the design using the receiver system efficiency that will be estimated and the appropriate solar multiple.

Similarly, the plant hydrogen production will be calculated using the simulation of plant performance.

Products specifications

Product shall comply with the specification of the ISO 14687:1999 as revised by corrective AC1:2001 and AC2:2008.

The plant will deliver hydrogen compliant with the requirements of internal combustion engines and stationary fuel cells for residential & commercial appliances (Type I grade A as per ISO 14687).

Therefore base specifications will be:

Minimum Hydrogen purity (mol %)	98

Max combined nitrogen, water, oxygen and argon content (%mol): 1,9

Max moisture content (dew point): not condensable
dewpoint < - 10°C @ 350 bar

Storage & export form: gaseous storage under pressure @ 350 bar
Export by trucks (tube trailers)

Plant boundary limits

Upstream: connection to the network supplying raw water, at plant fence.

Downstream: downstream the compression of hydrogen of commercial quality to 350bar. The storage containers and export facilities are considered out of the scope of the plant (distribution chain).

Plant lifetime

Plant lifetime considered: 20 years

Feed Water & Power suply

Feed water

Supplied water quality @ plant battery limit: raw fresh water

Delivery pressure @ plant battery limit 4 bar(g)

Power supply

Power supply @ plant battery limit: 4 kV @ 50 Hz

Particular Process limitations

Reactor

Normal reactor temperature Production / Regeneration (°C) 800 / 1200°C

Maximum temperature that reactor material can sustain (°C) 1400°C

Heliostats field

Max. wind under which field shall remain in precise tracking: 12 m/s

Max. wind under which heliostats shall stay safe in any position and be able to move to safe position: 16 m/s

Max. survival wind speed in safe position: see design wind below

Site conditions

Site solar irradiation

D.N.I. for the year 2008: 2143 kWh/m^2/year

Site nominal irradiation: 800 W/m^2 on March 21st at noon

Site temperature

Min (°C) -1.19

Average (°C)	17.19
Max (°C)	38.79

Average values of min/max of one hour average of years 2002 – 2009

Wind conditions

Design wind (for structures integrity – heliostats in safe position): 130 km/h

(Martin Marieta, source CIEMAT)

% of time with wind lower than tracking limit (as set in paragraph 3.4.2): 99 %

Rainfall

Annual rainfall (mm)	215, average 2001 - 2008
Max daily rainfall (mm)	30

Seismic level

Low-to-moderate seismic activity (in a world context), most hazardous Spanish seismic zone by the Spanish Building Code (NCSE,2002) (Universidad de Almería).

Soil conditions

Stone desert; suitable for large scale installation

Other specifications

Process design shall comply with the regulations in force in the demonstration plant host country.

When regulation is not prescriptive, reference codes used for process design will preferably be ISO EN standards.

Appendix B

PROCESS FLOWSHEET

Aspen-Plus flow sheet of the HYDROSOL 3D process

Operation	ID of the Components in the ASPEN-PLUS Flow Sheet
Solar reactors	REAC-RE,REAC-RE, ZYK1,ZYK2,N2TANK
Feed water evaporation and overheating	H2OTANK,PUMP,PREHX,EVAPORA1, EVAPORA2/EVAPORA3, SUPERHX1/SUPERHX2, SPLITT1, MIX1, AIR-HX
Air separation	COMP6,HX30/HX31,HX40/HX41,COLUMN1,COLUMN2,CHOKE1,CHOKE2,MIX2
Water separation	CONDENS1/CONDENS2
N_2 separation	COMP1,COMP2,PSA,COOLER1,COOLER2,BUFFER
H_2 compression	COMP3,COMP4,COOLER3,COOLER4,H2STORAG

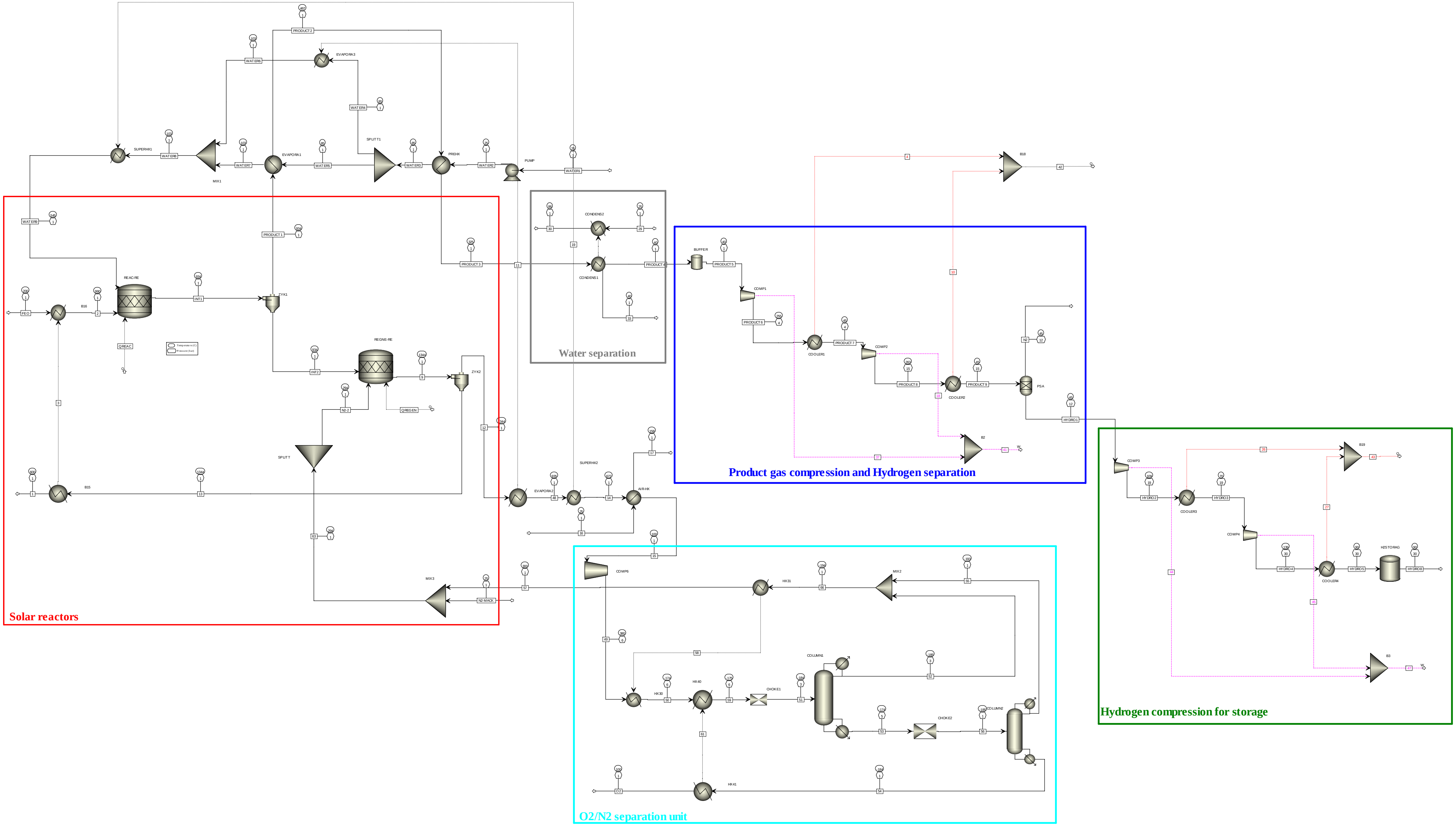
Abbreviation of the components

SUPERHX1/SUPERHX2	Super-heater: overheating of the water steam
EVAPORA1	Evaporator: feed water evaporation
EVAPORA2/EVAPORA3	Evaporator: feed water evaporation
REAC-RE	Solar reactor: water splitting
REGNE-RE	Solar reactor: reduction step
ZYK1	Cyclone: FeO separation
ZYK2	Cyclone: Fe_3O_4 separation
PREHX	Preheater: feed water preheating
PUMP	Feed water pump
H2OTANK	Feed water tank
COMP1/COMP2	Compressors: compression of the product gas up to the PSA operating pressure
COOLER1/COOLER2	Heat exchangers: intercooling of the product gas
PSA	Pressure swing absorber: N_2 separation
COMP3/COMP4	Compressors: compression of hydrogen for storage
COOLER3/COOLER4	Heat exchangers: intercooling of the hydrogen
H2STORAG	Hydrogen storage
BUFFER	Buffer: control of the N_2 concentration in the product gas
COMP6	Compressor: compression of the O_2/N_2 mixture for the air separation unit
HX30/HX31	Heat exchangers: heat recovery in the air separation unit
HX40/HX41	Heat exchangers: heat recovery in the air separation unit
COLUMN1	High pressure column for O_2/N_2 separation
COLUMN2	Low pressure column for O_2/N_2 separation
CHOKE1	Expansion valve
CHOKE2	Expansion valve
MIX1	Mixer: feed water mixing after evaporation
MIX2	Mixer: nitrogen mixing from the HP-column and LP-column
MIX3	Mixer: nitrogen make-up
SPLITT1	Splitter: feed water splitting into two sub-streams for evaporation
CONDES1/CONDES2	Heat exchangers: separation of the water from the product gas

The Flow Sheet

1. Start on the right side with the stream WATER1: demineralized water is fed at ambient temperature (25°C) and 1 bar from the water tank H2OTANK.
2. The feed water stream WATER2 is preheated up to 85°C in the heat exchanger PREHX by the product gas PRODUCT2.
3. After the preheating, the H2O stream WATER3 is split in the splitter SPLITT1 into two sub-streams: WATER6 and WATER4.
4. The H_2O sub-stream WATER6 is evaporated in the heat exchanger EVAPORA1 by the product gas PRODUCT1.
5. The H_2O sub-stream WATER4 is evaporated in the heat exchanger EVAPORA2/EVAPORA3 by the stream GAS-2, which leaves the solar reactor REGNE-R at 1344°C. The reduction step takes place in the mentioned reactor REGNE-R and the outlet stream 12 contains N_2 and O_2.
6. After evaporation, both streams WATER6 and WATER7 are mixed in the mixer MIX1.
7. The steam WATER8 is overheated up to 545°C in the super-heater SUPERHX1/SUPERHX2 by the stream 12, which consists of N_2 and O_2 (The redox material is normally fixed in the reactor, but due to the fact that ASPEN PLUS does not contain a reactor model, where solids can be implemented, the reduced material has been simulated as a stream which will be re-introduced to the water-splitting reactor REAC-R. After regeneration, the FeO stream 13 is removed in a cyclone and the stream 12 is used for water evaporation of the sub-stream WATER4 and the overheating of the stream WATER8).
8. The overheated steam WATER9 is introduced to the water splitting reactor REAC-R with the redox material stream FEO, which has been already heated up to 990°C by the stream 13. The water stream WATER9 flows into the reactor REAC-RE at a temperature of 545°C. According to ASPEN calculation, the water splitting reaction takes place at 934°C. A H_2O to H_2 conversion of 35% has been assumed according to the dynamic model of the reactor.
9. The water splitting reaction takes place in the reactor REAC-RE at 934°C and 1 bar. The H_2O to H_2 conversion has been assumed at 35%.
10. The reduced redox material (Fe_3O_4) is introduced to the cyclone ZYK 1 in order to separate the Fe_3O_4 from the solid/gas mixture INT1. The reduced material is then introduced to the reactor REGNE-RE, where the regeneration will take place at 1344°C. The nitrogen is entering into the reactor with a temperature of 294°C since a part of the heat has been recovered from the air separation unit.
11. The further use of the product gas stream PRODUCT1 has been described in steps 4.
12. The product gas contains water steam, which has to be removed. The water separation will occur in the heat exchanger CONDENS1/CONDENS2 and the cooling fluid is water. The product gas is cooled from 325°C down to 40 °C while the cooling stream 29 is heated up to 86°C.
13. Since the concentration of N_2 in the product gas PRODUCT4 can be variable, a buffer is required in order to control the concentration of N_2.
14. The N_2/H_2 separation takes place in a pressure swing absorber PSA. Since the operation pressure of the H2 purification unit PSA is 15 bar, a compression of the product gas PRODUCT5 from 1 up to 15 bar is required. The compression will take place in a 2 stage-compressor with inter-cooling. The compression ratio of each compressor is 3.89 with a isentropic efficiency of 0.69. The compression ratio represents the ratio of the outlet pressure to the inlet pressure. The pressure drop in the PSA has been assumed to be at 3 bar.
15. It was assumed that the purification value of H_2 will be at 99%.
16. The purified H_2-stream H_2-7 exiting the PSA will be stored in a tank at 30 bar. In order to achieve this pressure, a compression in a 2 stages compressor with inter-cooling is required. Each compressor has a compression ratio of 1.58 and an isentropic efficiency of 0.69 (In the case of the compression up to 90, 150 and 350 bar, the compression will be carried out in a 3-stages compressors with intercooling, each compressor has a compression ratio of 3.08).

Aspen Plus Flow Sheet



Appendix C

COST ESTIMATE OF THE “CONVENTIONAL PART” OF THE PROCESS

Exploration & Production

1. INTRODUCTION

The objective of the memo consists of getting the cost estimate of the first pre-industrial unit for a technology producing hydrogen by concentrated solar energy water splitting.

TOTAL partners (DLR & Hygear) are estimating the cost specifically related to solar equipment and PSA whereas TOTAL/EP/EST is estimating the “more conventional” part : raw material preparation (LP and HP steam, nitrogen) and product treatment. The unit should be built in the south of Spain (Almeria).

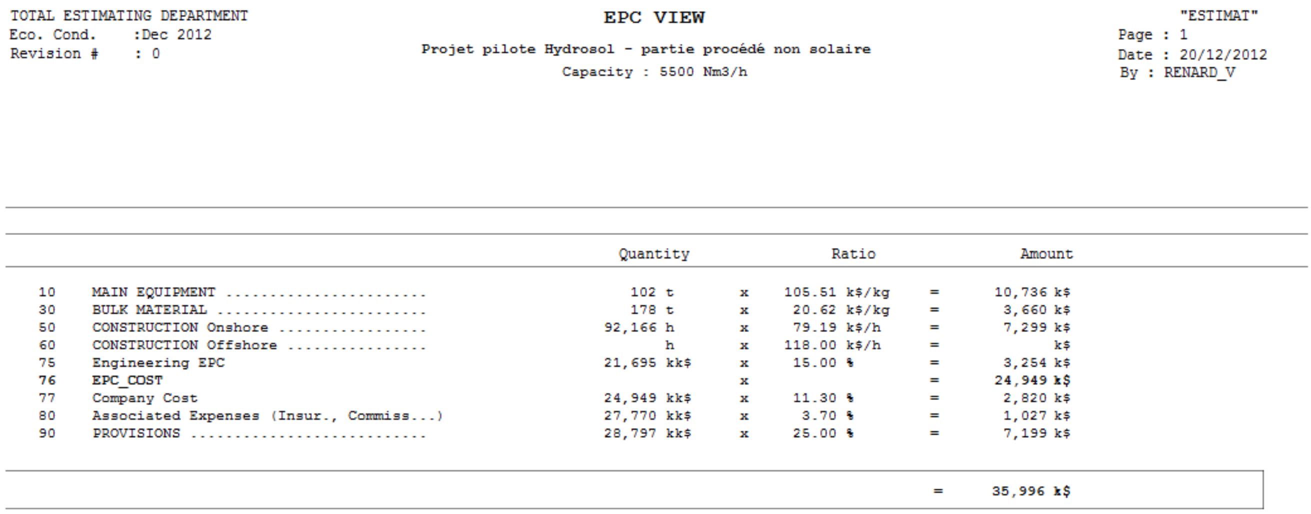
2. REFERENCE DATA

Classe / *Class*	: 5
Précision / *Accuracy*	: +40%/-30%
Devise / *Currency*	: USD
Conditions Economiques / *Economical Conditions*	: Q4 2012
Taux de conversion / *Currency Rate*	: 1€=1.3USD

3. ESTIMATE SUMMARY

Exclusions to this estimate are listed in Paragraph 6.

Capex	
P50	**36 M$**
P90	25 M$
P10	50 M$



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TOTAL ESTIMATING DEPARTMENT                    EPC VIEW                                  "ESTIMAT"
Eco. Cond.    :Dec 2012                                                              Page : 1
Revision #    : 0              Projet pilote Hydrosol - partie procédé non solaire   Date : 20/12/2012
                                       Capacity : 5500 Nm3/h                         By : RENARD_V

                                                         Quantity          Ratio              Amount

   10   MAIN EQUIPMENT .......................          102 t       x   105.51 k$/kg    =    10,736 k$
   30   BULK MATERIAL ........................          178 t       x    20.62 k$/kg    =     3,660 k$
   50   CONSTRUCTION Onshore .................       92,166 h       x    79.19 k$/h     =     7,299 k$
   60   CONSTRUCTION Offshore ................              h       x   118.00 k$/h     =           k$
   75   Engineering EPC                              21,695 kk$     x    15.00 %        =     3,254 k$
   76   EPC_COST                                                    x                   =    24,949 k$
   77   Company Cost                                 24,949 kk$     x    11.30 %        =     2,820 k$
   80   Associated Expenses (Insur., Commiss...)     27,770 kk$     x     3.70 %        =     1,027 k$
   90   PROVISIONS ...........................       28,797 kk$     x    25.00 %        =     7,199 k$

                                                                                        =    35,996 k$
```

4. TECHNICAL BASIS

Plant location	**Spain (Almeria)**

Rotating machinery								
	Number of units (including spare)	Fluid	Mass flow [kg/hr]	P_in [bar]	P_out [bar]	Weight (tons)	Power [kW]	Comments
PSA compression	2	Hydrogen + nitrogen	476.7	1	15		743.0	2 stages with interstage water coolers - Recciprocating
Hydrogen compressor *COMP3/4/5*	2	Hydrogen	431	15	350		956.3	3 stages with interstage water coolers
Feed water Pump	2	Demin water	10809	atm	2	0.4	0.8	
Cooling Water pumps	2	Cooling water	172595	atm	2	0.8	13.4	

Heat exchangers							
	Number of units (including spare if any)	*Material*	Fluids (tubes / shell)	Weight (empty) [ton]	P_{design} [barg] (tubes / shell)	*Heat transfer per unit [MW]*	*Heat transfer area [m²]*
PREHX A/B	*2*	Carbon steel	Steam with H2 / Evaporating steam	0.9	3,5/3,5	0.23	24.8
EVAPORA1 A/B/C	*3*	Stainless steel 316	Dry steam with high H2 content / Evaporating steam	1.8	3,5/3,5	1.3	40.2
EVAPORA2/EVAPORA3	*2*	Stainless steel 304	Dry air / Evaporating steam	0.7	3,5/3,5	0.86	16.6
CONDENS A/B/C	*3*	Stainless steel 316	Cooling water / Condensing steam	9.25	3,5/3,5	1.63	572

Utilities				
	Number of units (including spare if any)	*Weight (tons)*	Specification	*Comment*
Feed water treatment	1	*3*	Q=4,5m3/h of demin water	*Ion-exchange technology*
Feed water storage	*1*	*10*	1 demineralized water tank - CS with liner - 150 m3 capacity	
Service & instrument air	*1*	4	50 m3/h - 7 barg dry air	*+1 compressors packaged in one unit, 2 buffer vesse*
Potable & service water	*Distribution only*	n.a.	From external network	
Electricity	*Step-down transformer and distribution only*	n.a.	Power from grid - MV connection	

Buildings			
	Surface (m2)	*Height of floors*	*Comment*
Administration & social	*150*	standard	*single floor*
Control room	*60*	standard	*Out of hazardous zone - Not blastprrof - single floor*
Workshop & warehouse	*200*	5m	*single floor*
Gate house	*20*	standard	*single floor*

5. ESTIMATE BASIS

ESTIMAT and EST tools were used to estimate equipments cost, the bulk weight and cost and the construction hours and cost.

All-in rate: 64$/direct hr (estimated via the COMPASS 2011).

Site productivity: 1.2

Freight percentage used: 6% of equipment and bulk cost

Equipment, bulk and construction allowance percentage used as per Total internal Guide Manual GM EP EST 001: 15% of equipment, bulk and construction cost.

Engineering, Management and Supervision (EMS) percentage used: 15% of technical cost.

Company Cost (CC) percentage used: 15% of EPC cost.

Contingency percentage used: 25% of EPC+CC cost.

6. EXCLUSIONS

The costs specified in the present memo exclude:

- Development studies costs
- Land acquisition, right of way
- Operation Expenditures (OPEX)
    - 2-year spare parts,

DEPARTEMENT ESTIMATION

COST SUMMARY

"ESTIMAT"

20 Dec 2012

Unit: Projet pilote Hydrosol - partie procédé non solaire

Country Spain

rev n° : 0

Eco. Cond. : Dec 2012

SUMMARY	SUPPLY					CONSTRUCTION					TOTAL		
	% of M.E	Quantity	Ratio	Amount	of TOTAL	% of M.E	Quantity	Ratio	Amount	of TOTAL	Amount	Ratio	of TOTAL
10 Main Equipment	100.00 %	102 t	105.51 $/kg	10,736 k$	74.58 %		2,775	64.00 $/h	178 k$	2.43 %	10,913 k$	107257.54	30.32 %
Procurement		102 t	86.56 $/kg	8,807 k$	61.18 %	2.02 %	2,775	64.00 $/h	178 k$	2.43 %	8,985 k$	88301.72	24.96 %
Transport	6.00 %	8,807 k$	6.00 %	528 k$	3.67 %						528 k$	60.00	1.47 %
Techinical provisions	15.90 %	9,336 k$	15.00 %	1,400 k$	9.73 %						1,400 k$	150.00	3.89 %
30 Bulk Material	41.56 %	178 t	20.62 $/kg	3,660 k$	25.43 %	80.86 %	95,737	74.38 %	7,121 k$	97.57 %	10,781 k$	60729.80	29.95 %
31 Piping						15.71 %	21,615	64.00 $/h	1,383 k$	18.95 %	1,383 k$		3.84 %
32 Electrical	8.40 %	21 t	35.00 $/kg	740 k$	5.14 %	5.29 %	7,285	64.00 $/h	466 k$	6.39 %	1,206 k$	57055.16	3.35 %
33 Instrumentation	13.36 %	15 t	80.00 $/kg	1,176 k$	8.17 %	7.41 %	10,194	64.00 $/h	652 k$	8.94 %	1,829 k$	124368.11	5.08 %
34 Structural Steel	1.55 %	65 t	2.10 $/kg	136 k$	0.95 %	1.70 %	2,334	64.00 $/h	149 k$	2.05 %	286 k$	4404.01	0.79 %
35 Pipeline/sealine													
36 Civil Works	1.21 %	142 m3	750.00 $/m3	107 k$	0.74 %	2.73 %	3,761	64.00 $/h	241 k$	3.30 %	348 k$	2439.61	0.97 %
37 Insulation	0.77 %	4 t	18.20 $/kg	68 k$	0.47 %	1.18 %	1,623	64.00 $/h	104 k$	1.42 %	172 k$	46152.00	0.48 %
38 Painting	0.09 %	1 t	7.00 $/kg	8 k$	0.05 %	0.75 %	1,031	64.00 $/h	66 k$	0.90 %	74 k$	68461.82	0.20 %
39 Buildings	2.68 %	430 m2	548.84 $/m2	236 k$	1.64 %	7.81 %	10,750	64.00 $/h	688 k$	9.43 %	924 k$	2148.84	2.57 %
40 Fire fighting & Protection													
41 Site preparation	1.14 %	5,000 m2	20.00 $/m2	100 k$	0.69 %	2.03 %	2,797	64.00 $/h	179 k$	2.45 %	279 k$	55.80	0.78 %
42 Jacket													
43 Gravity base PLTF substructure '35 Storages													
44 Deck Module structure													
45 Floating storage													
45 Anodes & Cathodic protection													
46 Loading station superstructure													
47 Special operations													
48 Telecom and Computer													
49 Other Bulk													
5C Construction facilities													
5D Precommissioning						25.43 %	28,000	80.00 $/h	2,240 k$	30.69 %	2,240 k$		6.22 %
Transport	2.05 %	3,003 k$	6.00 %	180 k$	1.25 %						180 k$	60.00	0.50 %
Technical provisions	5.42 %	3,183 k$	15.00 %	477 k$	3.32 %	10.81 %	6,347	15.00 %	952 k$	13.04 %	1,429 k$	449.09	3.97 %
TECHNICAL COST	141.56 %			14,396 k$			98,512		7,299 k$		21,695 k$		60.27 %
70 Engineering, Management...							21,695	28.00 %	6,075 k$		6,075 k$		16.88 %
80 Associated Expenses							27,770	3.70 %	1,027 k$		1,027 k$		2.85 %
90 Contingencies							28,797	25.00 %	7,199 k$		7,199 k$		20.00 %
Subtotal COST											14,301 k$		39.73 %
TOTAL COST									**LANG FACTOR**	4.09	35,996 k$		100.00 %

DEPARTEMENT ESTIMATION

COST SUMMARY

"ESTIMAT"

20 Dec 2012

Unit: Projet pilote Hydrosol - partie procédé non solaire

Country Spain

rev n° : 0

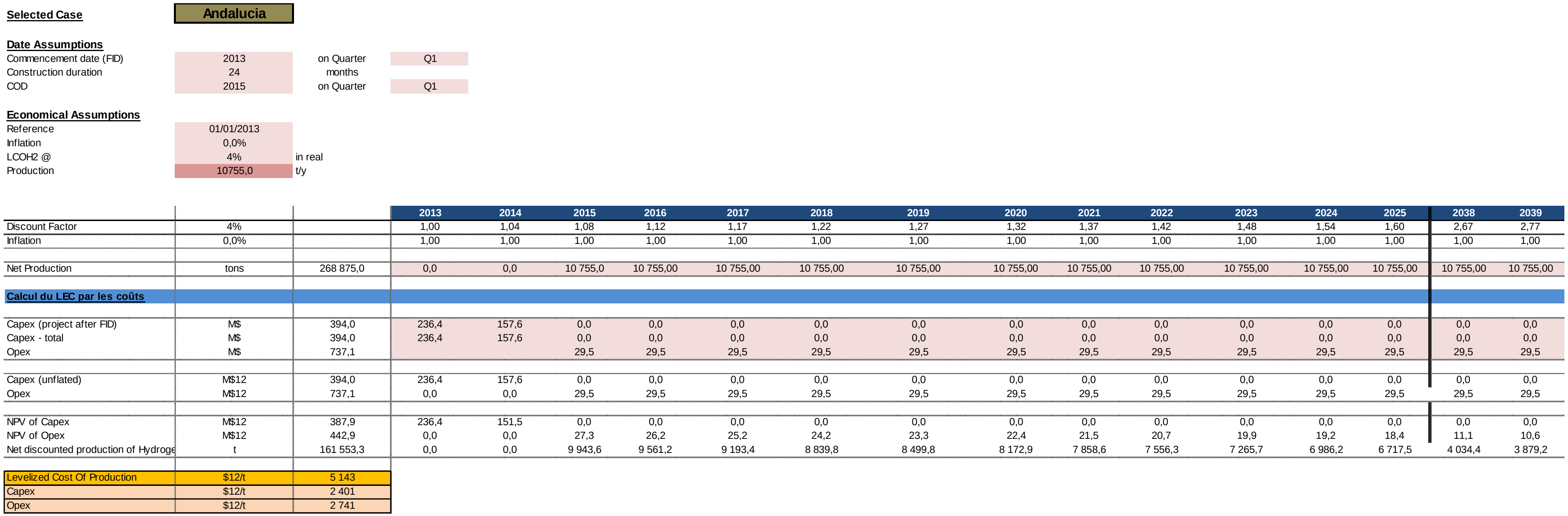
Eco. Cond. : Dec 2012

SUMMARY	SUPPLY					CONSTRUCTION					TOTAL		
	% of M.E	Quantity	Ratio	Amount	of TOTAL	% of M.E	Quantity	Ratio	Amount	of TOTAL	Amount	Ratio	of TOTAL
10 Main Equipment	100.00 %	102 t	105.51 $/kg	10,736 k$	74.58 %		2,775	64.00 $/h	178 k$	2.43 %	10,913 k$	107257.54	30.32 %
Procurement		102 t	86.56 $/kg	8,807 k$	61.18 %	2.02 %	2,775	64.00 $/h	178 k$	2.43 %	8,985 k$	88301.72	24.96 %
Transport	6.00 %	8,807 k$	6.00 %	528 k$	3.67 %						528 k$	60.00	1.47 %
Techinical provisions	15.90 %	9,336 k$	15.00 %	1,400 k$	9.73 %						1,400 k$	150.00	3.89 %
30 Bulk Material	41.56 %	178 t	20.62 $/kg	3,660 k$	25.43 %	80.86 %	95,737	74.38 %	7,121 k$	97.57 %	10,781 k$	60729.80	29.95 %
31 Piping						15.71 %	21,615	64.00 $/h	1,383 k$	18.95 %	1,383 k$		3.84 %
32 Electrical	8.40 %	21 t	35.00 $/kg	740 k$	5.14 %	5.29 %	7,285	64.00 $/h	466 k$	6.39 %	1,206 k$	57055.16	3.35 %
33 Instrumentation	13.36 %	15 t	80.00 $/kg	1,176 k$	8.17 %	7.41 %	10,194	64.00 $/h	652 k$	8.94 %	1,829 k$	124368.11	5.08 %
34 Structural Steel	1.55 %	65 t	2.10 $/kg	136 k$	0.95 %	1.70 %	2,334	64.00 $/h	149 k$	2.05 %	286 k$	4404.01	0.79 %
35 Pipeline/sealine													
36 Civil Works	1.21 %	142 m3	750.00 $/m3	107 k$	0.74 %	2.73 %	3,761	64.00 $/h	241 k$	3.30 %	348 k$	2439.61	0.97 %
37 Insulation	0.77 %	4 t	18.20 $/kg	68 k$	0.47 %	1.18 %	1,623	64.00 $/h	104 k$	1.42 %	172 k$	46152.00	0.48 %
38 Painting	0.09 %	1 t	7.00 $/kg	8 k$	0.05 %	0.75 %	1,031	64.00 $/h	66 k$	0.90 %	74 k$	68461.82	0.20 %
39 Buildings	2.68 %	430 m2	548.84 $/m2	236 k$	1.64 %	7.81 %	10,750	64.00 $/h	688 k$	9.43 %	924 k$	2148.84	2.57 %
40 Fire fighting & Protection													
41 Site preparation	1.14 %	5,000 m2	20.00 $/m2	100 k$	0.69 %	2.03 %	2,797	64.00 $/h	179 k$	2.45 %	279 k$	55.80	0.78 %
42 Jacket													
43 Gravity base PLTF substructure '35 Storages													
44 Deck Module structure													
45 Floating storage													
45 Anodes & Cathodic protection													
46 Loading station superstructure													
47 Special operations													
48 Telecom and Computer													
49 Other Bulk													
5C Construction facilities													
5D Precommissioning						25.43 %	28,000	80.00 $/h	2,240 k$	30.69 %	2,240 k$		6.22 %
Transport	2.05 %	3,003 k$	6.00 %	180 k$	1.25 %						180 k$	60.00	0.50 %
Technical provisions	5.42 %	3,183 k$	15.00 %	477 k$	3.32 %	10.81 %	6,347	15.00 %	952 k$	13.04 %	1,429 k$	449.09	3.97 %
TECHNICAL COST	141.56 %			14,396 k$			98,512		7,299 k$		21,695 k$		60.27 %
70 Engineering, Management...							21,695	28.00 %	6,075 k$		6,075 k$		16.88 %
80 Associated Expenses							27,770	3.70 %	1,027 k$		1,027 k$		2.85 %
90 Contingencies							28,797	25.00 %	7,199 k$		7,199 k$		20.00 %
Subtotal COST											14,301 k$		39.73 %
TOTAL COST									**LANG FACTOR**	4.09	35,996 k$		100.00 %

Appendix D

LOW & HIGH BOUNDARIES OF PRODUCTION COST ESTIMATE

Low boundary calculation



Selected Case **Andalucia**

Date Assumptions

Commencement date (FID)	2013	on Quarter	Q1
Construction duration	24	months	
COD	2015	on Quarter	Q1

Economical Assumptions

Reference	01/01/2013	
Inflation	0,0%	
LCOH2 @	4%	in real
Production	10755,0	t/y

			2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2038	2039
Discount Factor	4%		1,00	1,04	1,08	1,12	1,17	1,22	1,27	1,32	1,37	1,42	1,48	1,54	1,60	2,67	2,77
Inflation	0,0%		1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Net Production	tons	268 875,0	0,0	0,0	10 755,0	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00	10 755,00
Calcul du LEC par les coûts																	
Capex (project after FID)	M$	394,0	236,4	157,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Capex - total	M$	394,0	236,4	157,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Opex	M$	737,1			29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5
Capex (unflated)	M$12	394,0	236,4	157,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Opex	M$12	737,1	0,0	0,0	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5	29,5
NPV of Capex	M$12	387,9	236,4	151,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NPV of Opex	M$12	442,9	0,0	0,0	27,3	26,2	25,2	24,2	23,3	22,4	21,5	20,7	19,9	19,2	18,4	11,1	10,6
Net discounted production of Hydroge	t	161 553,3	0,0	0,0	9 943,6	9 561,2	9 193,4	8 839,8	8 499,8	8 172,9	7 858,6	7 556,3	7 265,7	6 986,2	6 717,5	4 034,4	3 879,2

Levelized Cost Of Production	$12/t	5 143
Capex	$12/t	2 401
Opex	$12/t	2 741

Summary of the variations to the “base” cost estimate:

- Better solar resources, bringing plant capacity factor to 25% instead of 20%
- Plant nominal capacity highest than the “base” one by a factor 12
- Reduction of specific Capex cost by 40% due to scale effect and by 30% to consider low range of the base estimate
- Reduction of specific Opex by 22% due to scale effect and by 30% to consider low range of the base estimate

High boundary calculation

Selected Case	**Andalucia**		
Date Assumptions			
Commencement date (FID)	2013	on Quarter	Q1
Construction duration	24	months	
COD	2015	on Quarter	Q1
Economical Assumptions			
Reference	01/01/2013		
Inflation	0,0%		
LCOH2 @	4%	in real	
Production	669,2	t/y	

			2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2038	2039
Discount Factor	4%		1,00	1,04	1,08	1,12	1,17	1,22	1,27	1,32	1,37	1,42	1,48	1,54	1,60	2,67	2,77
Inflation	0,0%		1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Net Production	tons	16 728,9	0,0	0,0	669,2	669,16	669,16	669,16	669,16	669,16	669,16	669,16	669,16	669,16	669,16	669,16	669,16
Calcul du LEC par les coûts																	
Capex (project after FID)	M$	107,9	64,8	43,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Capex - total	M$	107,9	64,8	43,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Opex	M$	146,3			5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9
Capex (unflated)	M$12	107,9	64,8	43,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Opex	M$12	146,3	0,0	0,0	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9	5,9
NPV of Capex	M$12	106,3	64,8	41,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NPV of Opex	M$12	87,9	0,0	0,0	5,4	5,2	5,0	4,8	4,6	4,4	4,3	4,1	4,0	3,8	3,7	2,2	2,1
Net discounted production of Hydroge	t	10 051,5	0,0	0,0	618,7	594,9	572,0	550,0	528,8	508,5	488,9	470,1	452,1	434,7	418,0	251,0	241,4

Levelized Cost Of Production	$12/t	19 316
Capex	$12/t	10 573
Opex	$12/t	8 742

Summary of the variations to the "base" cost estimate:

- Lower solar resources, decreasing plant capacity factor by about 7%
- Unchanged plant nominal capacity
- Increase of specific Capex by 40% to consider high range of the base estimate
- Increase of specific Opex by 30% to consider high range of the base estimate