CERN Academic Training Programme 2005-2006
Towards Sustainable Energy Systems ?
Geneve, 28-31 March, 2006

Environmental Applications of Solar Thermal Energy: From Water Treatment to Soil Remediation

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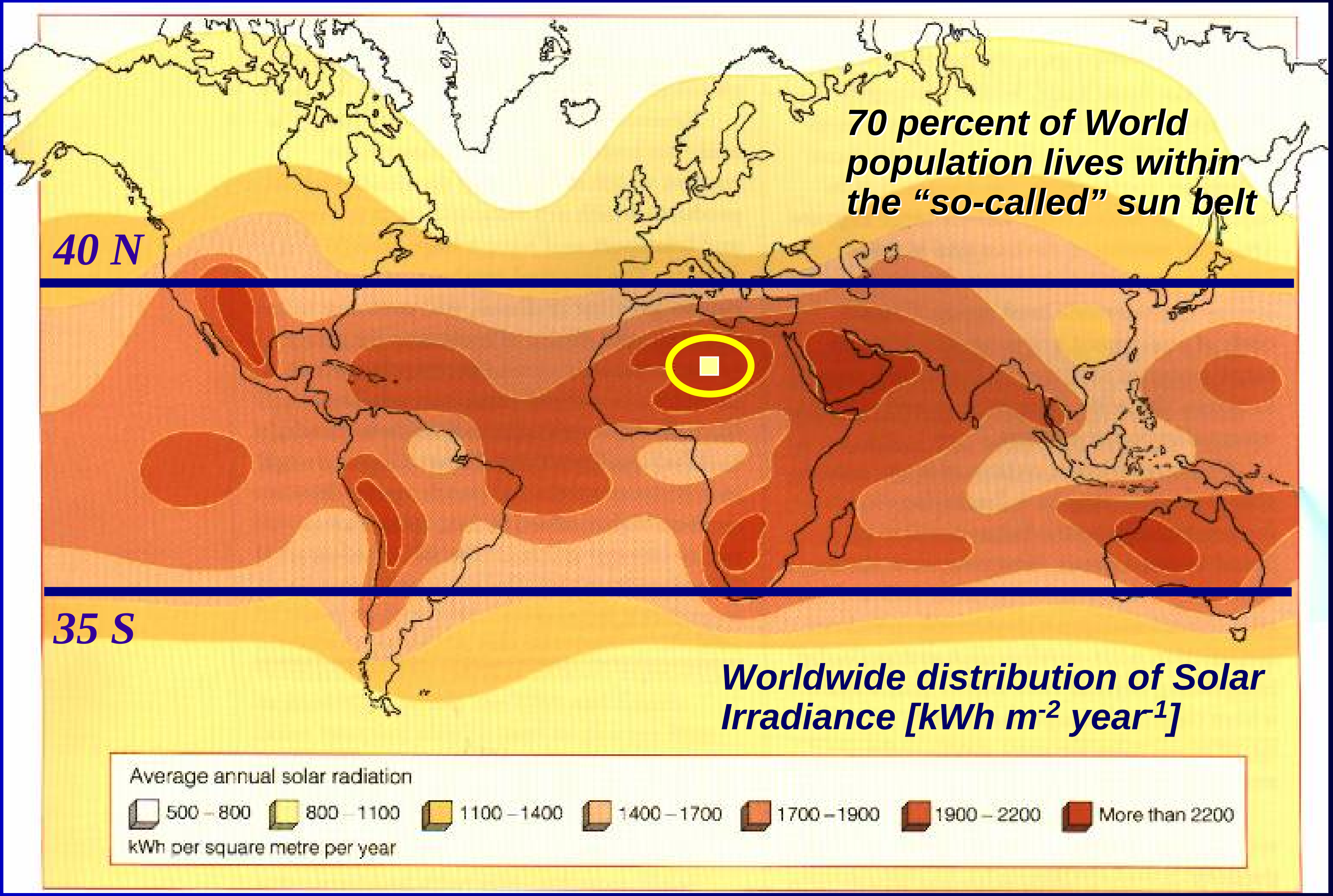
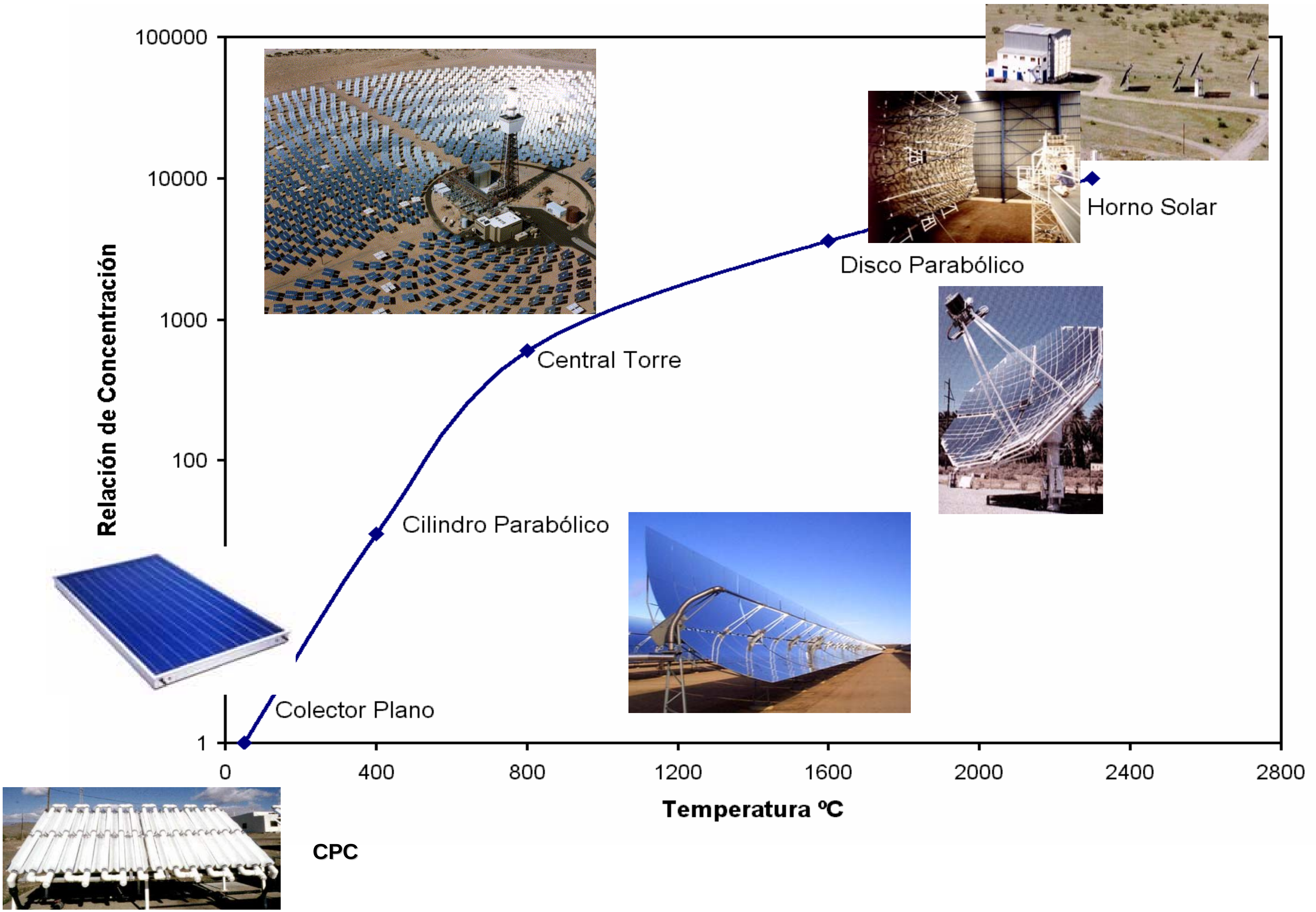
SOLAR ENERGY POTENTIAL

- Total energy yearly consumed by mankind (2003): ***105 E+6 GWh***
- Average yearly radiation location ***2200 kWh/m²***
- Total collection efficiency: ***35%***
- Combined cycle efficiency: ***45%***
- Solar collector surface needed: ***square of 550 km (side) (or 500 of 25 km side)***





Relación de Concentración
100000
10000
1000
100
1
0
400
800
1200
1600
2000
2400
2800
Temperatura ºC
Horno Solar
Disco Parabólico
Central Torre
Cilindro Parabólico
Colector Plano
CPC

PLATAFORMA SOLAR DE ALMERÍA (PSA)

P.S.A.

Large European Scientific installation belonging to the public Spanish research institution CIEMAT (devoted to Energy and Environmental issues).

PSA is one of the most complete existing facilities to the research, testing and development of solar technologies and applications

Solar Heat for Industrial Processes

BACKGROUND

Around 105 GW_{th} corresponding to 150 million square meters of solar thermal collectors were installed by the year 2004 worldwide.

Until now the widespread use of solar thermal plants has focused almost exclusively on swimming pools, hot water preparation and space heating in the residential sector.

Solar Heat for Industrial Processes

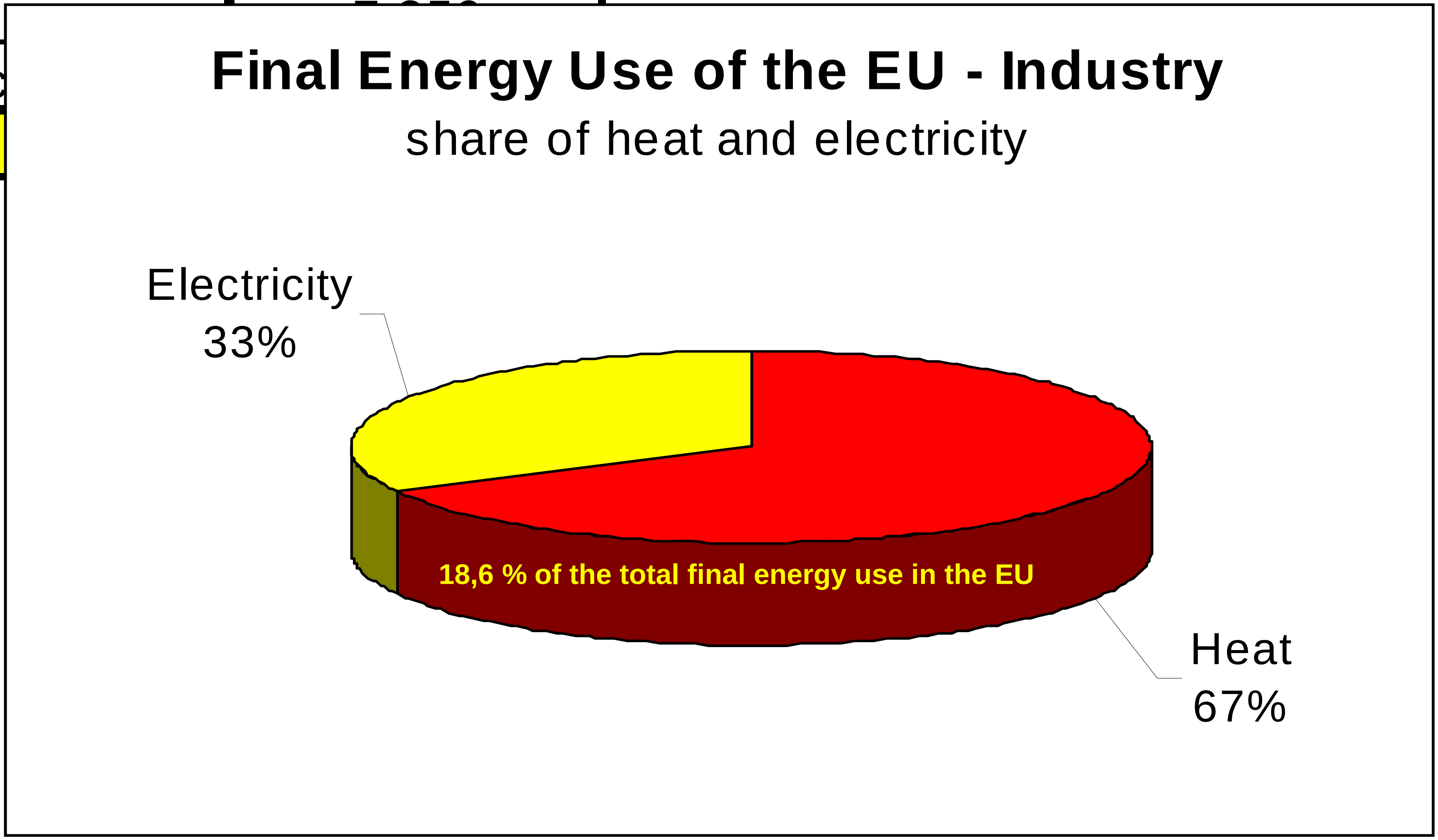
BACKGROUND 2

The use of solar energy in industrial companies is currently insignificant compared to the use in the residential sector.

On the other hand: **The industrial sector has the biggest energy consumption in the OECD countries at approximately 30%.**

EU - Industry: Share of Heat and Electricity

Industry	[PJ]
Heat	[illegible]
Electric	
Total	



Source: GREEN PAPER – TOWARDS A EUROPEAN STRATEGY FOR THE SECURITY OF ENERGY SUPPLY

MAIN BLOCKS

- LOW TEMPERATURE (T< 100ºC): WATER TREATMENT

- MEDIUM TEMPERATURE (T< 250ºC): STEAM FOR INDUSTRIAL PROCESSES

- HIGH TEMPERATURE (T> 250ºC) PROCESSES

WATER TREATMENT

R&D UNIT AT PSA-CIEMAT

ENVIRONMENTAL APLICATIONS OF SOLAR ENERGY AND CHARACTERIZATION OF SOLAR RADIATION

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RESEARCH PROGRAM OBJETIVES

- **Main objective: TECHNOLOGY DEVELOPMENT**
- **Core research activities: APPLICATION OF SUNLIGHT TO WATER PROCESSES**

Research areas:

- Solar detoxification of water
- Solar water disinfection
- Gas-phase solar detoxification
- Solar seawater desalination
- Characterization of solar radiation

ADVANCED OXIDATION PROCESSES (AOPs)

- H_2O_2/Fe^{2+} (Fenton): $Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH^\bullet$
- H_2O_2/Fe^{2+} (Fe^{3+})/UV (Photo-Fenton): $Fe^{3+} \xrightarrow{h\nu} Fe^{2+} + HO^\bullet$
- $TiO_2/h\nu/O_2$ (Photocatalysis): $TiO_2 \xrightarrow{h\nu} e^- + h^+$

  $h^+ + H_2O \rightarrow {}^\bullet OH + H^+$

- O_3/H_2O_2:

  $H_2O_2 \xleftrightarrow{H^+} HO^- + O_3 \rightarrow O_2 + HO_2^-$

  $HO_2^- + O_3 \rightarrow HO_2^\bullet + O_3^{\bullet-}$

  $HO_2^\bullet \Leftrightarrow H^+ + O_2^{\bullet-}$

  $O_2^{\bullet-} + O_3 \rightarrow O_2 + O_3^{\bullet-}$

  $O_3^{\bullet-} + H^+ \rightarrow HO_3^\bullet$

  $HO_3^\bullet \rightarrow HO^\bullet + O_2$

  $HO^\bullet + O_3 \rightarrow HO_2^\bullet + O_2$

- O_3/UV: $O_3 \xrightarrow{h\nu} O^1(D) + O_2$ $\quad O^1(D) + H_2O \longrightarrow H_2O_2$ $\quad H_2O_2 \xrightarrow{h\nu} 2HO^\bullet$
- H_2O_2/UV: $H_2O_2 \xrightarrow{h\nu} 2OH^\bullet$

Processes based on the generation of powerful oxidant hydroxyl radicals (•OH)

WATER TREATMENT: INDEX

1. Introduction
2. Background and previous technological developments. SOLARDETOX project
3. Commercial development: '*Albaida*' plant
4. Water disinfection applications. SOLWATER & AQUACAT projects
5. Future outlook. CADOX project
6. Conclusions

FIRST EXPERIMENTAL SOLAR FACILITIES

Sandia National Laboratories (Albuquerque, USA) developed in 1989 the first experimental solar installation for water detoxification at pre-industrial level. Used technology was based on One-Axis Parabolic-Trough Collectors

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FIRST EXPERIMENTAL SOLAR FACILITIES

One year later, CIEMAT (1990-1991), erected the second experimental facility at PSA (Spain), using Two-Axis Parabolic-Trough Collectors. These pilot plants were the first step in the development of the solar photocatalytic technology

FIRST ON-SITE ASSESSMENT

In the early 90's, the NREL, Sandia National Labs and the Lawrence Livermore National Lab addressed the so called "Livermore experiment" (USA). A Solar Detox Plant was installed using one-axis PTCs to treat groundwater contaminated with TCE (from the II World War)

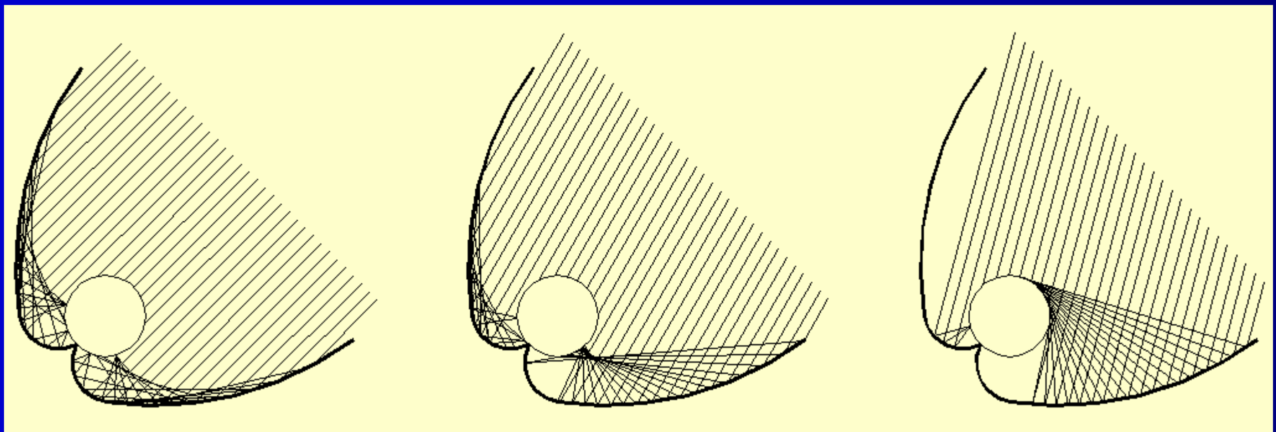
Tests were successful but the economic figures not!

PSA PHOTOCATALYTIC FACILITY (1991)

NON-CONCENTRATING SOLAR COLLECTORS

A large number of **non-concentrating solar collectors** (CR = 1) were designed during the 90s to the achievement of the most adequate reactors to solar photocatalytic processes, due to their **important advantages:** easy manufacturing, low investment cost, simple operation and supervision, low maintenance requirements, use of UV diffuse radiation, etc. As consequence, an extensive effort in the design of static non-tracking collectors, was made.

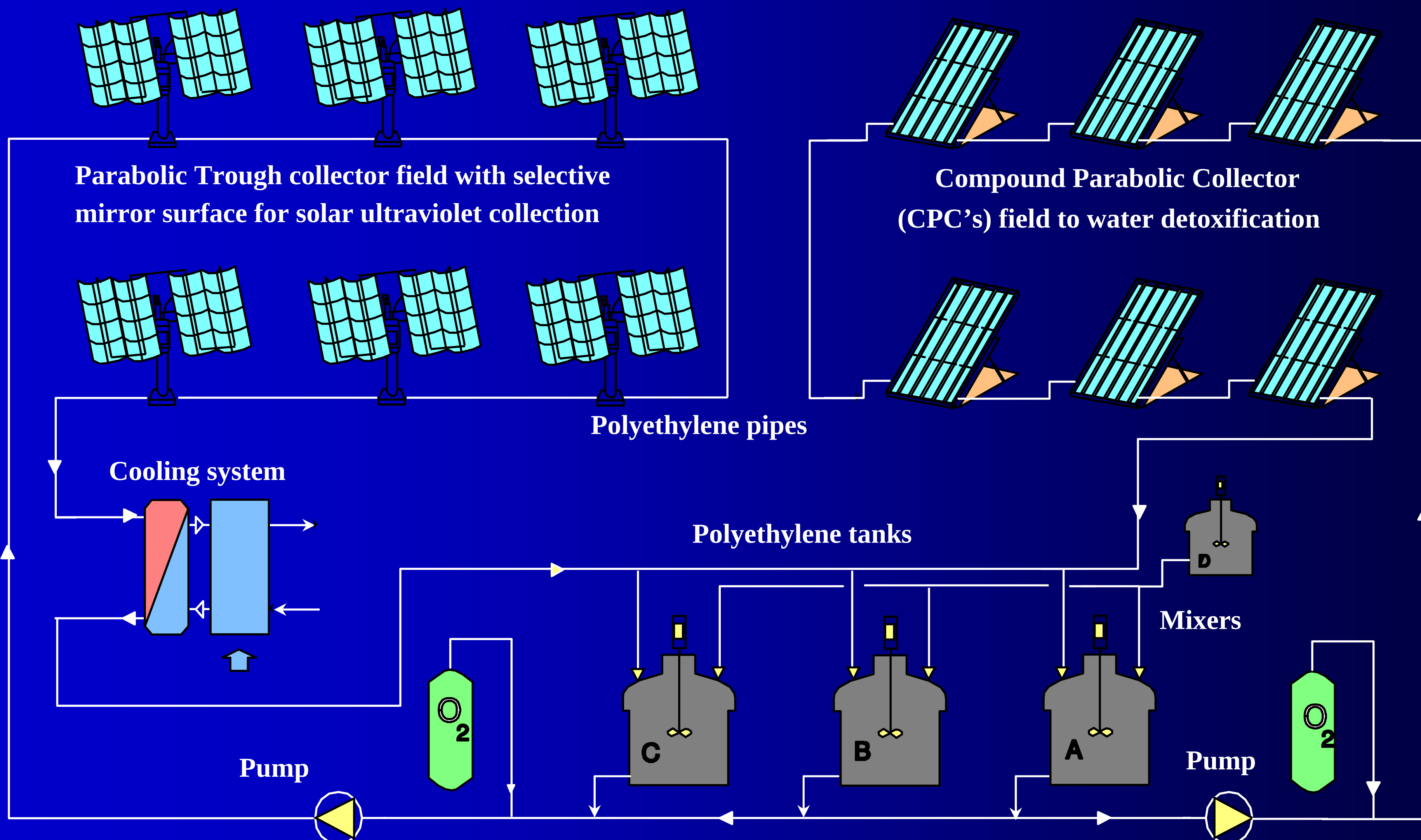
COMPOUND PARABOLIC CONCENTRATORS



Compound Parabolic Concentrators (CPCs) are a very good option for Solar Detoxification applications

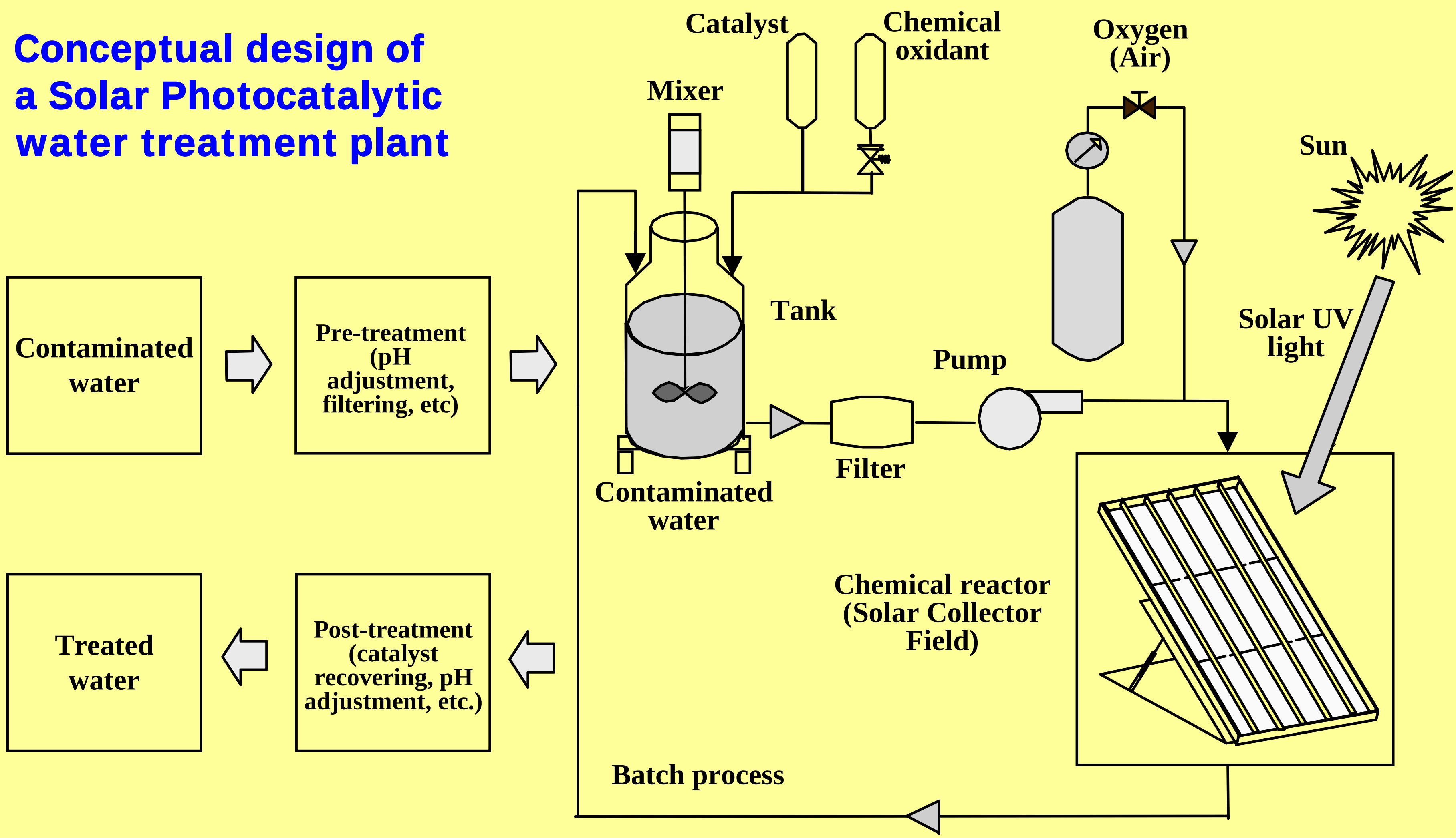
These static collectors, constituted by aluminium reflective surface formed by an involute around a cylindrical reactor, have the **best optics** for low concentration systems (better performance of solar photocatalytic systems)

PSA PHOTOCATALYTIC FACILITY (1995)



PHOTOCATALYTIC PLANT CONCEPT

Conceptual design of a Solar Photocatalytic water treatment plant



BACKGROUND: SOLARDETOX PROJECT

The **SOLARDETOX Project** (1997-2000) was financially supported by EU-DGXII. Project budget: **1.87 million €**

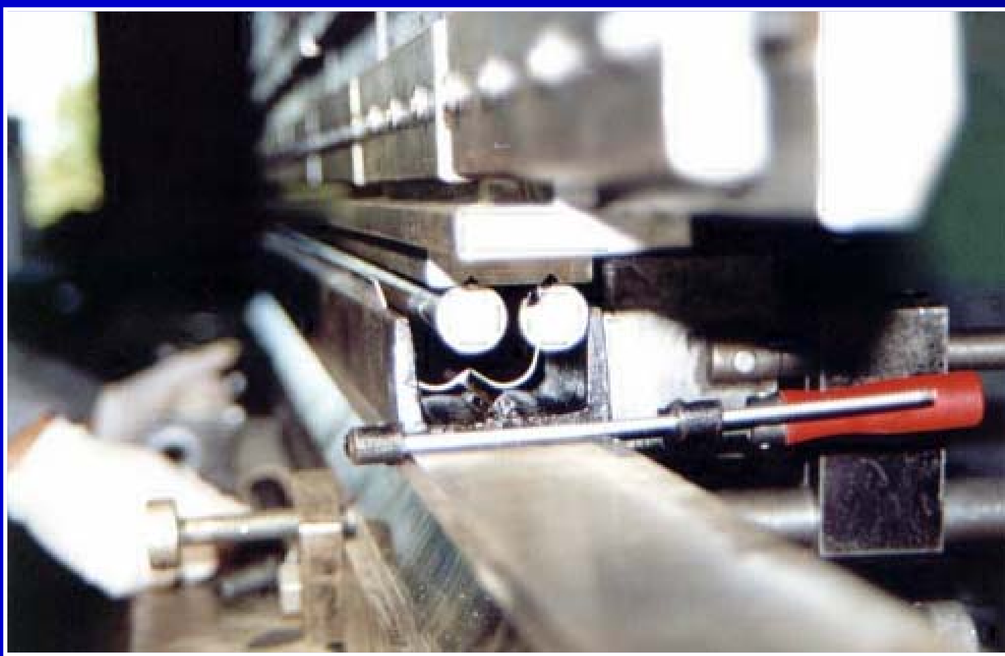
MAIN OBJECTIVE: Creation of an Industrial Consortium to develop the overall solar technology to make possible the manufacturing and set-up of plants to the treatment of hazardous water contaminants using solar photocatalysis

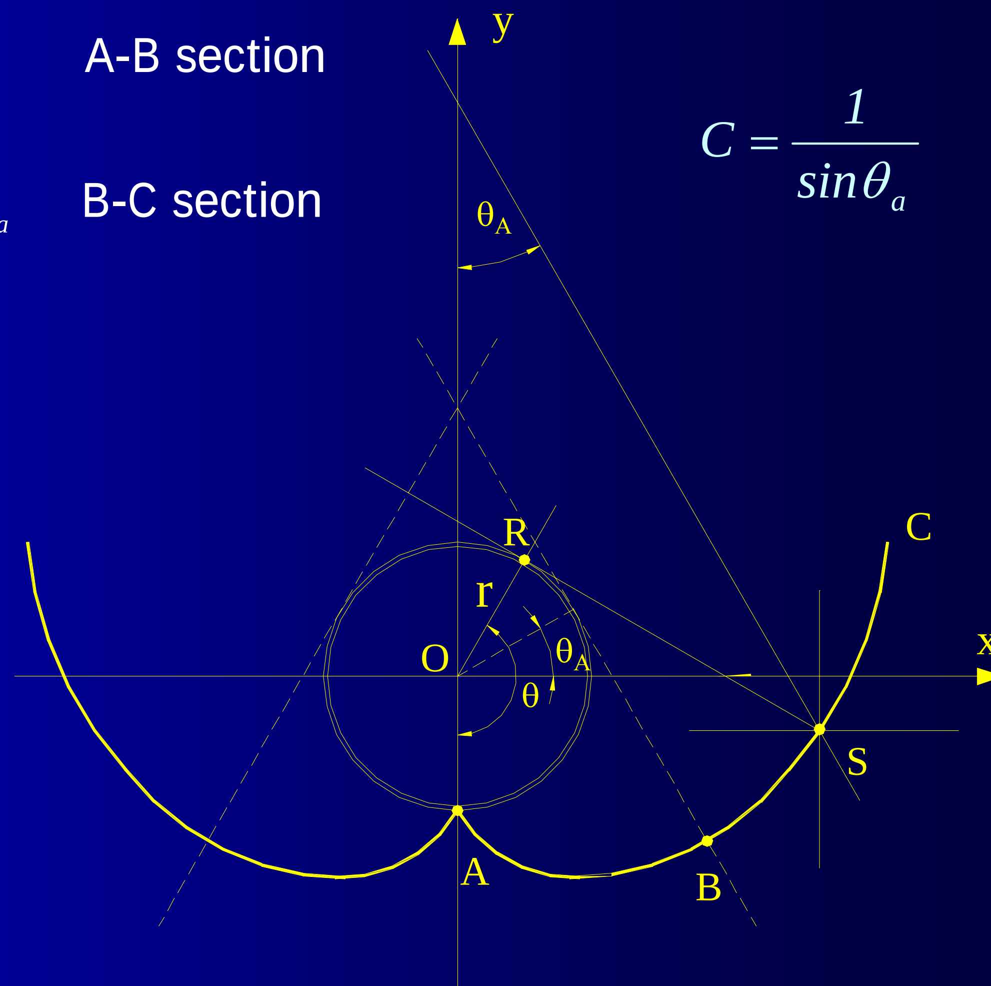
CPC COLLECTOR DESIGN

CPC equation: $\rho = r\theta \quad for \quad |\theta| \le \theta_a + \pi/2$ A-B section

$$\rho = r\frac{\theta + \theta_a + \pi/2 - cos(\theta - \theta_a)}{1 + sin(\theta - \theta_a)} \quad for \;\; \theta_a + \frac{\pi}{2} \le |\theta| \le \frac{3\pi}{2} - \theta_a$$ B-C section

$$C = \frac{1}{sin\theta_a}$$

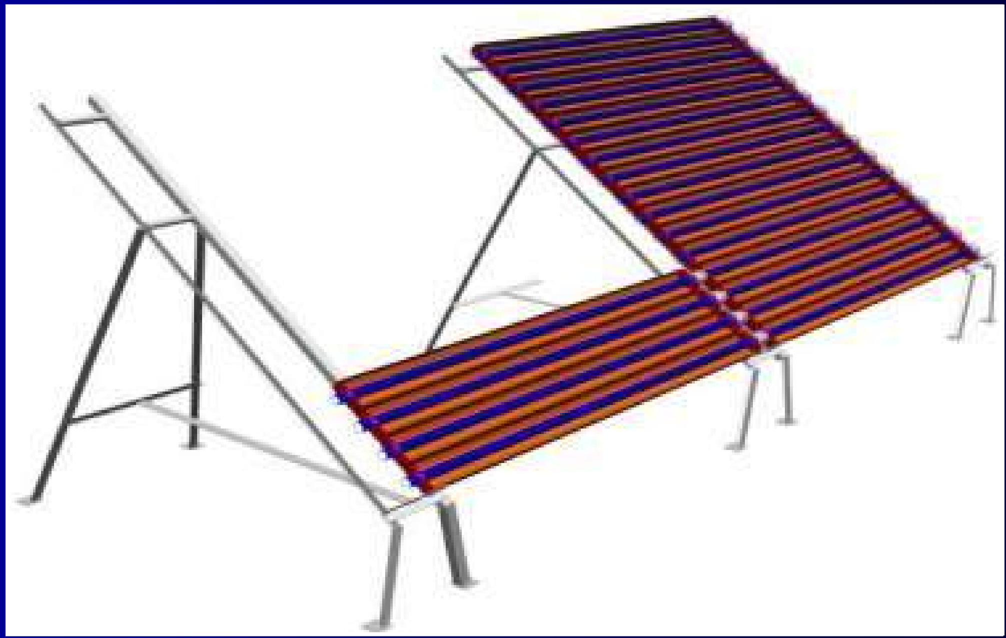




One Sun CPC collector manufacturing: θ_a = 90º ⇒ all direct and diffuse solar photons can be collected and used (diffuse UV radiation is a very important fraction of total solar UV)

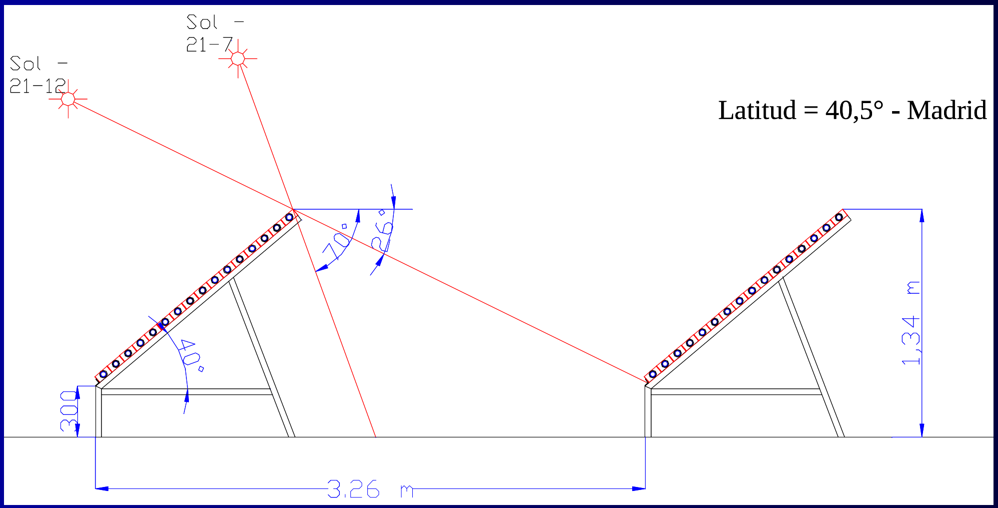
SOLAR COLLECTOR ENGINEERING

A very simple one-sun CPC collector was designed, constructed and tested to optimize the **manufacturing process** (modularity), **on site installation** (minimum interconnecting pieces and dark zones) and **cost saving**

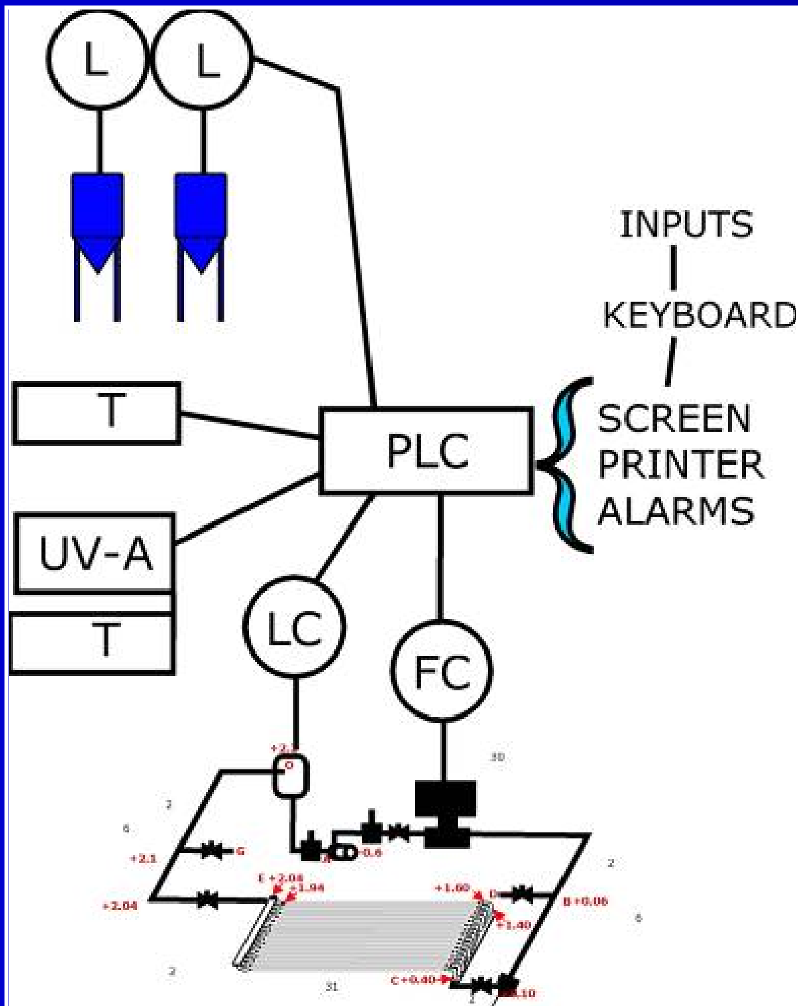


Reactors, made of glass with low iron content to optimize UV transmission efficiency, are disposed horizontally in 16 parallel rows. Manifold headers designed to uniform flow distribution among all parallel tubes. Turbulent flow (Re = 15000)

CPC ASSEMBLY AND SETUP



CONTROL SYSTEM



The plant is designed with full automatic systems and minimum operation & maintenance requirements. A Programmable Logic Controller **(PLC)** receives all plant data signals (flow-rate, tanks level, temp, solar UV-A irradiation, etc) and control pumps and system valves. Process evolution is monitored through the measuring and integration of UV light up to a fixed level.

FINAL SOLAR PHOTOCATALYTIC PLANT

Plant located at HIDROCEN S.L. factory (Arganda del Rey, Madrid, Spain), 2000

- *100 m^2 of CPC collector field*
- *Total treatment volume: 800 L*
- *Batch Operation*
- *Automatic operation*

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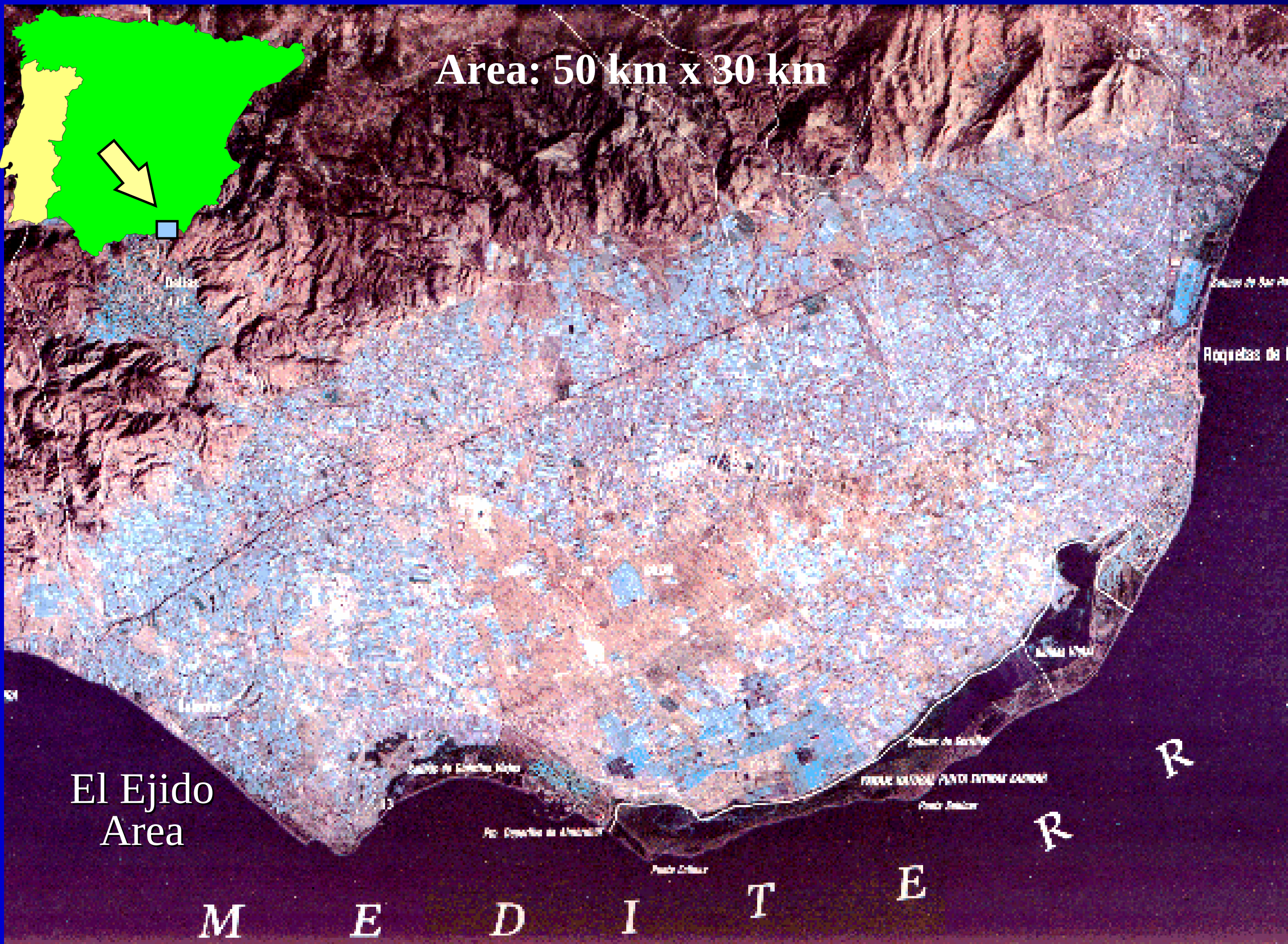
GREENHOUSE INTENSIVE AGRICULTURE



- The intensive greenhouse's agricultural activity is a very important economical sector in Almería
- Today, there are about 30,000 hectares of greenhouses in Almería province
- Due to continuous expansion, the sector is becoming more complex and associated problems are heavily pressing the environment

GREENHOUSE INTENSIVE AGRICULTURE

Distribution deposits

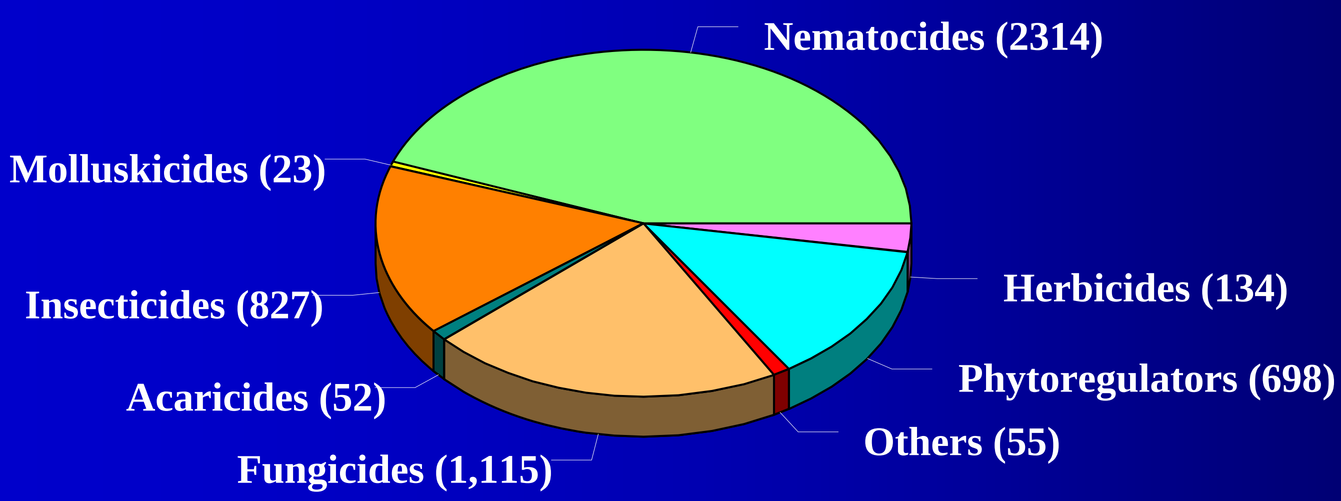
Intensive greenhouse agriculture requires about 200 times more pesticides than conventional one

PESTICIDE PLASTIC BOTTLES RECYCLING

- One of these problems is that derived from the wide use of pesticides and the consequent **empty plastic bottles**
- 30,000 hectares of greenhouses existing in Almería yearly consume about **5,200 Tons** of phytosanitary chemical products (1.5 million of bottles; 1.9 L average volume)
- Once used, these empty plastic bottles are a hazardous residue
- To solve the environmental problem, a selective collection and recycling of these bottles was proposed

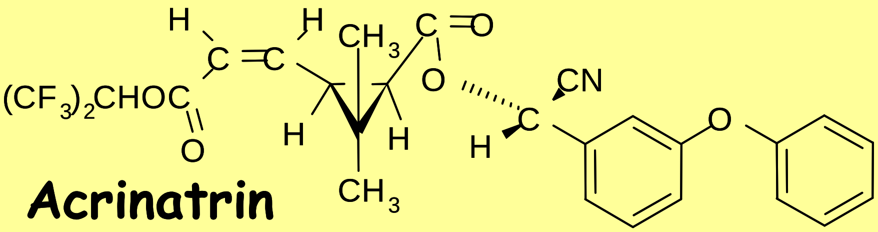
SOLUTION PROPOSED

- The recycling process needs an industrial washing of shredded plastic bottles
- This produces a contaminated water with some hundreds of mg L^{-1} of dissolved persistent toxic compounds
- As the water must be recycled, the contaminants must be treated
- No conventional treatment exist
- Solar photocatalysis was proposed to this treatment

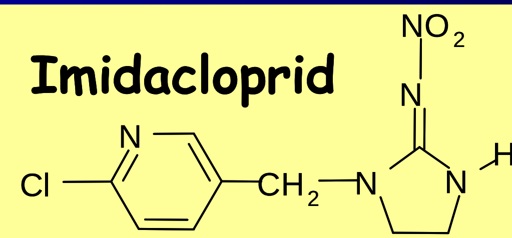


Distribution of 5,200 tons of pesticide products used in Almeria (1995 data)

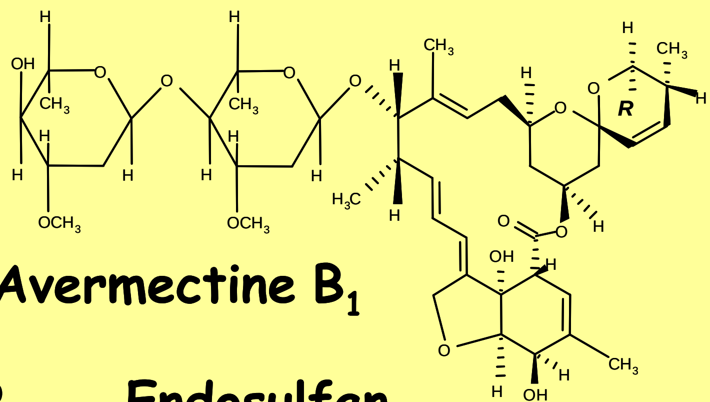
SELECTED AGROCHEMICAL SUBSTANCES



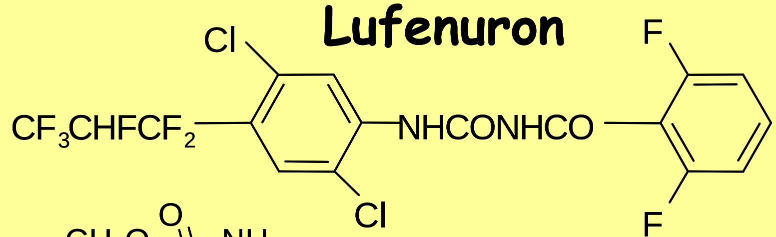
Acrinatrin



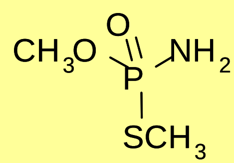
Imidacloprid



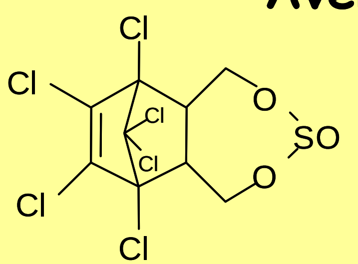
Avermectine B_1



Lufenuron

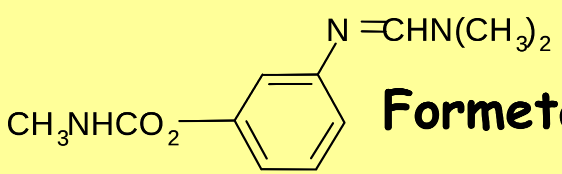


Metamidofos



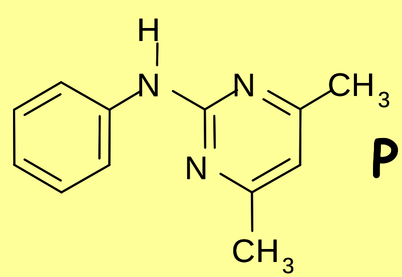
Endosulfan

$(CH_3)_2NCOC=NOCONHCH_3$ (with SCH_3 on C) Oxamilo



Formetanato

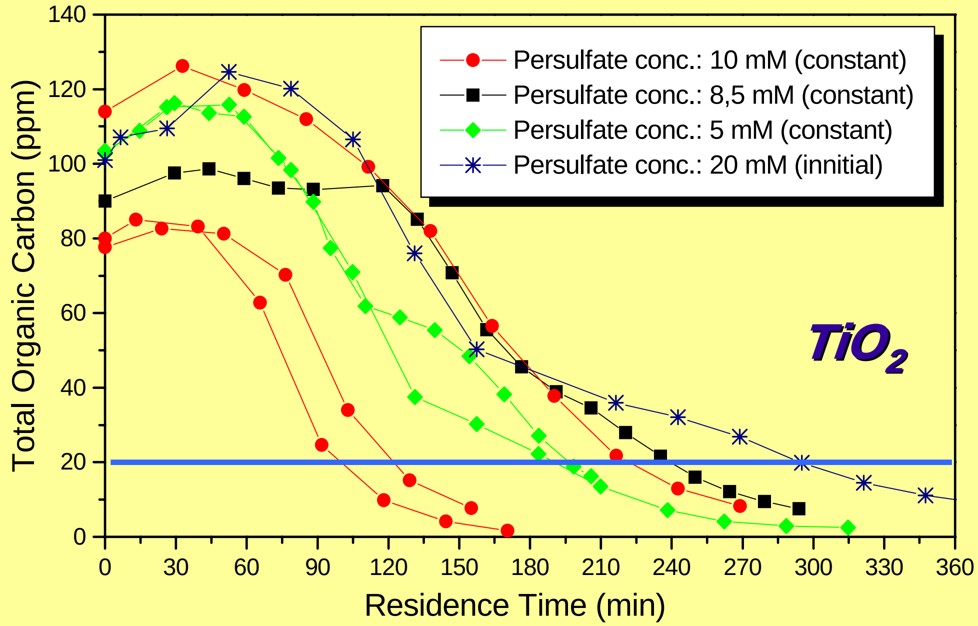
$(CH_3)_2NCH_2CH_2CH_2NHCO_2CH_2CH_2CH_3$ Propamocarb

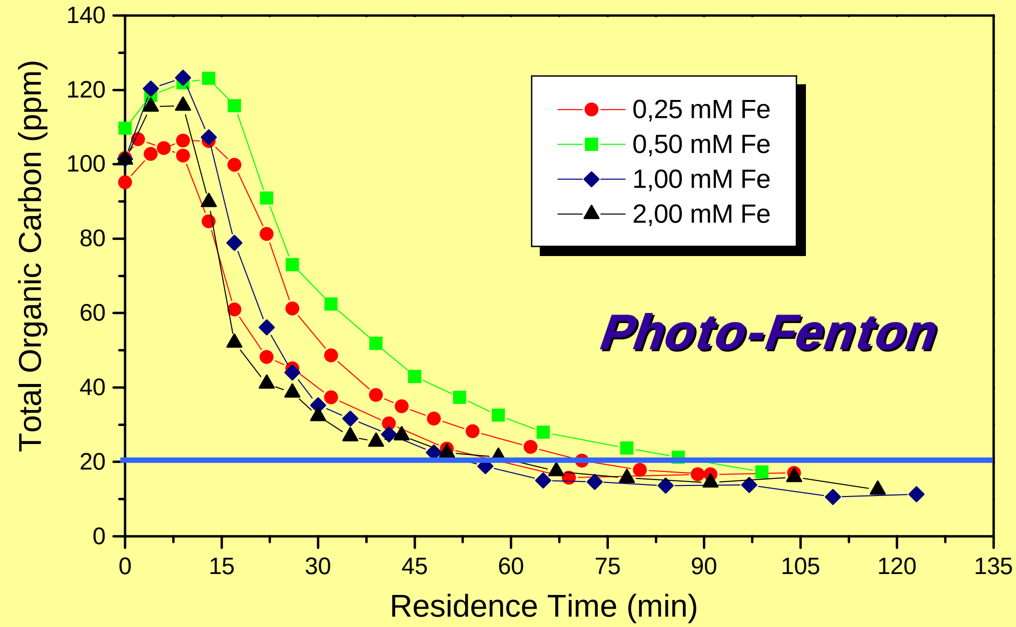


Pirimetanil

FEASIBILITY STUDY PERFORMED

Mineralisation of Total Organic Carbon of a mixture of 10 selected pesticides





- Obtained degradation rates were from **0.55** to **1.13 mg/L min** for the different single pesticides and **0.99 mg/L min** for the 10 pesticide mixtures. Residual average residue of an empty bottle is between **0.1** and **0.7 g** → an average value of **0.5 g** is considered
- Estimating a yearly treatment of 750,000 bottles → **375 kg/year** of pesticides to be treated

PROPOSED EVALUATION METHODOLOGY

The uses of residence time could give erroneous conclusions when there are important differences in the incident radiation in the reactor due to clouds or different periods of the day. One way to avoid this problem is to use a relationship between experimental time, plant volume, collector surface and the radiant power density ($UV_G = W_{UV}/m^2$) by:

$$Q_{UV,n} = Q_{UV,n-1} + \Delta t_n \overline{UV}_{G,n} \frac{A_{CPC}}{V_{TOT}}; \qquad \Delta t_n = t_n - t_{n-1}$$

$Q_{UV,n}$: accumulated energy, per unit of volume, incident on the reactor for each sample taken during the experiment ($kJ\ L^{-1}$).

$\overline{UV}_{G,n}$: average incident radiation on the collector surface within each t interval ($kW\ m^{-2}$)

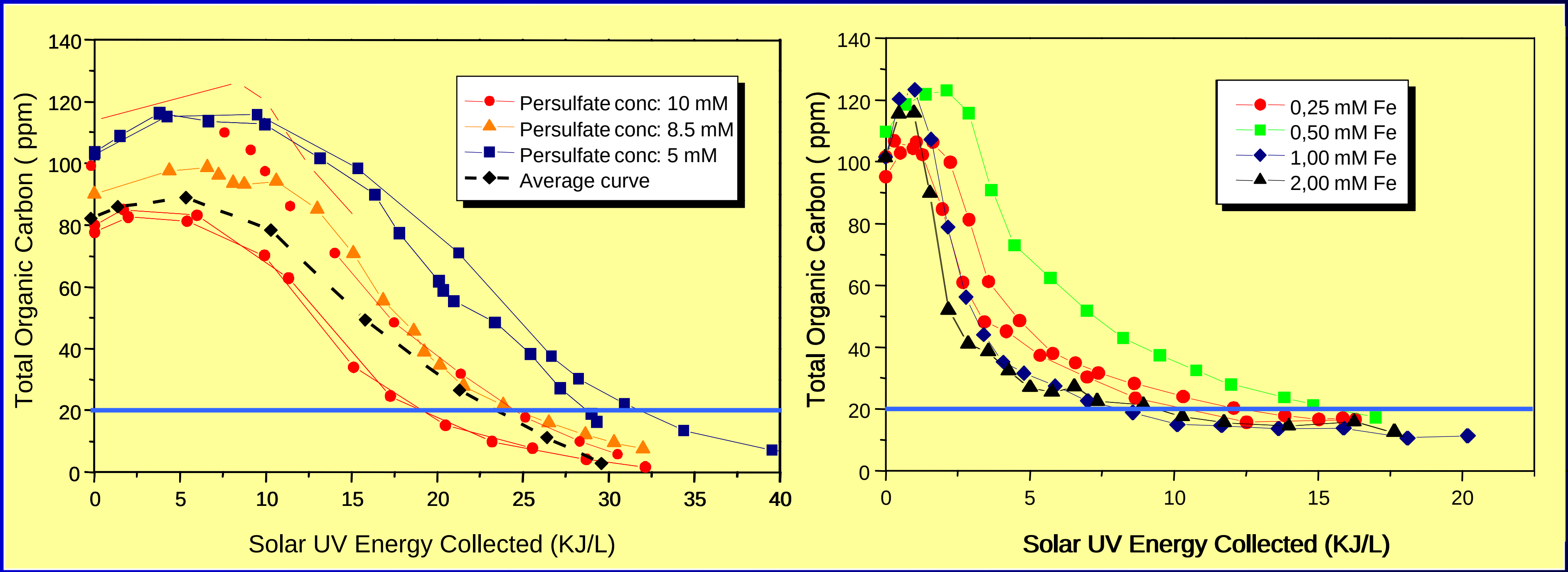
t_n : experimental time for each sample (s)

A_{CPC} : collector surface (m^2)

V_{TOT} : total plant volume (L)

FEASIBILITY STUDY PERFORMED

Mineralisation of Total Organic Carbon of a mixture of 10 selected pesticides



- TiO_2 photocatalysis needs between **20** and **30 kJ/L** of Solar UV energy
- Photo-Fenton process is more effective, needing between **8** and **15 kJ/L** → A factor of **12 kJ_{UV}/L** is finally considered to the design of the plant (total surface of the solar collector field)

ALBAIDA PLANT DIMENSIONING

$$A_r = \frac{Q_{UV}\,V_t}{T_s\,\overline{UV_G}} = \frac{12\,x\,10^3\;x\,1875\,x\,10^3}{3000\,x\,3600\,x\,18.6}\left[\frac{J\;L^{-1}\;L}{s\,W\;m^{-2}}\right] = 112\,m^2$$

Final selected plant dimensioning (solar collector area) was: **150 m²**

Plant design data:

a) Total yearly volume of water to be treated (V_t): **1,875 m^3**

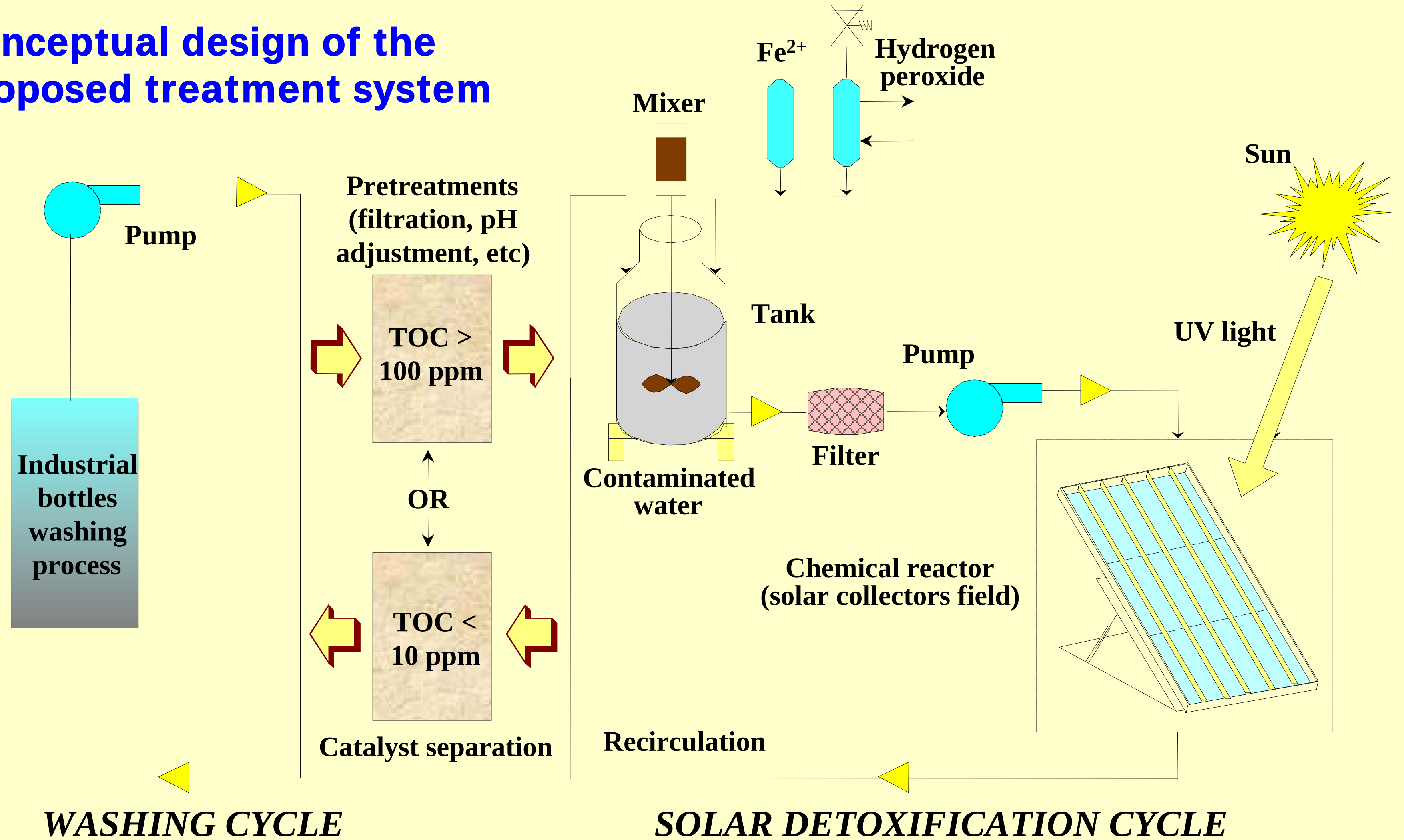
b) Yearly operating hours of solar facility (T_s): **3000 h**

c) Yearly average global UV irradiation (UV_G), sunrise to sunset: **18.6 $W_{UV}\ m^{-2}$**

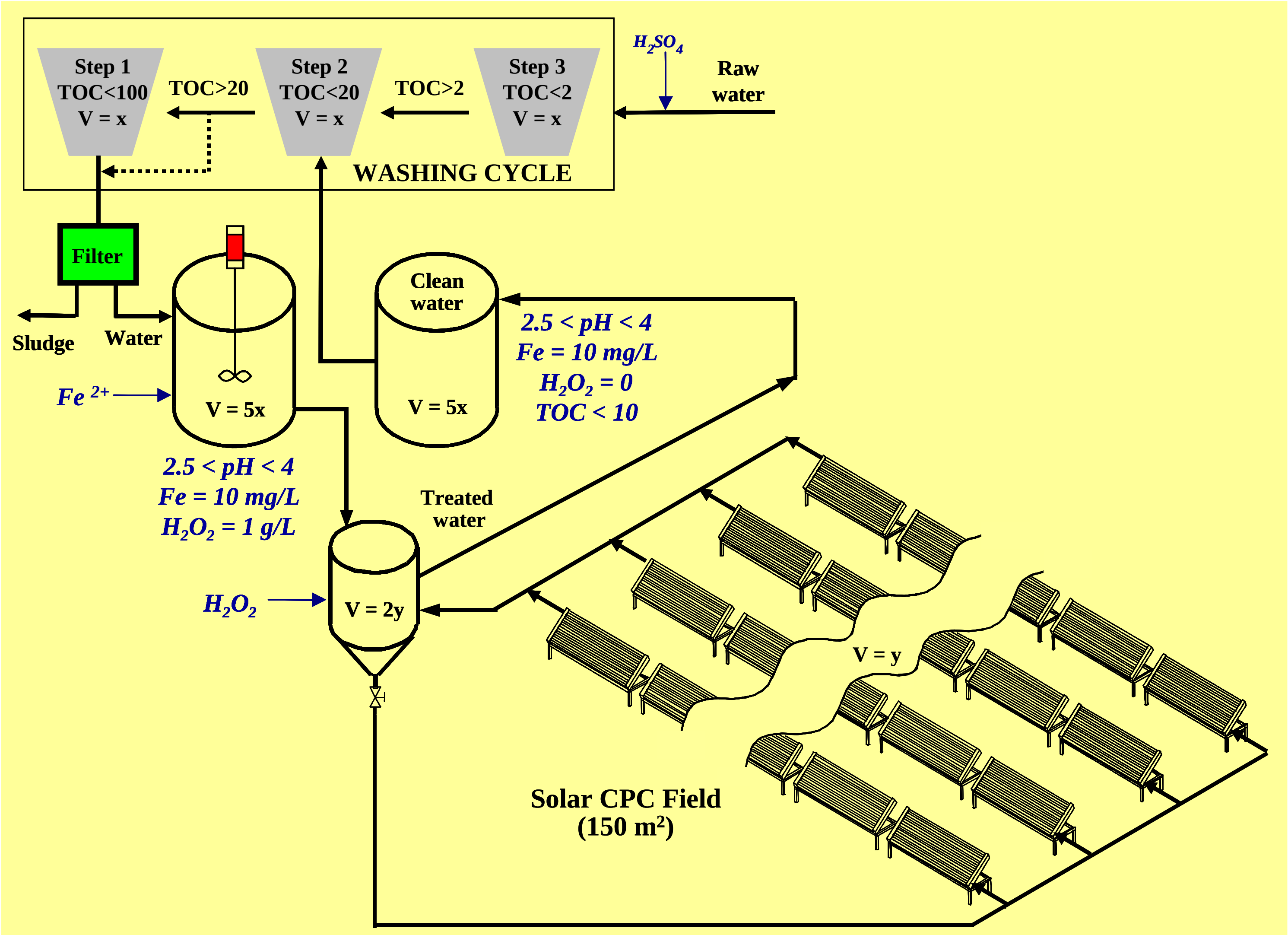
d) Average solar energy needed to degrade the contaminants (Q_{UV}): **12 $kJ_{UV}\ L^{-1}$**

GENERAL CONCEPT OF THE PLANT

Conceptual design of the proposed treatment system



PLANT LAYOUT & OPERATION PROCEDURE



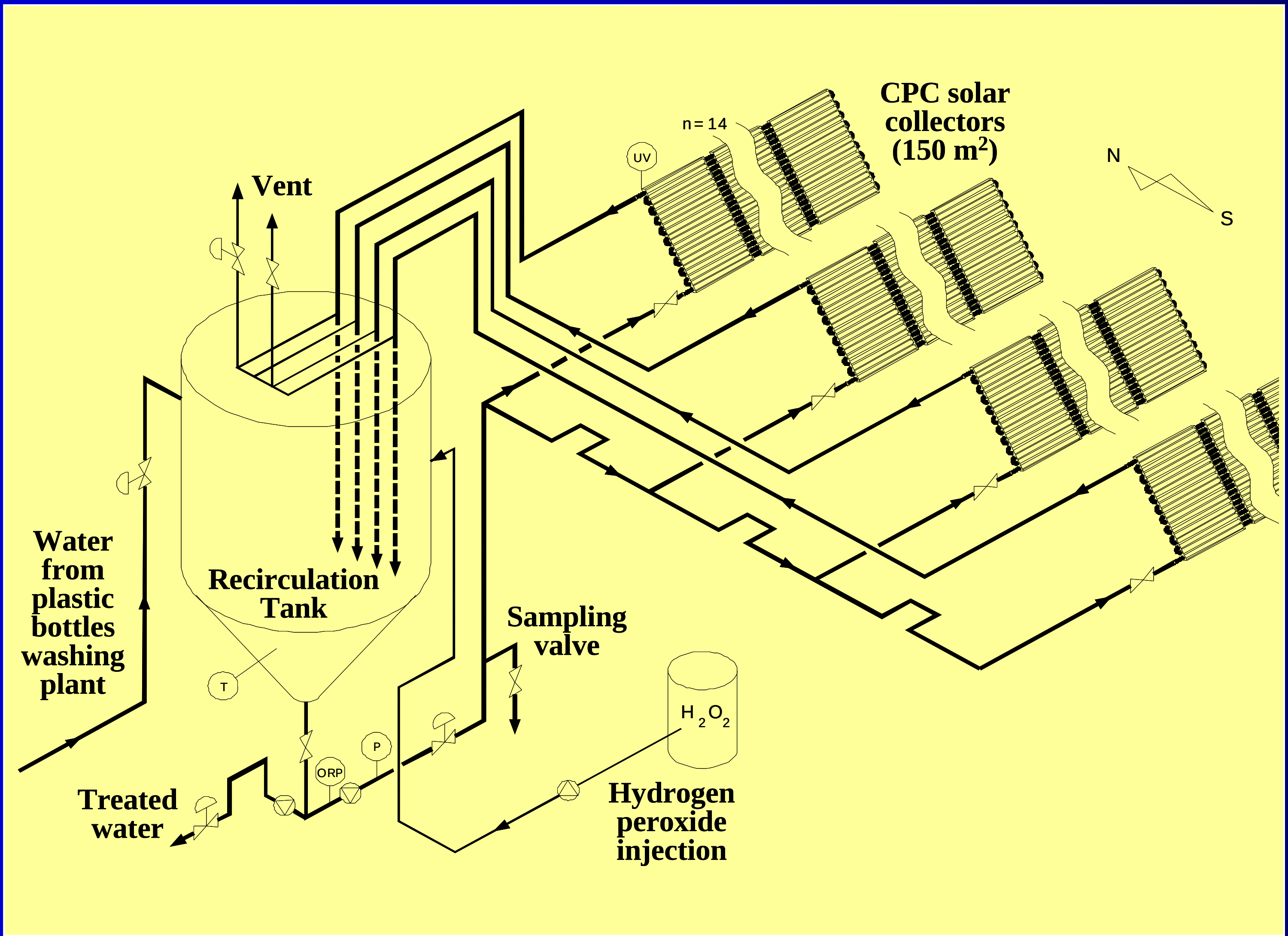
Operating procedure:

a) A triple washing process is applied to the shredded plastic (water is reused until **TOC = 100 mg L**)

b) Water is filtered to sludge removal and transfer to a **3000 L** tank previously to the photocatalytic treatment

c) There, **pH** is adjusted and **Iron** added to prepare the water to the **Photo-Fenton** treatment process

PLANT LAYOUT & OPERATION PROCEDURE



Operating procedure:

d) The system is run in **batch mode** using a **2000 L** recirculation tank

e) The **4 rows** are connected in parallel (independently operated) and the **14 modules** of each row in series

f) After treatment water is **returned** to the washing system and the tank is **refilled** with new contaminated water

FINAL TECHNICAL DATA

Solar field figures:

a) Individual CPC modules formed by **20 parallel tubes** (surface: **2.7** m^2/module)

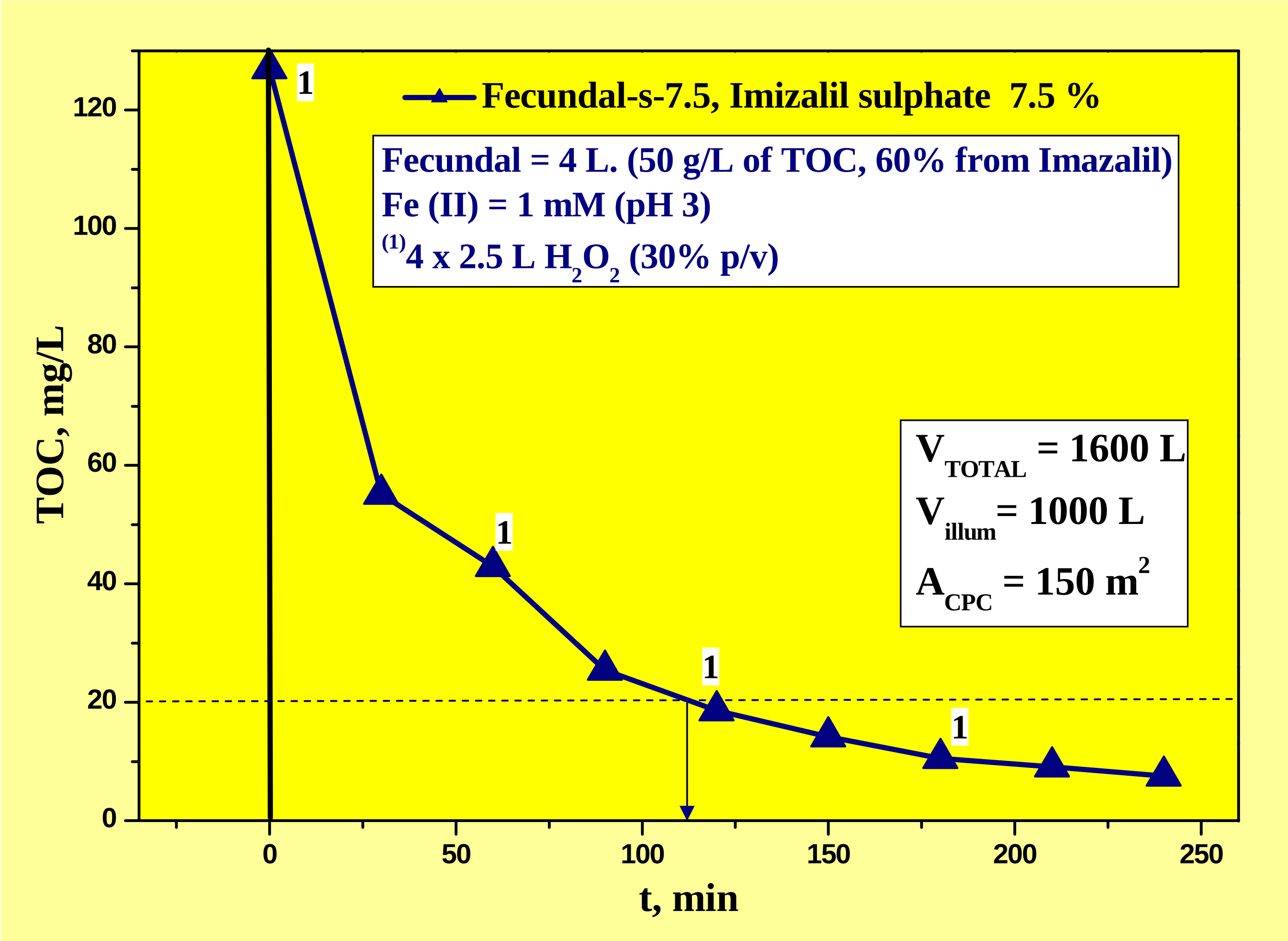
b) 4 parallel rows with **14 modules** each mounted on a 37º-tilted platform (local latitude)

c) total collectors surface: **150 m^2**

d) Total photoreactor volume: **1,061 L**

e) Total volume per batch: **1,500** to **2,000 L**

ALBAIDA PLANT INITIAL PERFORMANCE



First real test performed at the ALBAIDA plant using Imazalil pesticide (Janssen Pharmaceutica). Active ingredient: Imazalil. 80 percent of Total Organic Carbon (TOC) degradation is achieved in 115 min. (real time)

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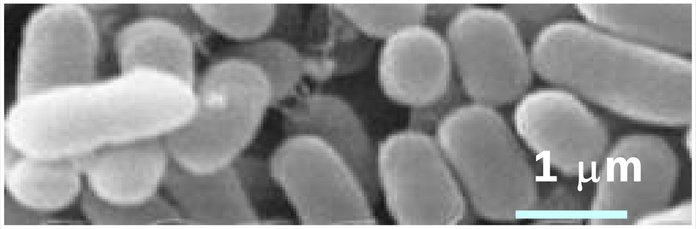
TiO_2 PHOTOCATALYTIC DISINFECTION

Application to the <u>photocatalysed destruction of bacteria, virus, etc.</u>

- **BACTERIA:** *Enterococcus faecalis (Gram+), Eschericia coli (Gram-)*



- **VIRUS & BACTERIO-PHAGE:** *Poliovirus* 1, *Pharge MS2 (RNA-bacteriophage)*
- **TUMOR CELLS:** *HeLa Cells (cervical carcinoma), T24 (bladder transicional cell carcinoma), U937 (monocytic leukemia).*

"Advanced Oxidation Processes for Water and Wastewater Treatment". *IWA Publishing* (Simon Parsons Ed.), 2004

DRINKING WATER DISINFECTION

Development and optimisation of the technology for drinking water disinfection in remote allocations of rural communities of developing countries, by means of photochemical processes based on natural solar light.

Catalyst immobilized on supports:

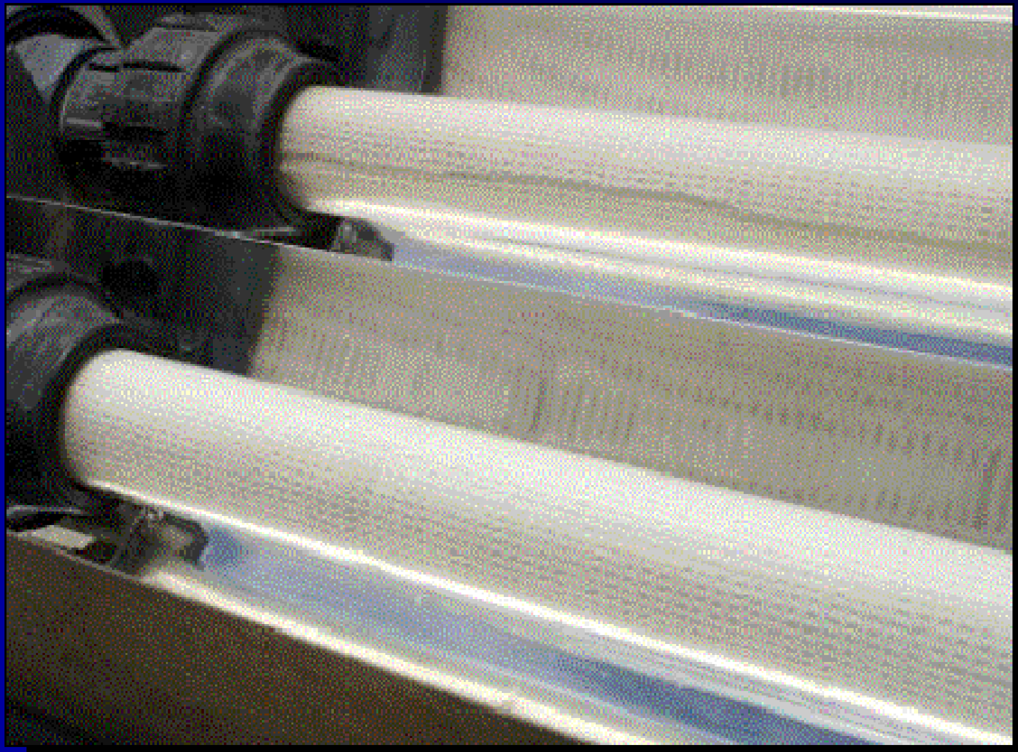
- TiO_2 over Ahlstrom Paper ©
- Ruthenium (II) Complexes immobilised over silicon

Development of an **autonomous solar reactor prototype based on CPC optic**

- Viability of bacteria
- Management of potential applications in rural communities of developing countries)

Validation for two types of bacteria

- *Gram - (Eschirichia Coli)*
- *Gram + (Enterococcus Faecalis)*



TiO_2 fixed over Ahlstrom paper inside a CPC reactor

SOLWATER & AQUACAT Objectives

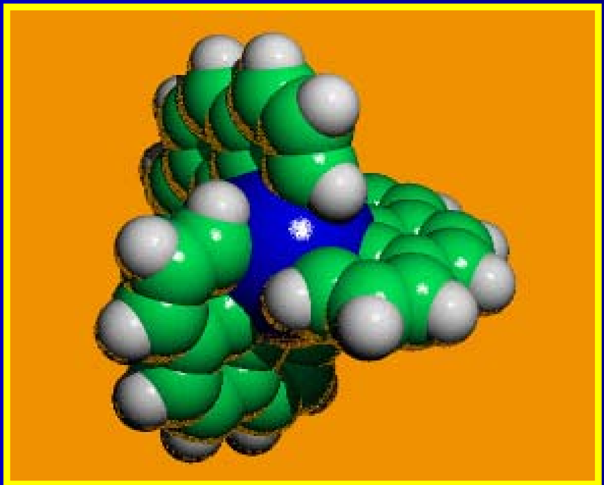
Main objective of the activity of PSA in this area is the development and optimisation of solar photocatalytic processes for drinking water disinfection

AQUACAT & SOLWATER main features

- **Objective:** **development of a completely autonomous solar system chemical-free to drinking water disinfection and, additionally, elimination of potential organic pollutants at trace level (avoiding conventional processes such as chlorination, filtration, ozone, irradiation, etc)**
- **Placement:** **rural remote locations of developing countries**
- **Proposed technique:** **photocatalytic processes activated by sunlight**
- **Technology:** **solar collectors based on CPC optic**

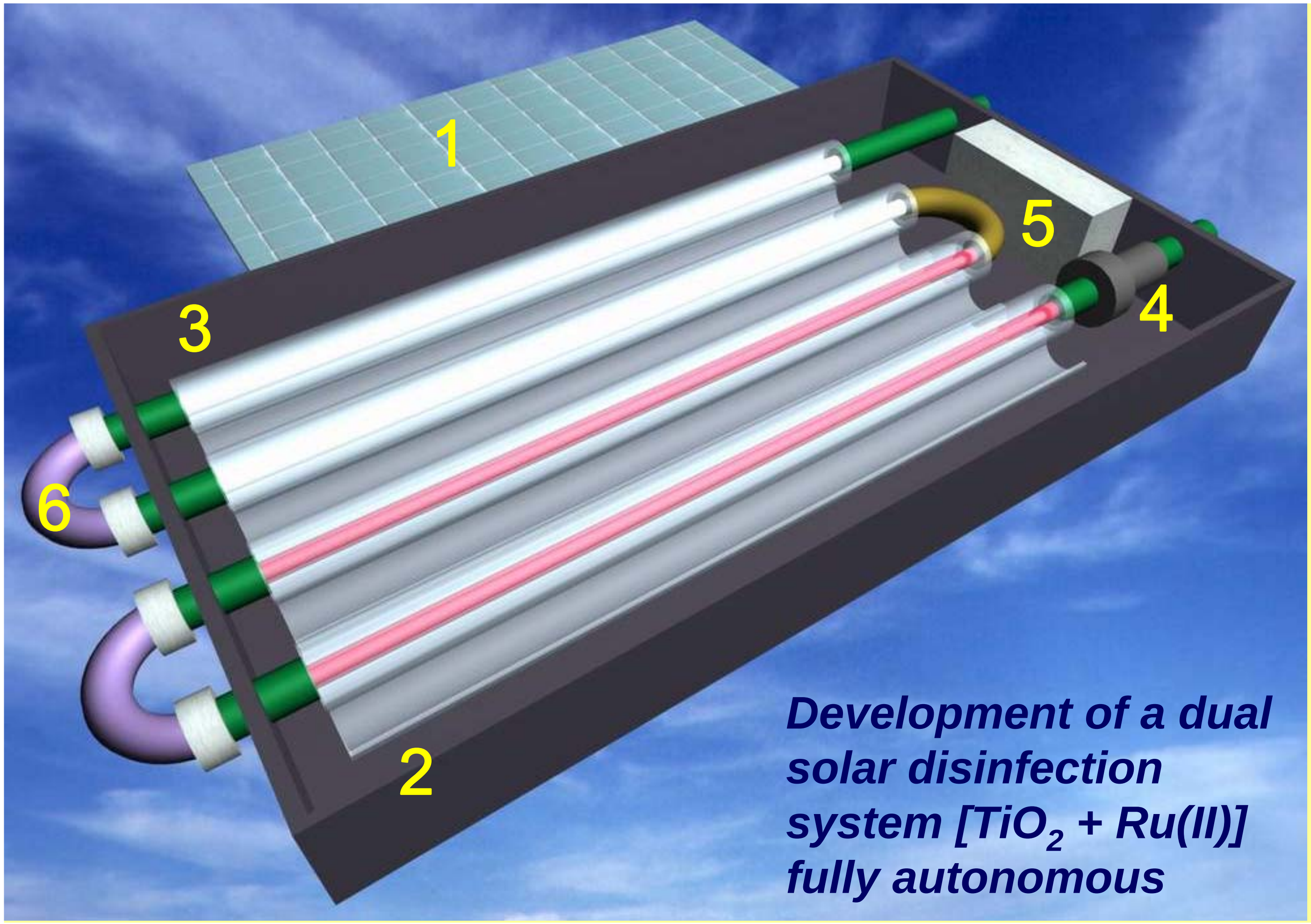
SOLWATER & AQUACAT Objectives

Main projects objective: Development of a 100% fully autonomous detoxification-disinfection solar reactor system based on the photocatalytic generation of **hydroxyl radicals (•OH)** and **singlet oxygen ($^1O_2$) species** to detoxify and disinfect contaminated drinking water. **TiO_2** supported catalyst will be used to •OH generation and **Ru(II) polypyridyl complexes** will be used to $^1O_2$ production. A small photovoltaic cell would provide the energy to continuously pump the water throughout the reactors.



$Ru(L)_3^{2+}$ photosensitizer (L, polyazaaromatic chelating ligand)

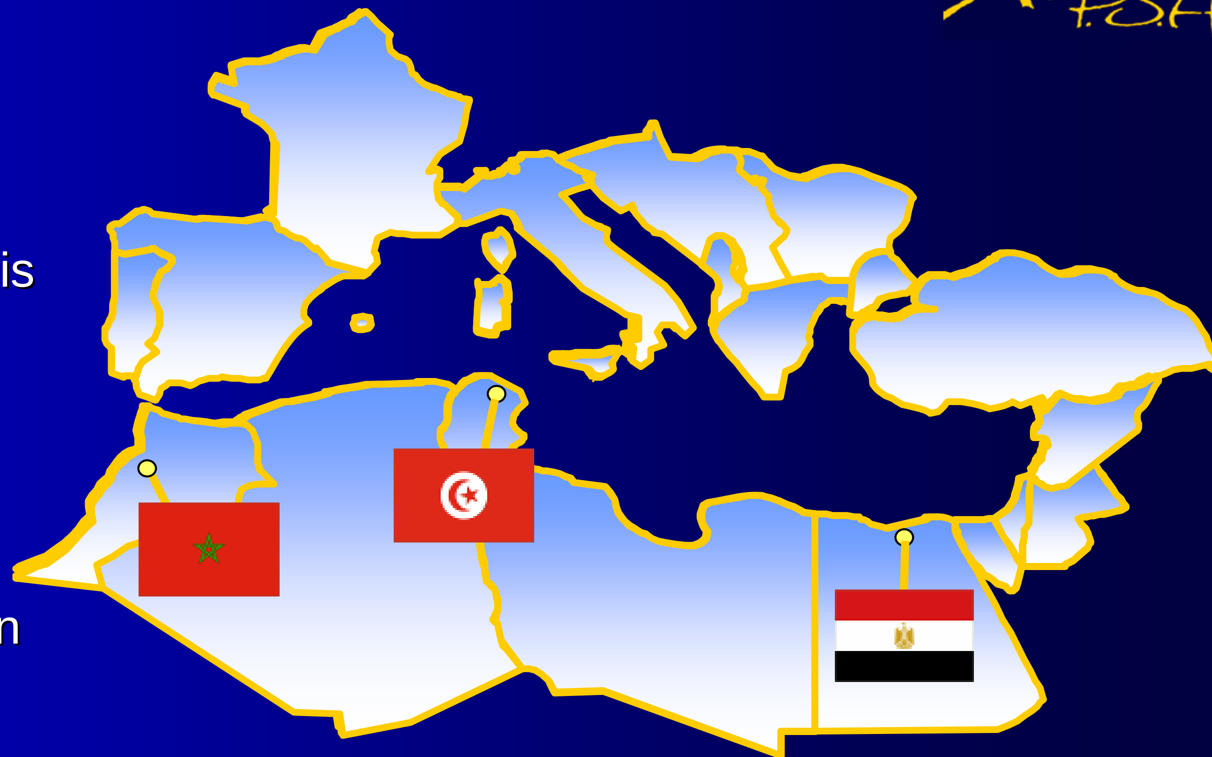
TECHNOLOGICAL CONCEPT



1. **Photovoltaic panel**
2. **Ru(II) photo-reactors**
3. **Supported TiO_2 photo-reactors**
4. **Pump**
5. **Electrical box**
6. **Easily opening to photo-reactors exchange**

AQUACAT PROJECT

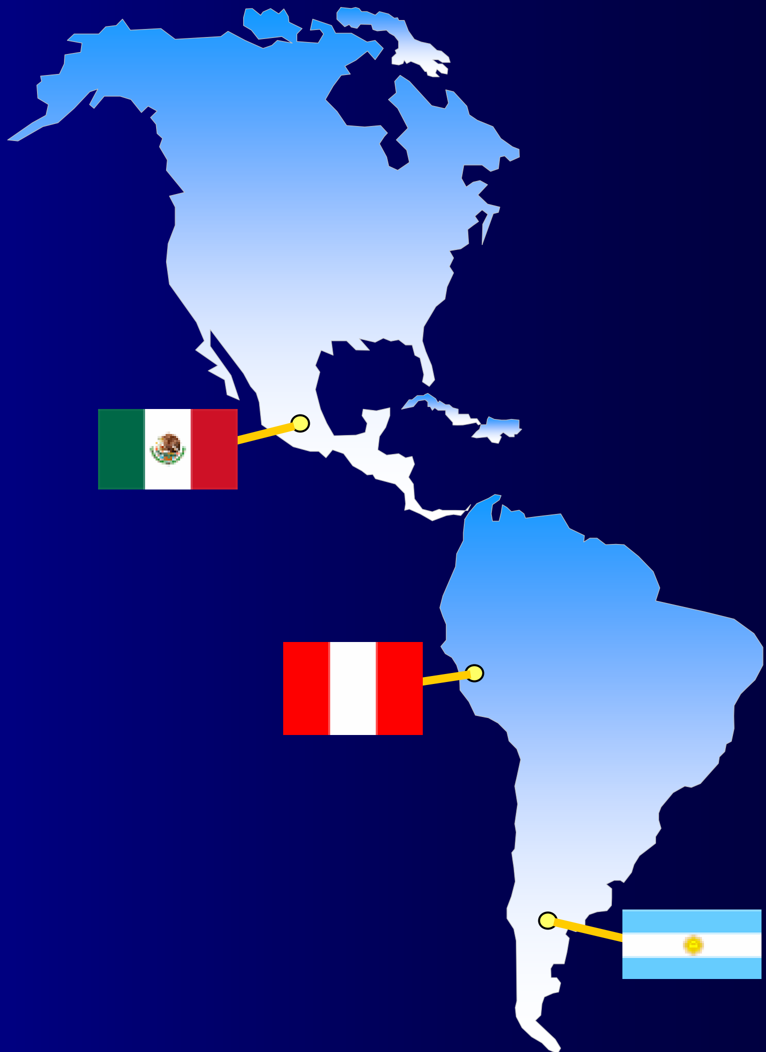
- **Project name**: Detoxification of Waters for their Recycling and Potabilisation by Solar Photocatalysis in Semi-arid Countries (AQUACAT)
- **Frame**: EU-DGXII FP V – International Cooperation Program. Contract ICA3-CT-2002-10028
- **Total budget**: 1.706 k€. Contribution of EC International Collaboration Program: 1000 k€



- **European partners**: Univ. Claude Bernard Lyon1 (coordinator), Univ. de Poitiers, Ahlstrom Paper Group [France], CIEMAT – PSA, Univ. Complutense, Ecosystem [Spain], Ao Sol [Portugal], EPFL [Switzerland]
- **North African partners**: Projema, Ecole Superieure de Technologie de Fes [Morocco], Photoenergy Center [Egypt], Ecole Nationale d'Ingenieurs de Gabes [Tunisia]

SOLWATER PROJECT

- **Project name**: Cost Effective Solar Photocatalytic Technology to Water Decontamination and Disinfection in Rural Areas of Developing Countries (SOLWATER)
- **Frame**: EU-DGXII FP V – International Cooperation Program. Contrato ICA4-CT-2002-10001
- **Total budget**: 1.819 k€. Contribution of EC INCO Program: 960 k€
- **Latin-American partners**: CNEA, Comisión Nacional de Energía Atómica, [Argentina]; Universidad Nacional de Ingeniería [Peru]; Instituto Mexicano de Tecnología del Agua [Mexico]; Tinep S.A. de C.V. [Mexico]
- **European partners**: CIEMAT-PSA (coordinator), Universidad Complutense de Madrid, Ecosystem [Spain], Technical University of Athens [Greece], Aosol [Portugal], EPFL [Switzerland], Univ. Claude Bernard Lyon1 [France]



BACTERIA REGROWING

KN47 photocatalytic test
Initial conc: 10^6 CFU/mL
Final conc: 100 CFU/mL (after 90 min)
Regrowing after 24 hours

Solar photolysis only
Initial conc: 10^5 CFU/mL
Final conc: 20 CFU/mL (after 90 min)
Regrowing after 24 hours

BACTERIA REGROWING

KN47 photocatalytic test
Initial conc: 10^6 CFU/mL
Final conc: 100 CFU/mL (after 90 min)
Regrowing after 24 hours

Solar photolysis only
Initial conc: 10^5 CFU/mL
Final conc: 20 CFU/mL (after 90 min)
Regrowing after 24 hours

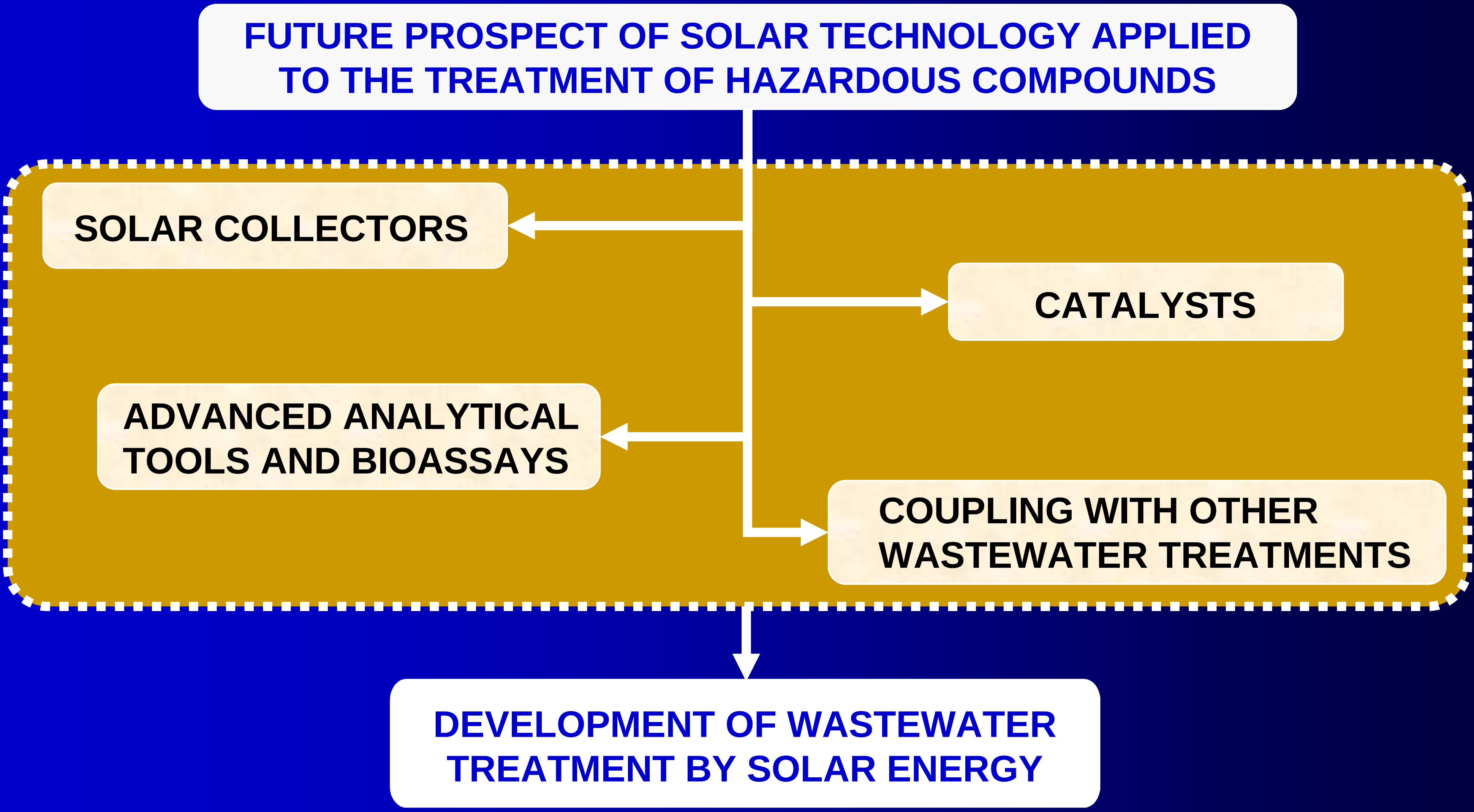
Possible explanations

- The damage performed on the cell by photocatalysation is higher than irradiation alone
- Photocatalysis could affect the enzymatic repairing mechanisms of the cell (DNA)
- Other authors [*Z. Huang et. al. Bactericidal mode of titanium dioxide photocatalysis. Journal of Photochemistry and Photobiology A: Chemistry 130 (2000), 163-170*] propose the possible existence of post-irradiation events, such as free radical chain reactions, lipid peroxidation and dark Fenton reaction (appearance of peroxides) [*Environ. Sci. Technol, 1994, 28, 934-938*]

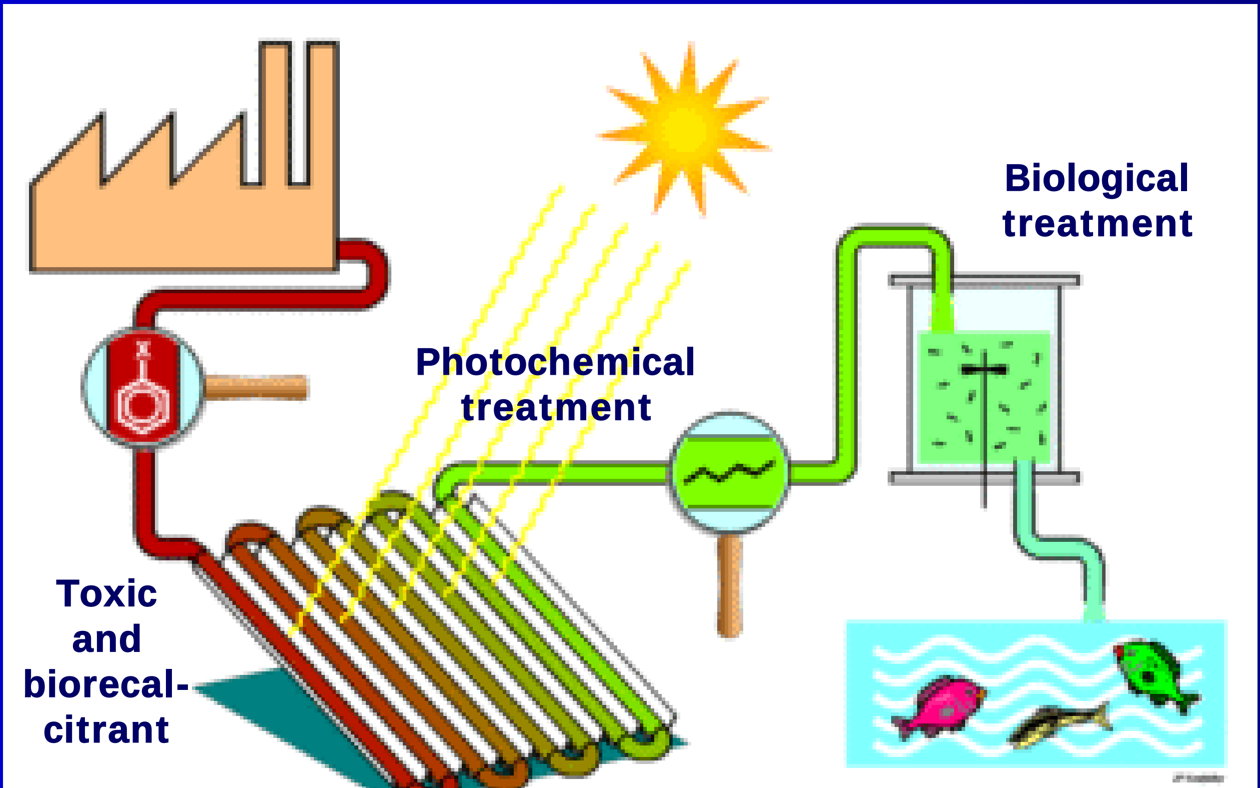
PRESENTATION INDEX

1. Introduction
2. Background and previous technological developments. SOLARDETOX project
3. Commercial development: Albaida plant
4. Water disinfection applications SOLWATER & AQUACAT projects
5. Future outlook. CADOX project
6. Conclusions

Outlook to the future



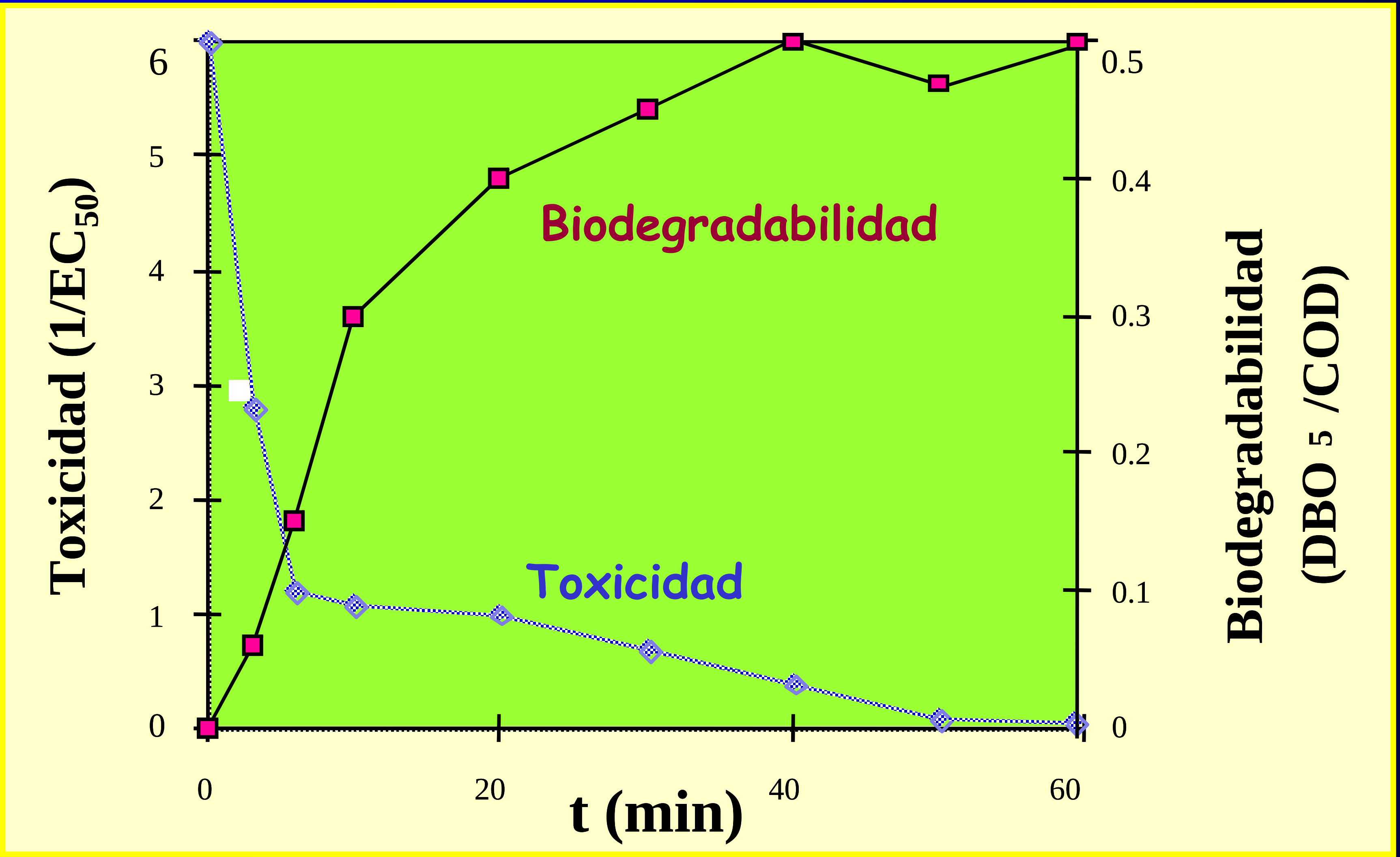
PHOTOCATALYSIS + BIOLOGICAL PROCESSES



Courtesy of EPFL (Switzerland)

Conceptual scheme of technology coupling: Solar Photocatalysis followed by Biological Treatment

BIODEGRADABILITY / TOXICITY



CADOX PROJECT OBJECTIVES

Industrial Wastewater (IPPC directive) containing PS<500 mg/L (WF directive)

Toxic & non-biodegradable

Solar Photons

$^{\bullet}OH$

Photo Fenton

O_3

$^{\bullet}OH$

TiO_2

Solar Photons

Non-toxic & Biodegradable Compounds

Bio-treatment

Water Reuse

<u>Main Project Objective:</u> To determine the best conditions to combine TiO_2/Photo-Fenton photocatalysis (driven by Solar Energy), Ozone and Biodegradation to the treatment of industrial wastewaters containing highly toxic compounds considered as Prioritary Substances

PRESENTATION INDEX

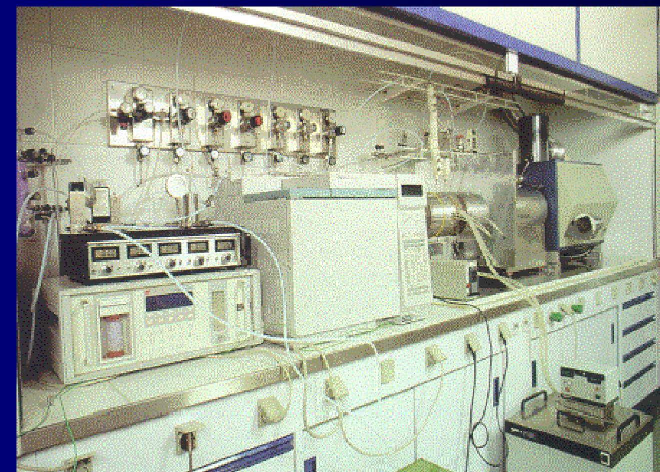
1. Introduction
2. Background and previous technological developments. SOLARDETOX project
3. Commercial development: Albaida plant
4. Water disinfection applications. SOLWATER & AQUACAT projects
5. Future outlook. CADOX project
6. Conclusions

CONCLUSIONS

- Research activity performed at PSA has permitted the development of an **innovative technology** to the implementation at industrial scale of solar photocatalytic processes for the degradation of non-biodegradable contaminants in water, thus providing a significant **environmental added value**
- This solar technology is based on the **Compound Parabolic Collector** concept (CPC), which is considered as one of the most suitable solutions for the efficient utilization of solar light in Solar Photocatalytic processes related with water
- The ALBAIDA plant is the **first commercial application of Solar Detoxification** ever developed and erected in the world (Application: cleaning of water from the process of recycling of pesticide plastic bottles)
- The use of photocatalytic processes to drinking **water disinfection** is also an interesting application which still needs scientific and technology development
- The R+D activities, coordinated by the **Plataforma Solar de Almeria** (Large European Scientific Installation), have been highly interdisciplinary and developed in collaboration with many EU companies and research centres

GAS-PHASE PHOTOCATALYSIS

- ✓ **Elimination of persistent organic pollutants from gaseous effluents by advanced photo oxidation**
- ✓ **Determination and treatment of pollutants on the indoor air buildings**
  - Test and determination of photo activity of monolithic catalyst
  - Preparation, characterization and testing of photoactive coatings by Sol-Gel and Spray techniques on different supports
  - Development of low price prototype photoreactors



Solar simulator and analytical

VOCs sampler on air and analysis by GC-MS

Flat photoreactors arranged in serie

SOLAR DESALINATION: INDEX

1. BACKGROUND ACTIVITIES ON SOLAR DESALINATION AT PSA
2. THE AQUASOL PROJECT
3. FIRST EXPERIMENTAL RESULTS
4. CONCLUSIONS

SOLAR THERMAL DESALINATION PROJECT

- In 1988, the Solar Thermal Desalination (STD) Project was initiated at the facilities of the Plataforma Solar de Almería to demonstrate the technical feasibility of coupling a one-axis tracking parabolic-trough solar field with a 14-effects Multi-Effect Distillation plant
- This first research project lasted until 1994 and had two main objectives:
  - To study the technical and financial feasibility of seawater desalination with solar thermal energy
  - To optimize the solar thermal desalination system implemented by introducing and evaluating improvements minimizing electrical and thermal energy consumption

PARABOLIC TROUGH COLLECTORS

P.S.A.

OBJETIVES:

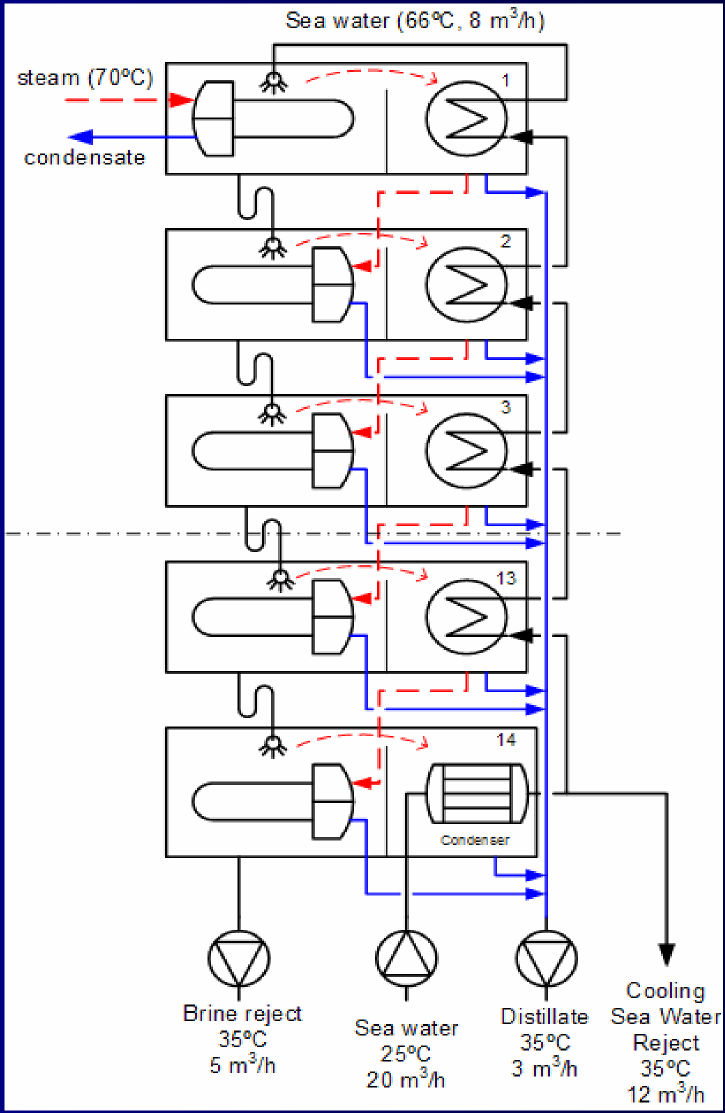
- One-axis tracking collector. Focal line.
- Concentrating ratio: 30-50
- Maximum temperature: 400-500 ºC

MULTI-EFFECT DISTILLATION UNIT

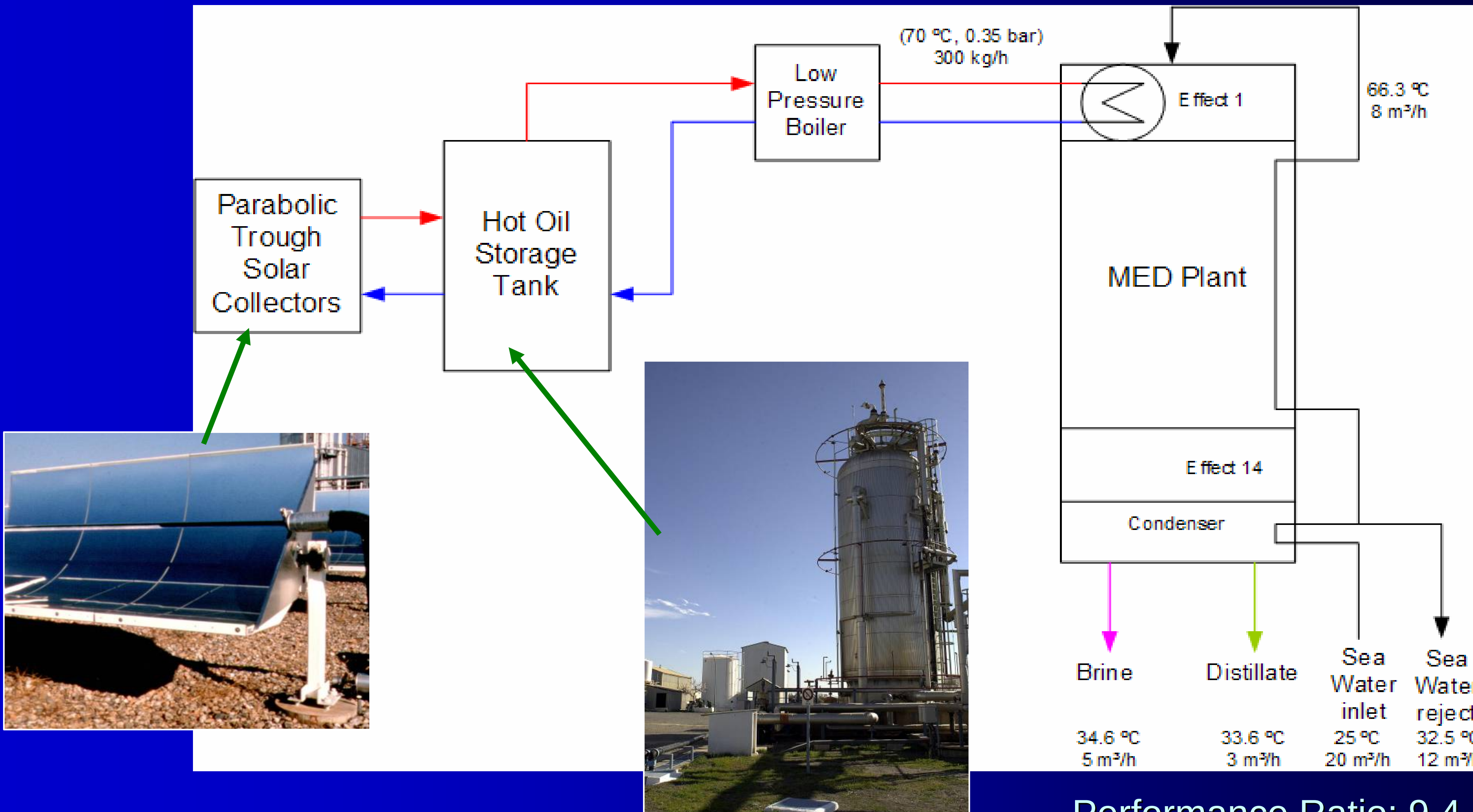
The distillation plant installed at the PSA is a forward-feed, vertically-stacked, multi-effect distillation unit with 14 effects.

TECHNICAL SPECIFICATIONS OF THE SOL-14 DESALINATION PLANT

Feedwater flow	8 m^3/h
Brine reject	5 m^3/h
Distillate production	3 m^3/h
Seawater flow at condenser: at 10ºC: at 25ºC:	 8 m^3/h 20 m^3/h
Output salinity	5 ppm TDS
Number of cells	14
Heat source energy consumption	190 kW
Performance Ratio	>9
Vacuum system	Hydroejectors (seawater at 3 bar)
Top brine temperature	70ºC
Condenser temperature	35ºC

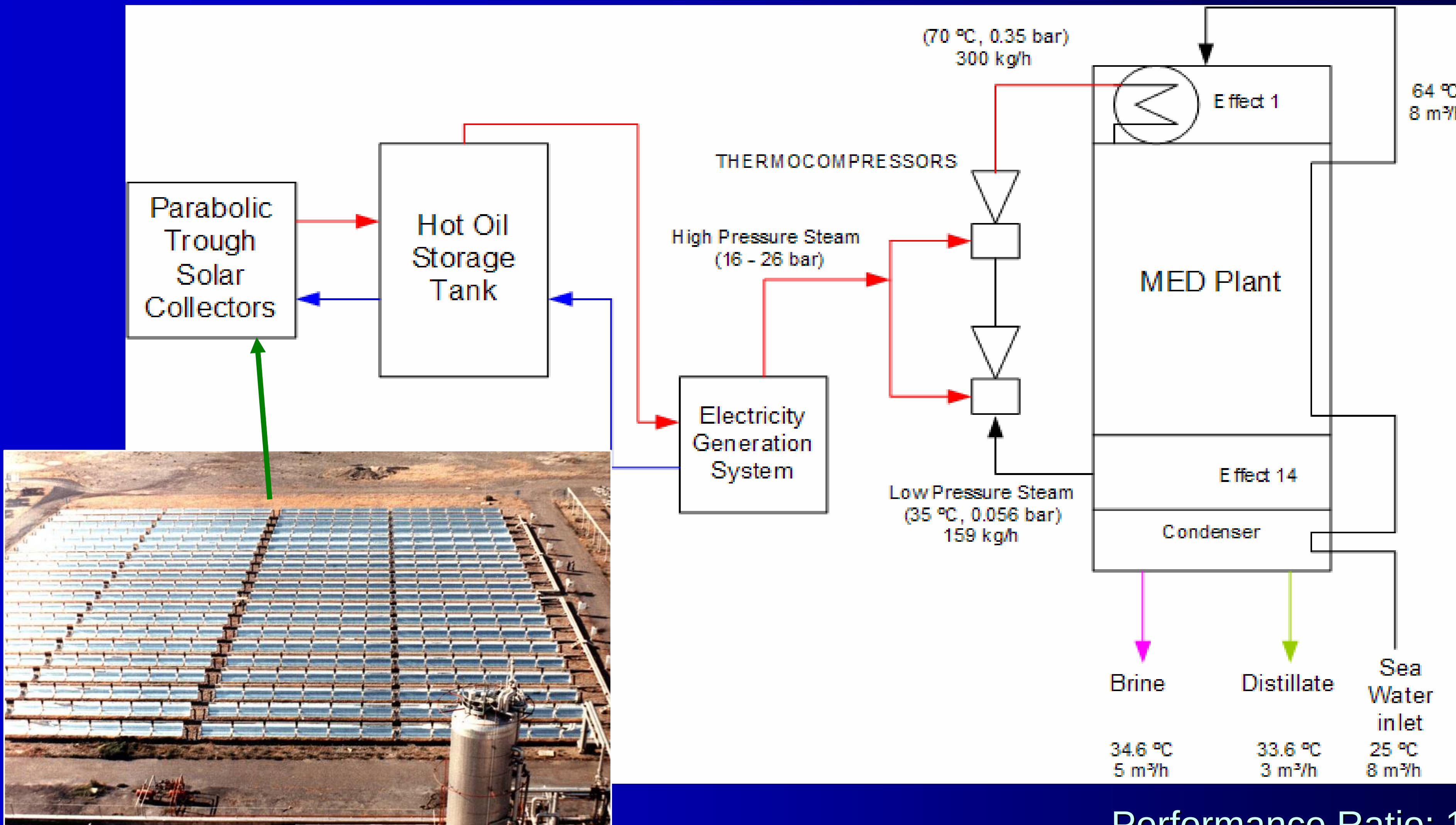


STD PROJECT - PHASE I



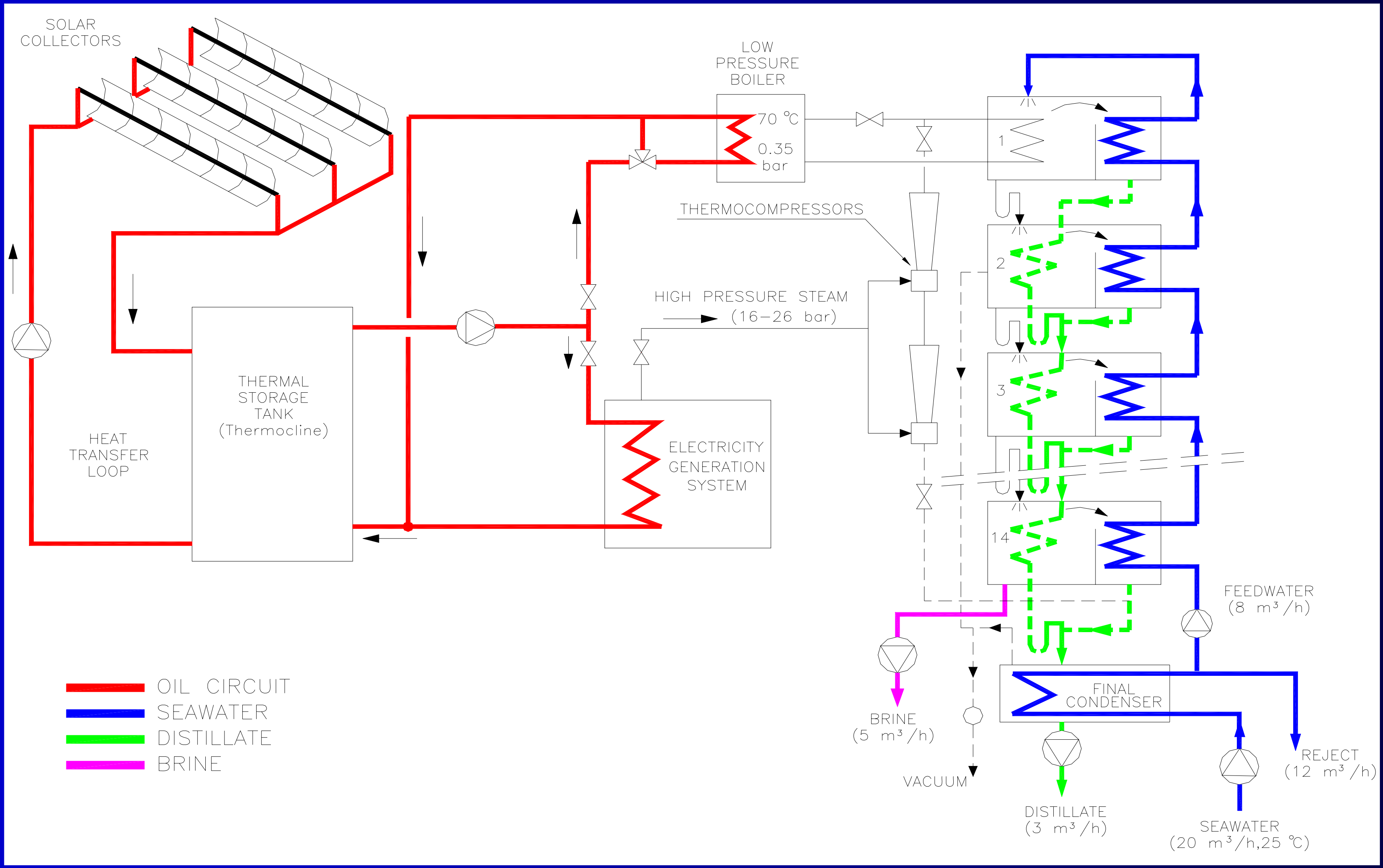
Performance Ratio: 9.4 – 10.4

STD PROJECT - PHASE I



Performance Ratio: 12 – 14

SOL-14 PLANT DIAGRAM



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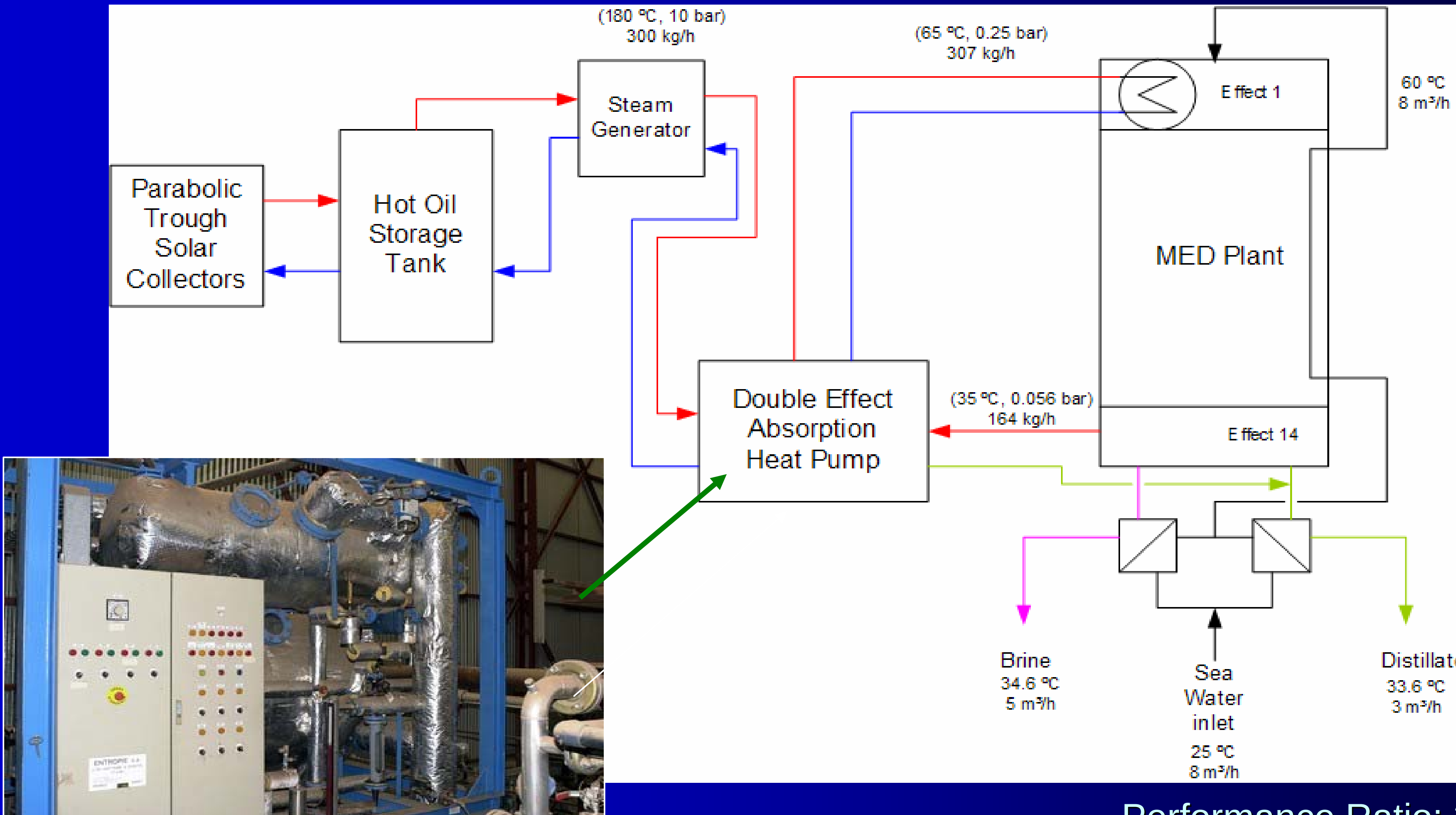
STD PROJECT - PHASE II



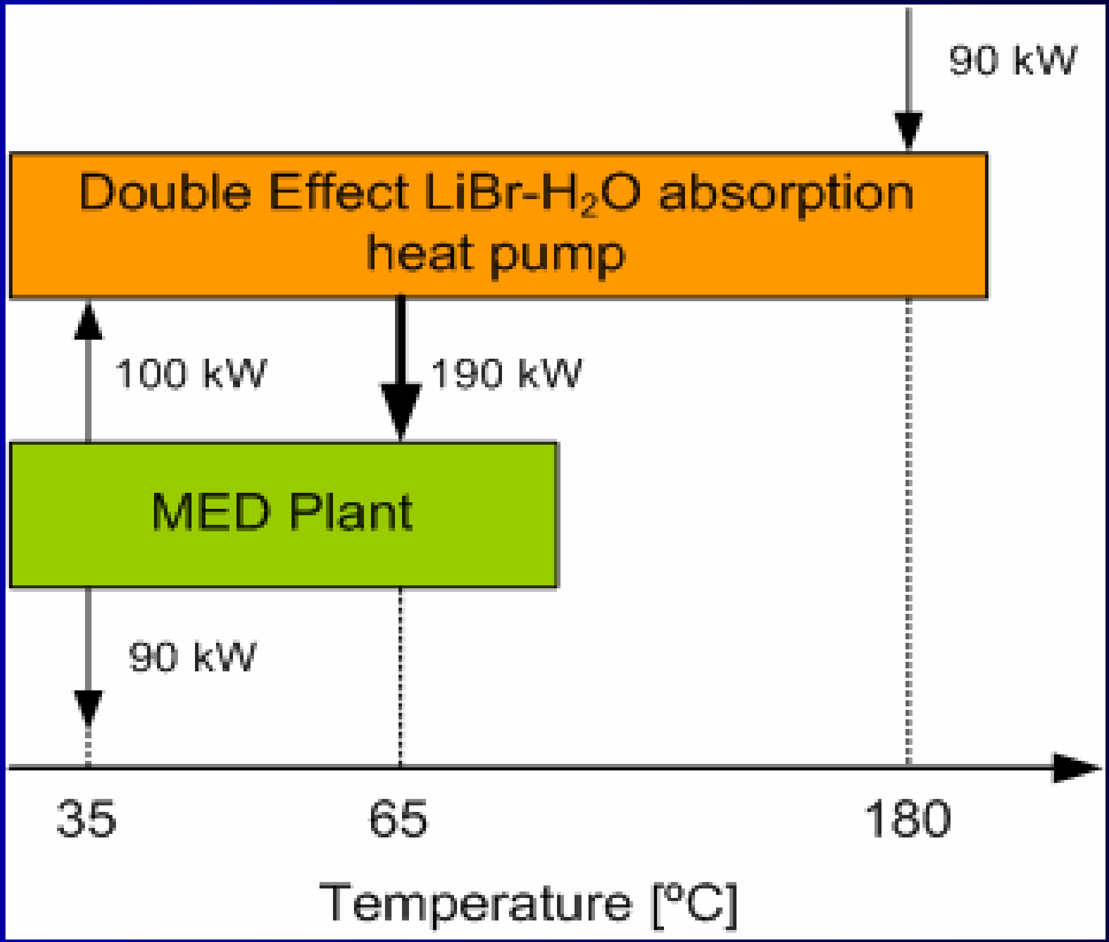
Performance Ratio: 20 - 21

DOUBLE EFFECT ABSORPTION HEAT PUMP

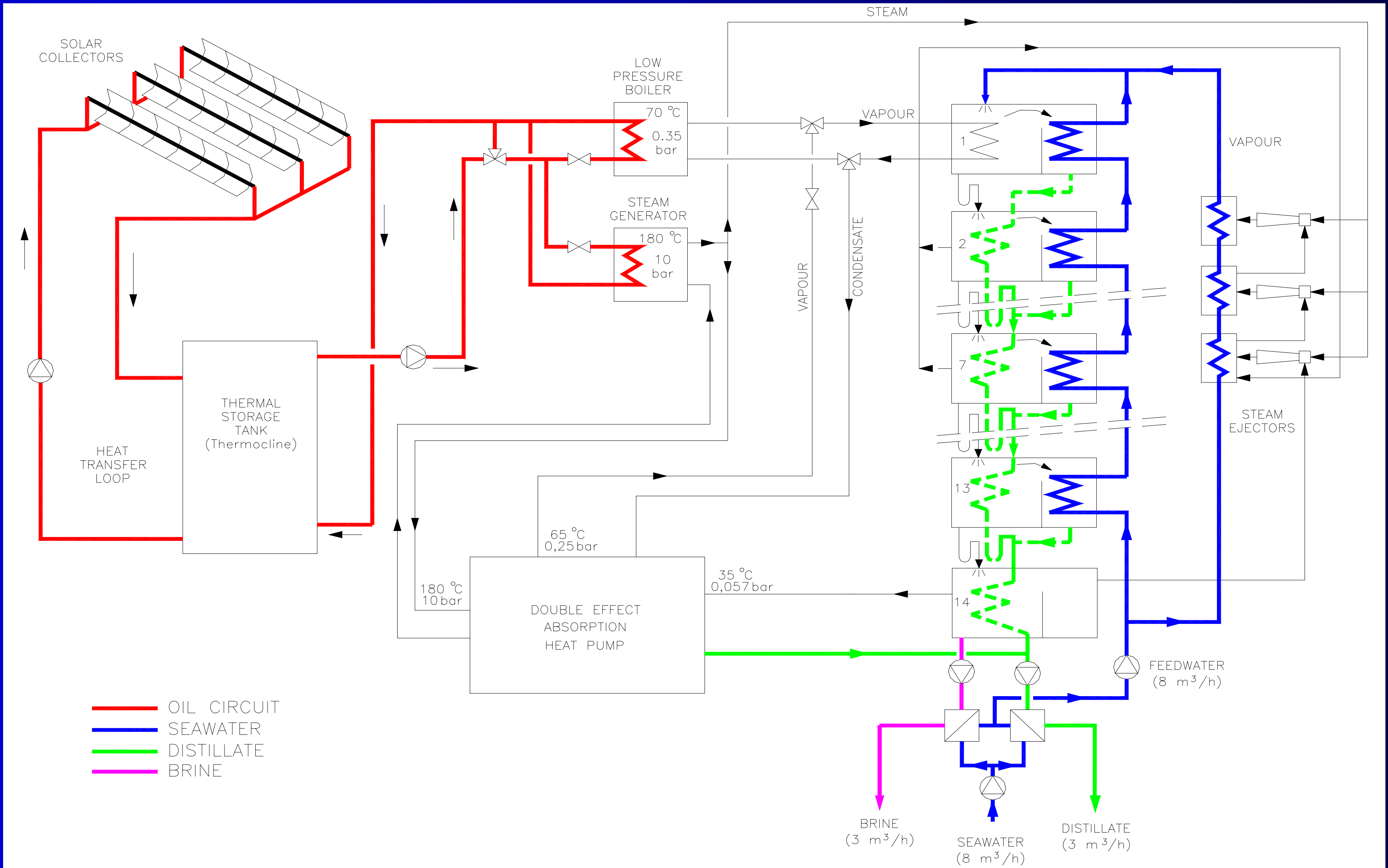
The Double Effect Absorption Heat Pump, delivers 190 kW of thermal energy at 65°C to the MED plant.

The desalination process in the plant evaporator body uses only 90 of the 190 kW, while the remaining 110 kW are recovered by the heat pump evaporator at 35°C and pumped to usable temperature of 65°C.

For this, the heat pump needs 90 kW thermal power at 180°C.



IMPROVED MED SYSTEM



INDEX

1. BRIEF PSA INTRODUCTION
2. BACKGROUND ACTIVITIES ON SOLAR DESALINATION AT PSA
3. THE AQUASOL PROJECT
4. FIRST EXPERIMENTAL RESULTS
5. CONCLUSIONS

THE AQUASOL PROJECT

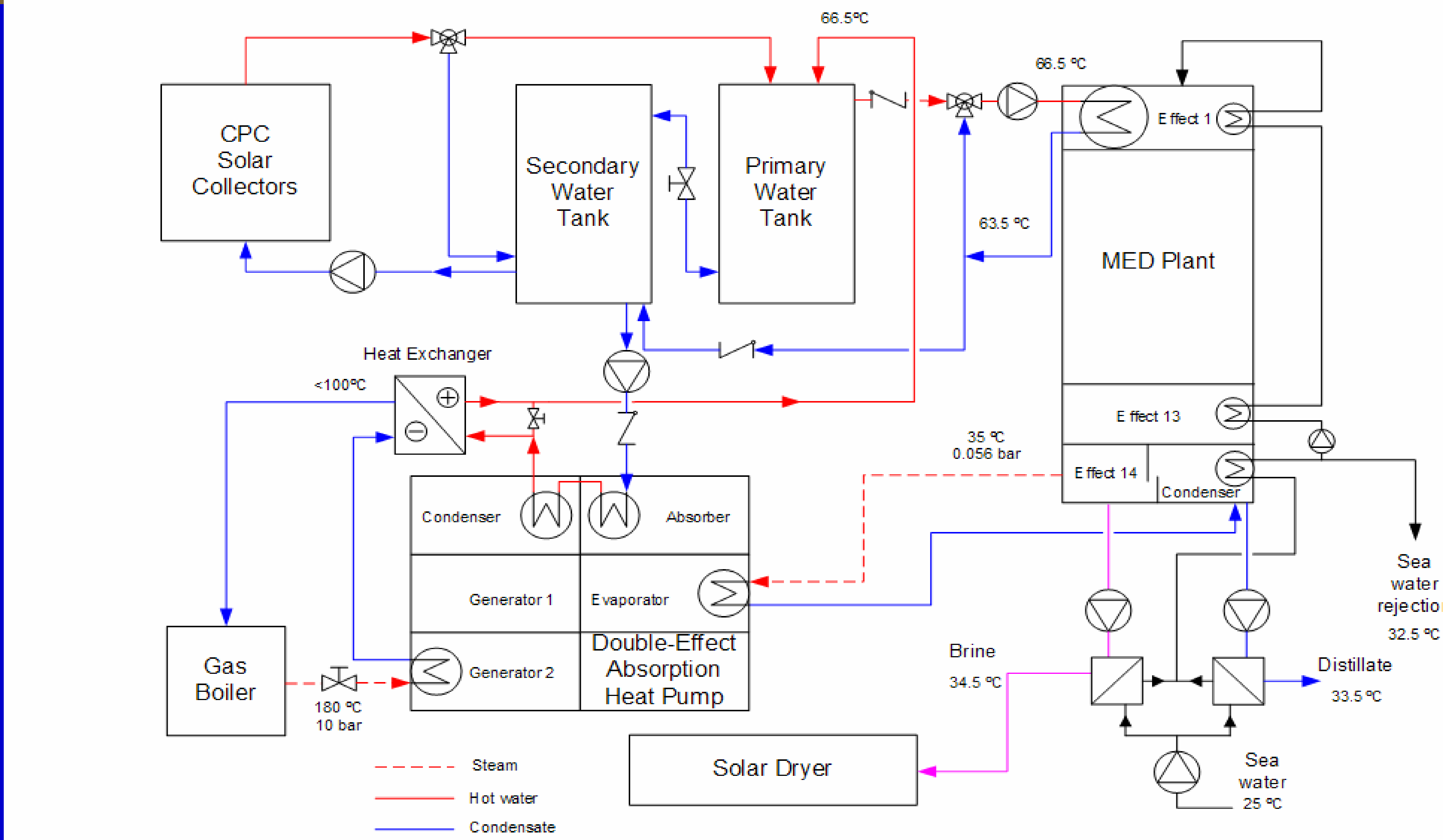
- In 2001, the project named “Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology” (AQUASOL) was approved by the European Commission and the activities were initiated in 2002
- Partners:
  - Spain: CIEMAT, INABENSA, CAJAMAR, Comunidad de Regantes Cuatro Vegas
  - Portugal: INETI, AO SOL Energias Renovàveis
  - Greece: Hellenic Saltworks, National Technical University of Athens
  - France: WEIR Entropie

AQUASOL SUB-SYSTEMS

Main components of the system designed and erected are:

a) A multi-effect distillation plant (14 effects, 3 m^3/h distillate prod.)
b) A stationary CPC (Compound Parabolic Concentrator) solar collector field
c) A thermal storage system based on water (total volume: 24 m^3)
d) A double-effect (LiBr-H_2O) absorption heat pump
e) A smoke-tube gas boiler
f) An advanced solar dryer for final treatment of the brine

THE AQUASOL PROJECT

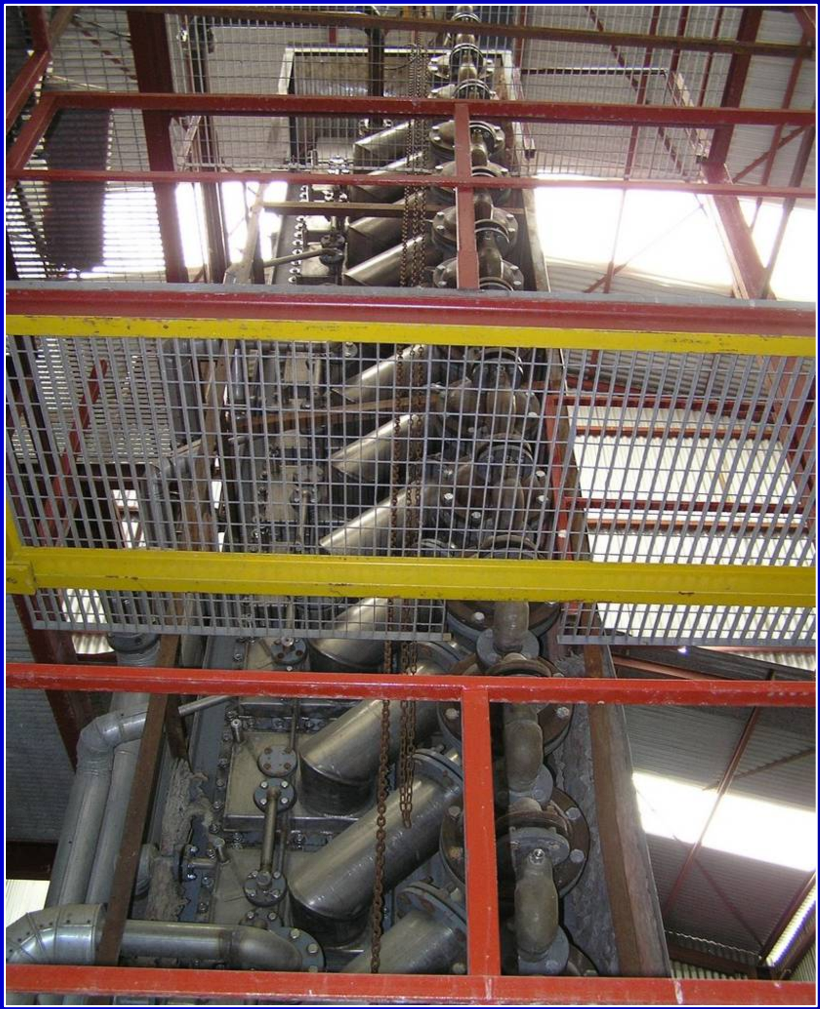


THE AQUASOL PROJECT

Three desalination system operating modes are possible depending on where the desalination unit energy supply comes from:

- **Solar-only mode**: energy to the first distillation effect comes exclusively from thermal energy from the solar collector field.
- **Fossil-only mode**: the double-effect heat pump supplies all of the heat required by the distillation plant.
- **Hybrid mode**: the energy comes from both the heat pump and the solar field. Two different operating philosophies are considered:
  - The heat pump works continuously 24 hours a day with a 30% minimum contribution.
  - Start-up and shutdown of the pump when requested, depending on the availability of the solar resource.

MULTI-EFFECT DISTILLATION UNIT



FRONT VIEW

REAR VIEW

MULTI-EFFECT DISTILLATION UNIT

The original first cell that worked with low-pressure steam (70ºC, 0.31 bar) has been replaced by a new one, working with the hot water coming directly from the thermal storage tank.

CPC SOLAR COLLECTOR FIELD

The solar field is made up of 252 stationary solar collectors (CPC Ao Sol 1.12x) with a total surface area of 500 m^2 arranged in four rows of 63 collectors.

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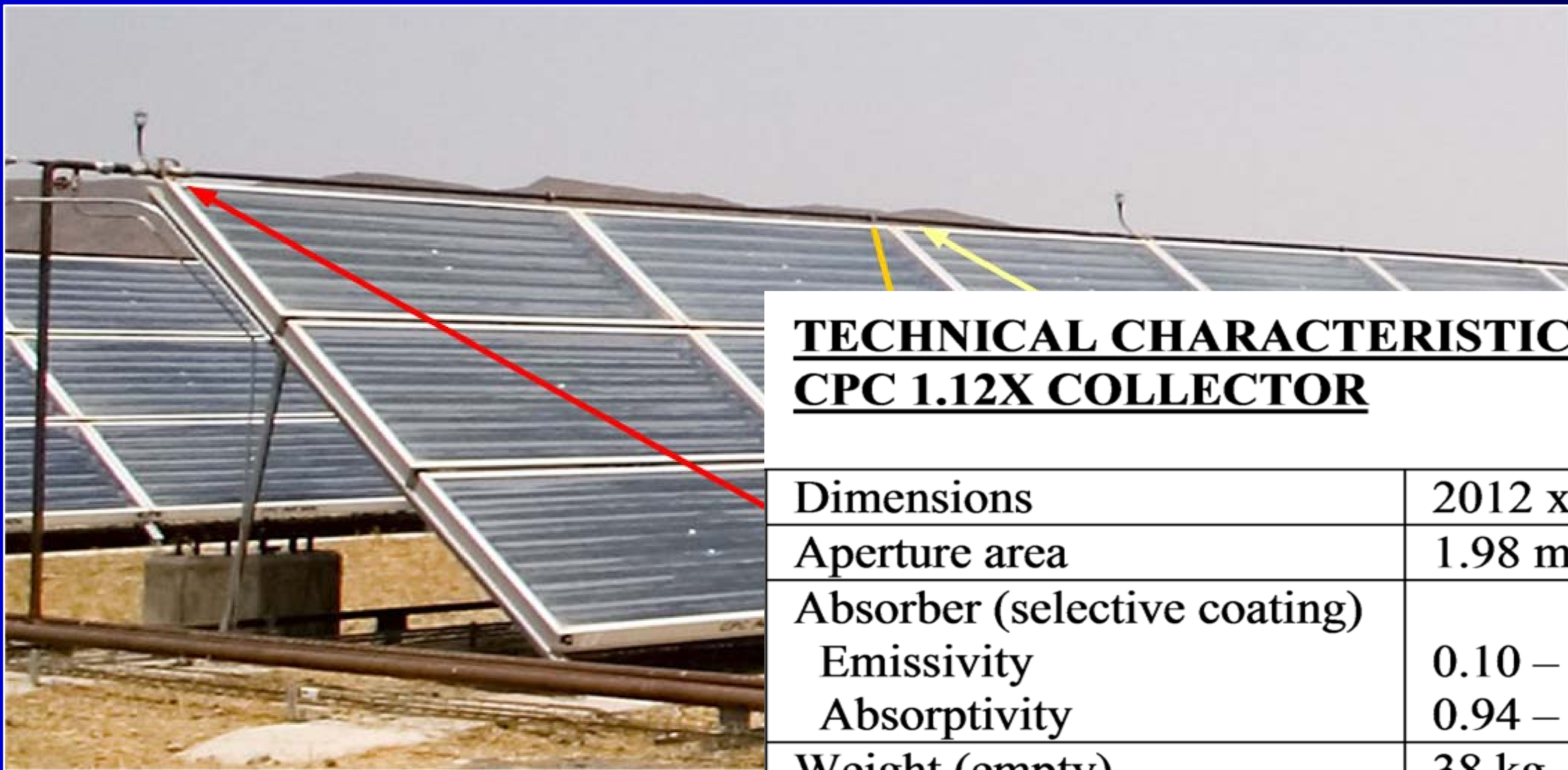
CPC SOLAR COLLECTOR FIELD



TECHNICAL CHARACTERISTICS OF AO SOL CPC 1.12X COLLECTOR

Dimensions	2012 x 1108 x 107 mm
Aperture area	1.98 m^2
Absorber (selective coating) Emissivity Absorptivity	 0.10 – 0.15 0.94 – 0.95
Weight (empty)	38 kg
Operating pressure	6 bar
Testing pressure	12 bar
Optical efficiency	0.70 – 0.71
Thermal loss factor	3.4 W/m^2K

THERMAL STORAGE TANKS

The thermal storage system is made up of two interconnected 12-m3-capacity water tanks. This storage volume is based on the response time required by the gas boiler and the DEAHP to reach nominal operating conditions

THERMAL STORAGE TANKS

TANK INNER SURFACE PAINT TREATMENT

Preparation	Sandblasting SA-2	
Metal primer	Zinc silicate	75 µm
Intermediate layer	Two-epoxy components paint	100 µm
External layer	Aluminum silicone	45 µm

The use of two tanks enables the solar contribution to be increased over the year as well as obtain certain temperature stratification necessary to avoid the DEAHP water inlet temperature exceeding the permissible range (60ºC-70ºC).

The tanks are A106 grade B carbon steel treated (paint treatment resistant to water up to 150ºC) to prevent corrosion on the surfaces in contact with hot water.

GAS BOILER

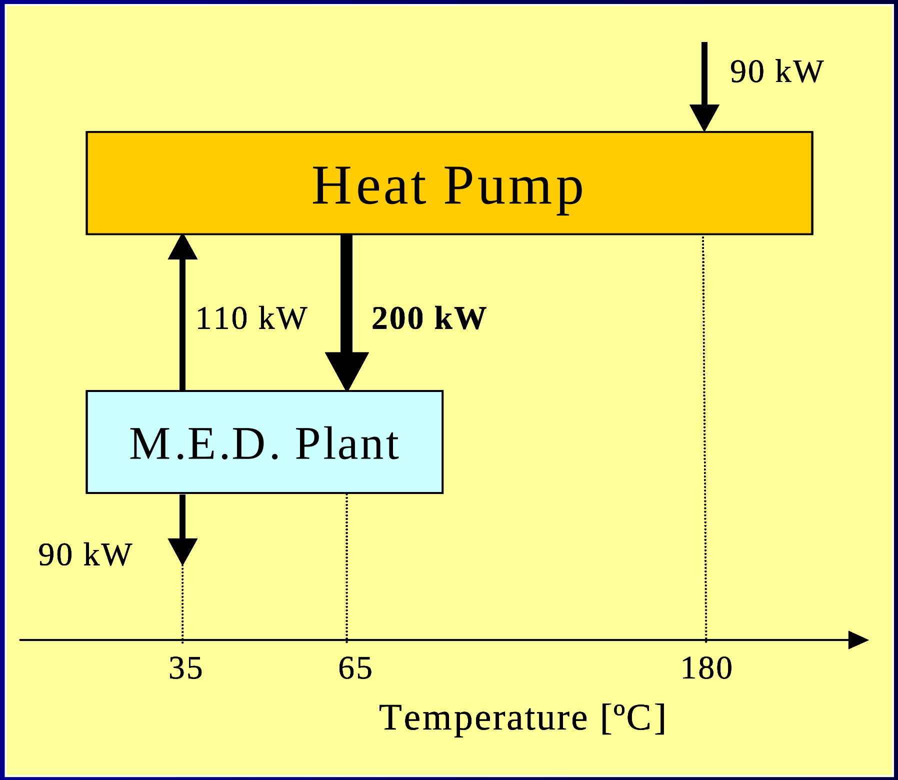
A propane gas-fired system is necessary to guarantee the necessary operating conditions (DEAHP requires steam at 180ºC) and permit 24-hours operation in absence of solar radiation

GAS BOILER

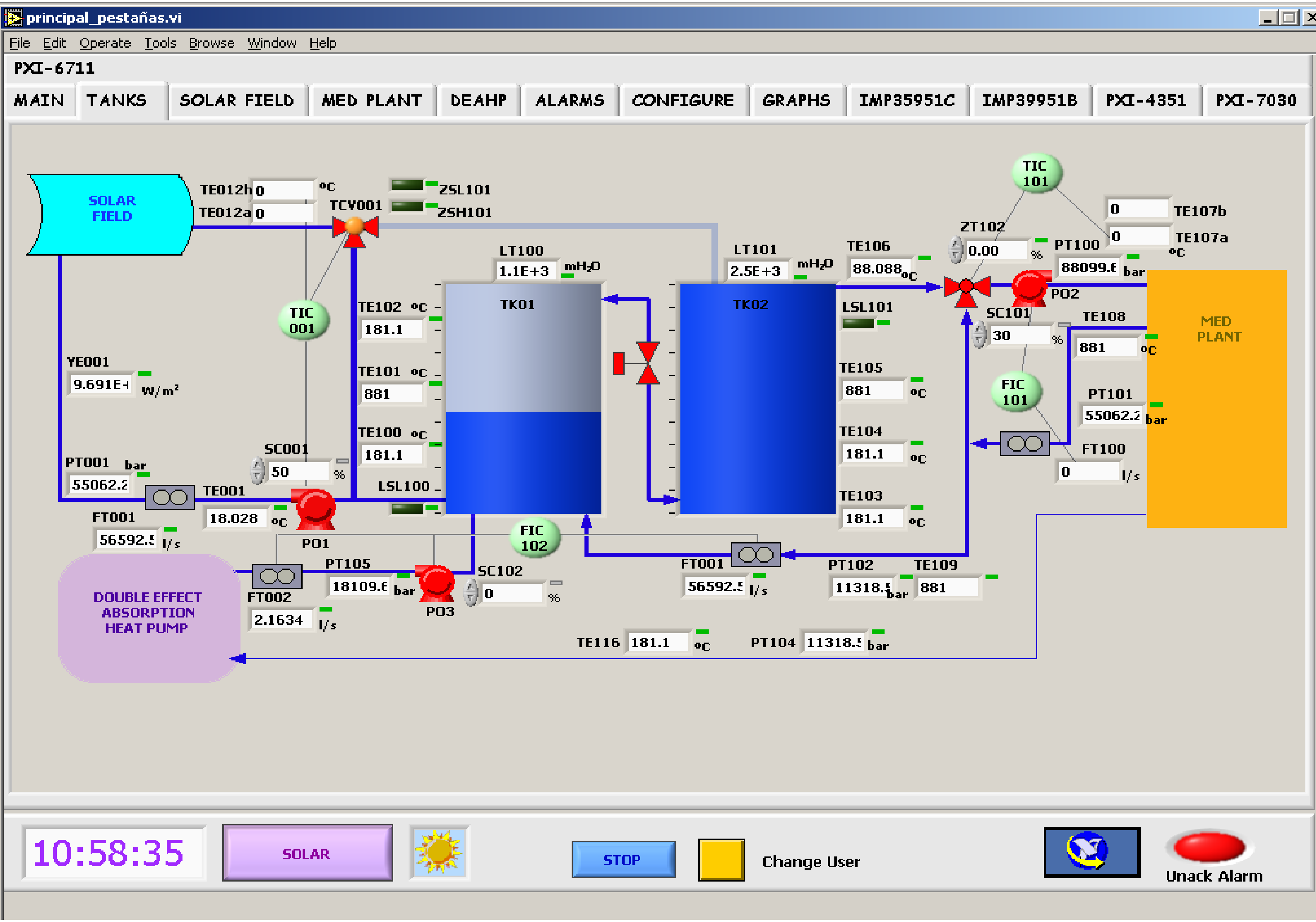
The gas to be burnt is stored in a 2,450-liter tank installed next to the distillation plant building. This tank volume provides an estimated autonomy of 143 hours at full load.

DOUBLE-EFFECT ABSORPTION HEAT PUMP

DEAHP increases the energy efficiency of the distillation process by making use of the 35ºC saturated steam produced in the last MED plant effect, recovering the energy to be lost in the evacuation of the cooling fluid used for its condensation.



DOUBLE-EFFECT ABSORPTION HEAT PUMP


principal_pestañas.vi
File Edit Operate Tools Browse Window Help
PXI-6711
MAIN
TANKS
SOLAR FIELD
MED PLANT
DEAHP
ALARMS
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PXI-7030
SOLAR FIELD
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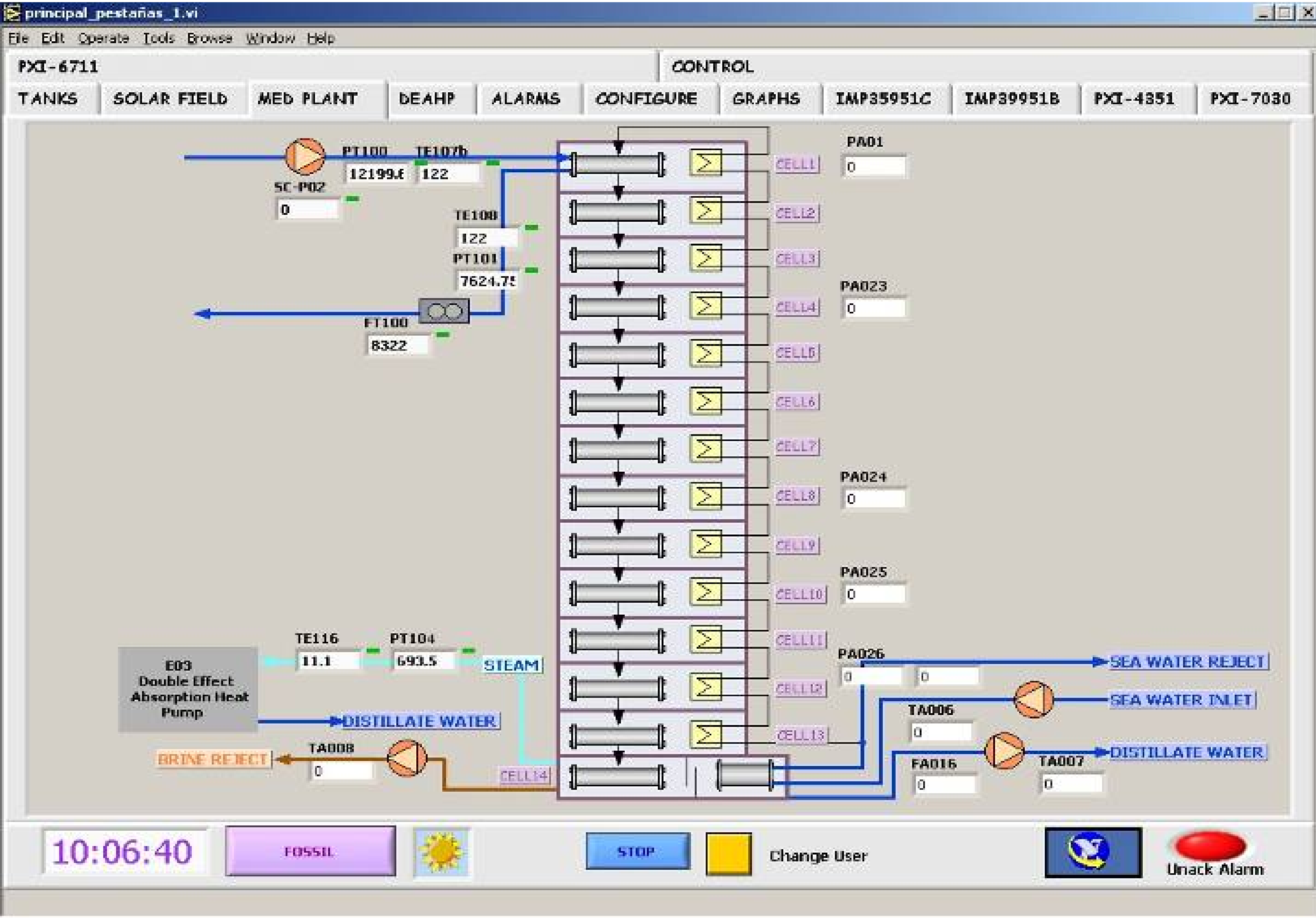
TE012a 0
ZSL101
ZSH101
TCV001
TIC 001
YE001
9.691E+ W/m²
PT001 bar
55062.2
SC001
50 %
TE001
18.028 ºC
FT001
56592.5 l/s
P01
LT100
1.1E+3 mH₂O
TK01
TE102 ºC
181.1
TE101 ºC
881
TE100 ºC
181.1
LSL100
FIC 102
LT101
2.5E+3 mH₂O
TK02
LSL101
TE105
881 ºC
TE104
181.1 ºC
TE103
181.1 ºC
TE106
88.088 ºC
ZT102
0.00 %
TIC 101
PT100
88099.6 bar
0 TE107b
0 TE107a ºC
P02
SC101
30 %
TE108
881 ºC
MED PLANT
FIC 101
PT101
55062.2 bar
FT100
0 l/s
FT001
56592.5 l/s
PT102
11318.5 bar
TE109
881
DOUBLE EFFECT ABSORPTION HEAT PUMP
PT105
18109.6 bar
FT002
2.1634 l/s
P03
SC102
0 %
TE116 181.1 ºC
PT104 11318.5 bar
10:58:35
SOLAR
STOP
Change User
Unack Alarm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E03
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Absorption Heat
Pump
DISTILLATE WATER
BRINE REJECT
TA008
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SEA WATER REJECT
SEA WATER INLET
TA006
0
DISTILLATE WATER
FA016
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TA007
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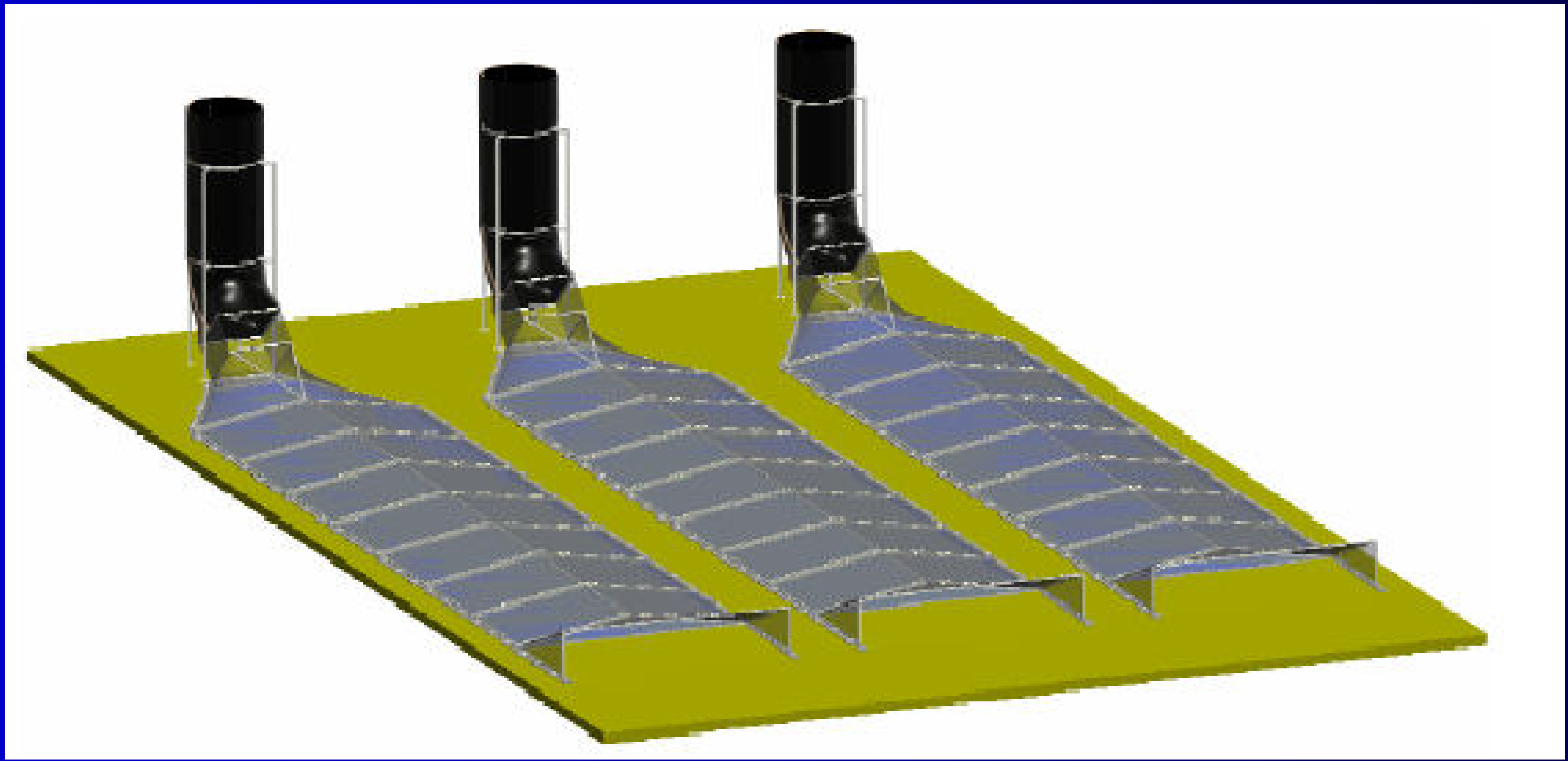
10:06:40
FOSSIL
STOP
Change User
Unack Alarm

ADVANCED SOLAR DRYER

The purpose of the solar dryer is to increase the concentration in the brine until it has reached the saturation point of calcium carbonate (16ºBe, Baumé scale). A final system constituted by three parallel 4-m x 17-m interconnected evaporation channels with brine stream circulating inside them was designed and constructed.



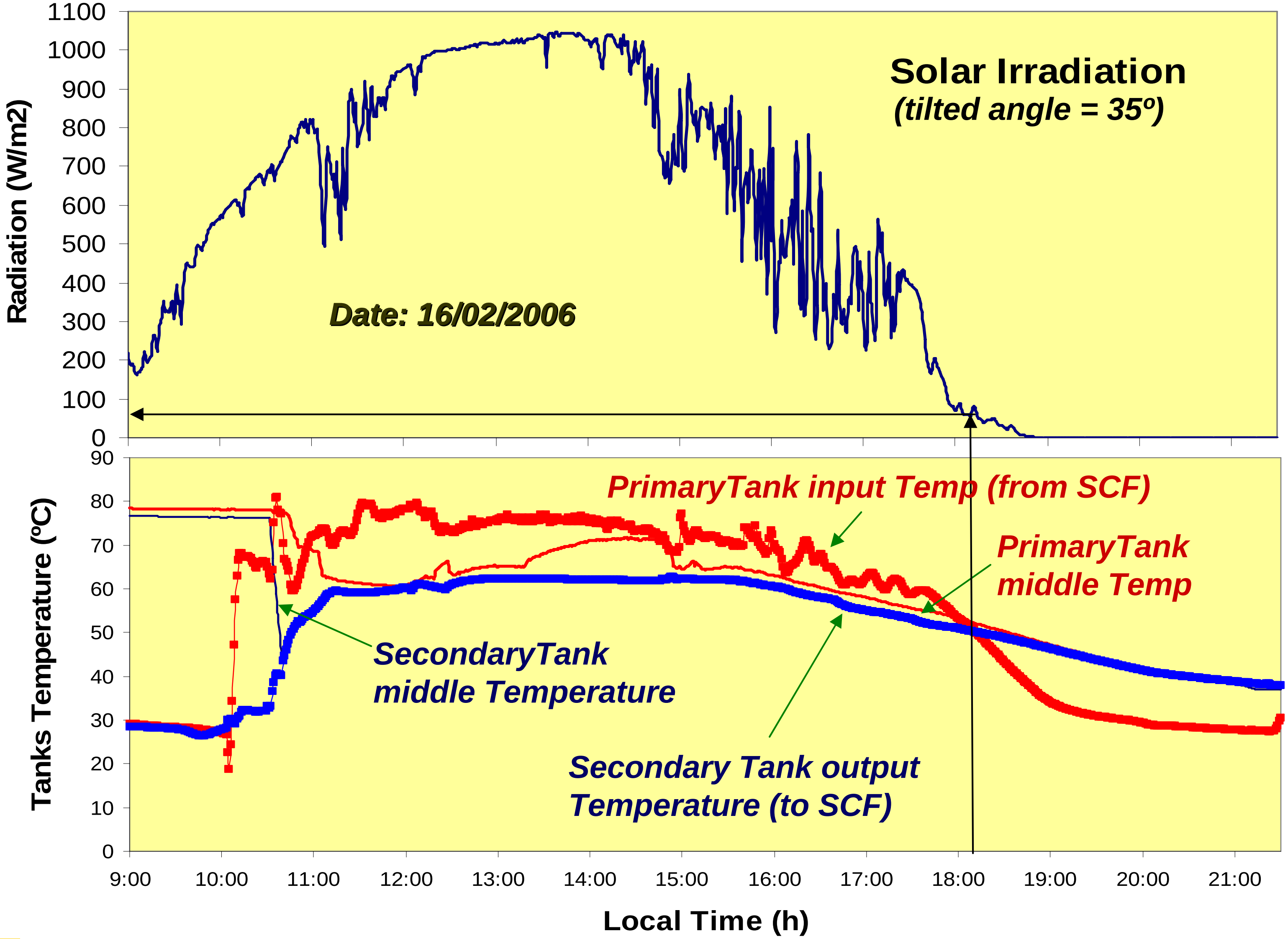
ADVANCED SOLAR DRYER

A North-South orientation was finally chosen due to the predominant winds at the installation site. Simulation models foresee a 2.5 increase in efficiency compared to traditional open-air salt evaporation ponds.

INDEX

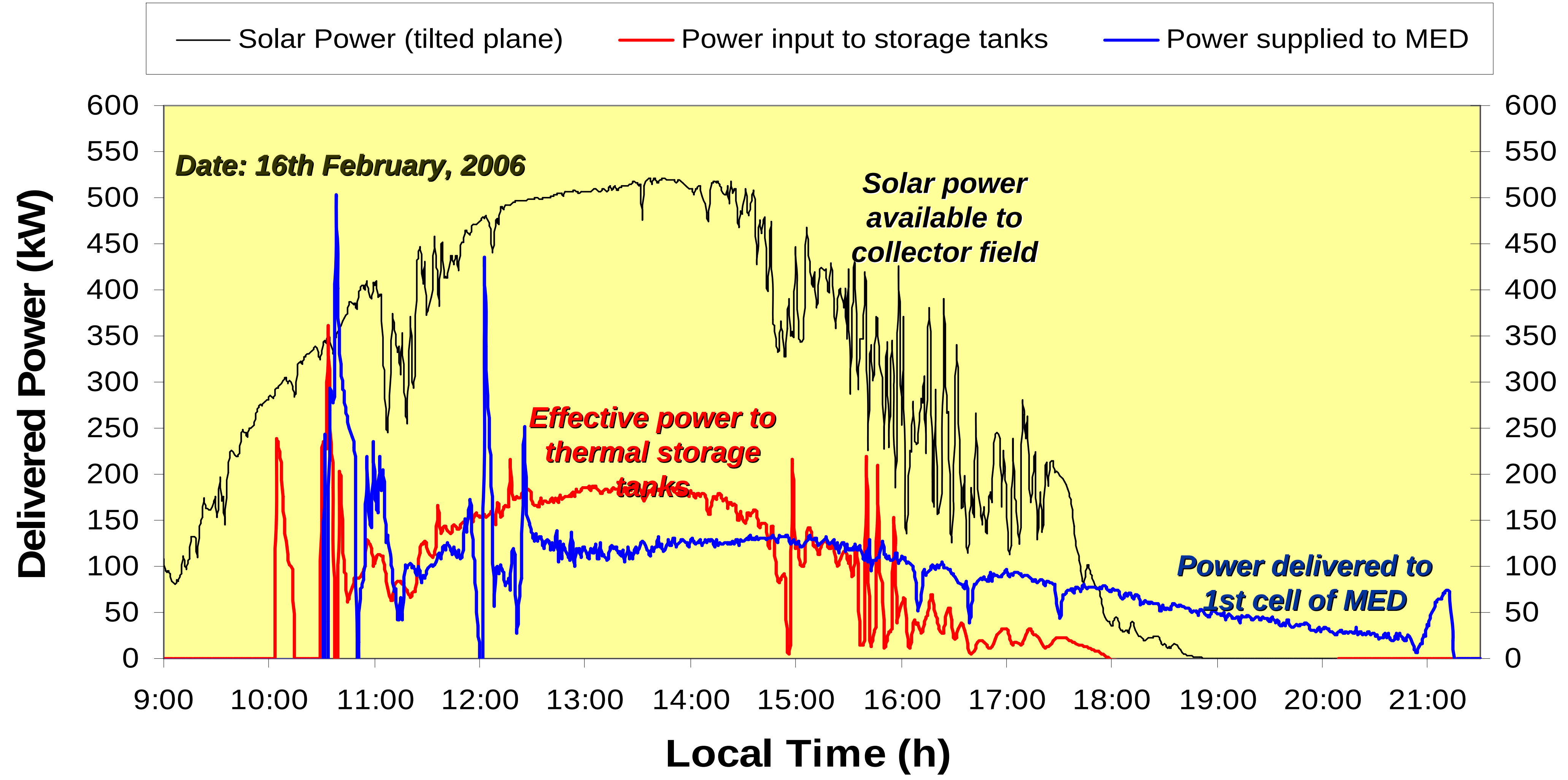
1. BACKGROUND ACTIVITIES ON SOLAR DESALINATION AT PSA
2. THE AQUASOL PROJECT
3. FIRST EXPERIMENTAL RESULTS
4. CONCLUSIONS

THERMAL STORAGE TANKS TEMPERATURE



- **SCF = Solar Collector Field**
- **The SCF provides positive ΔT with solar (global) irradiation around 100 W/m2**
- **A few minutes later, we have thermal inversion within the two thermal storage tanks**
- **The thermal storage system can operate well beyond the sunset**

POWER DELIVERED TO MED



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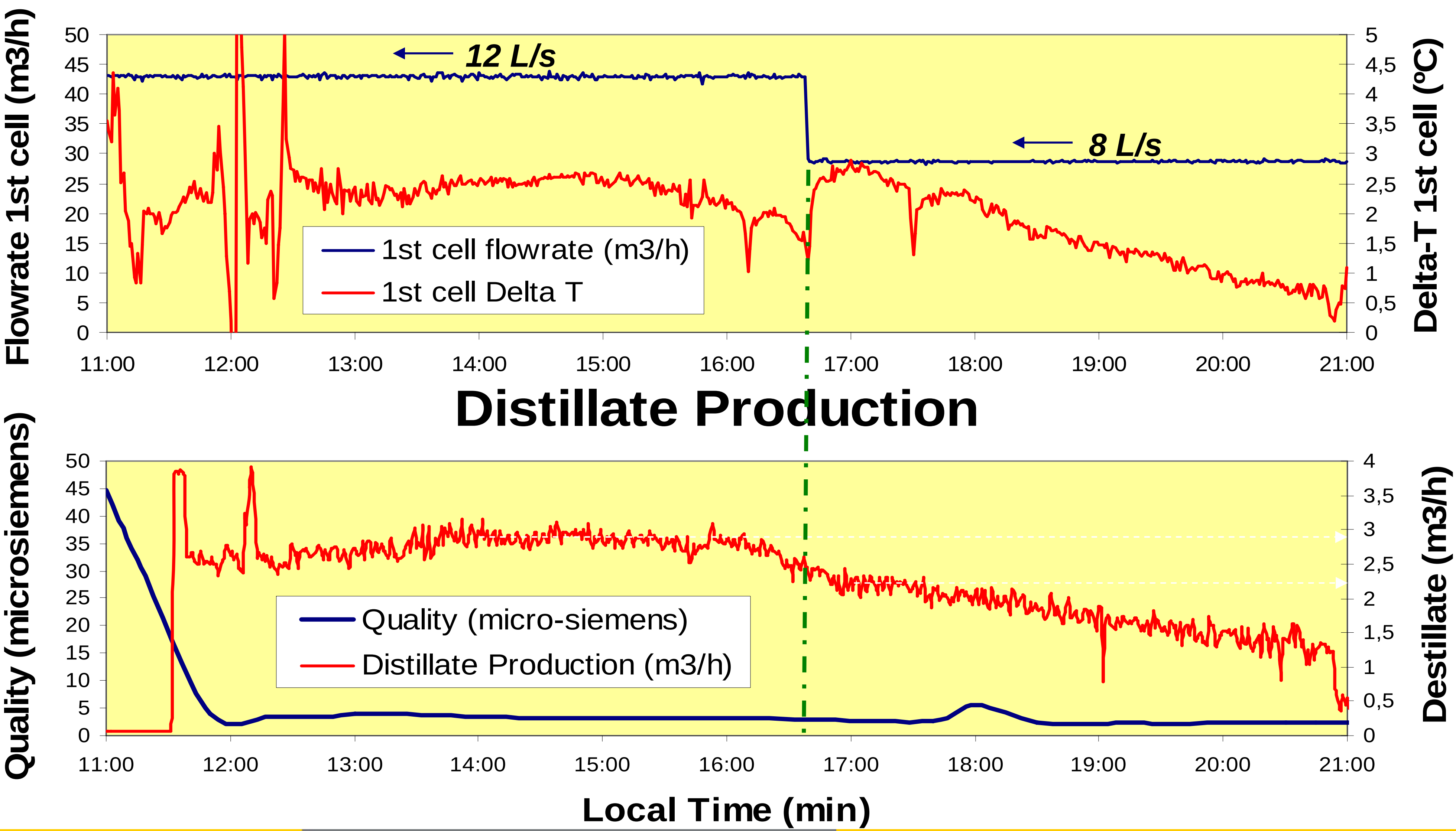
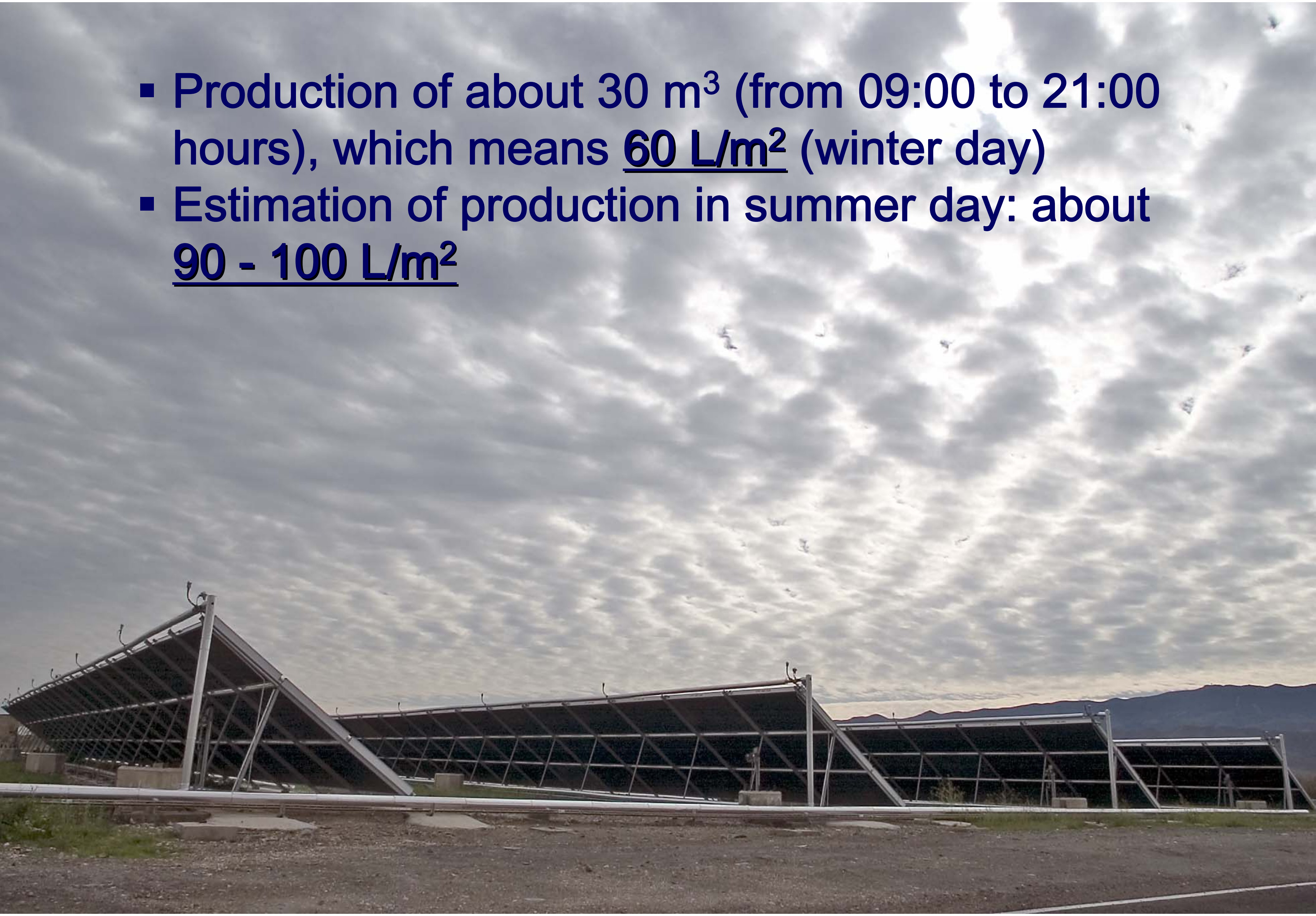
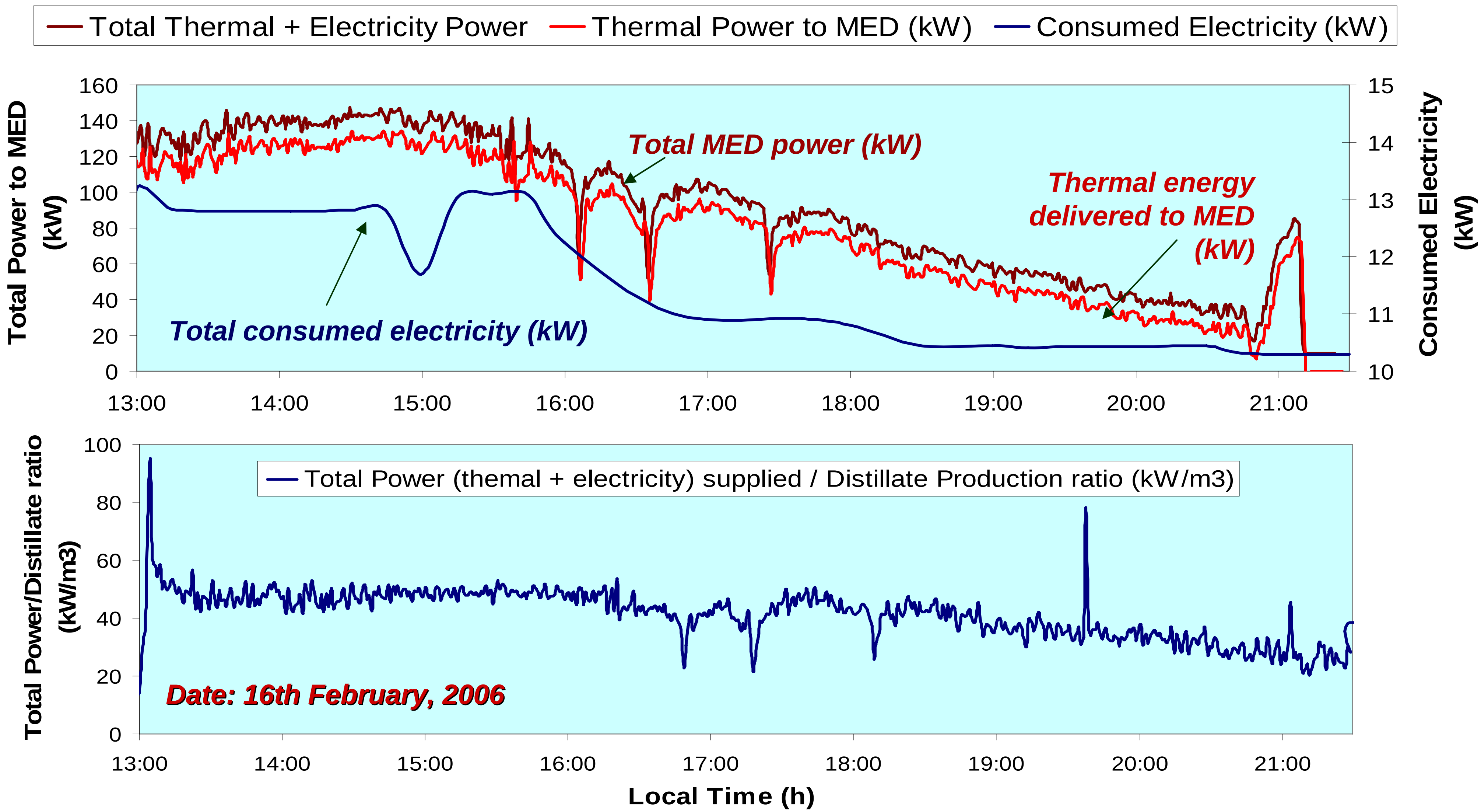
1st MED CELL PERFORMANCE



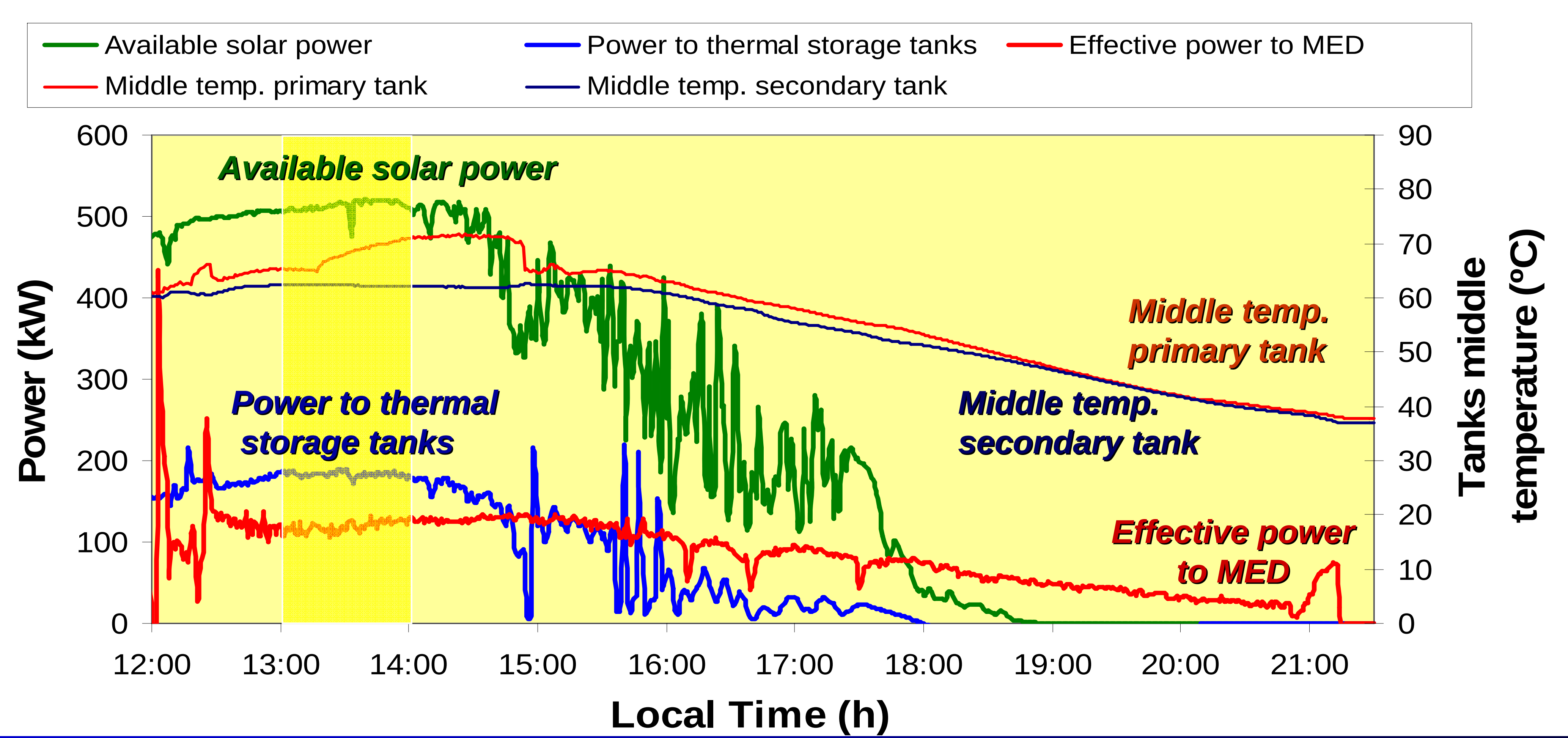
- Production of about 30 m^3 (from 09:00 to 21:00 hours), which means <u>60 L/m^2</u> (winter day)
- Estimation of production in summer day: about <u>90 - 100 L/m^2</u>



TOTAL POWER SUPPLIED TO PROCESS

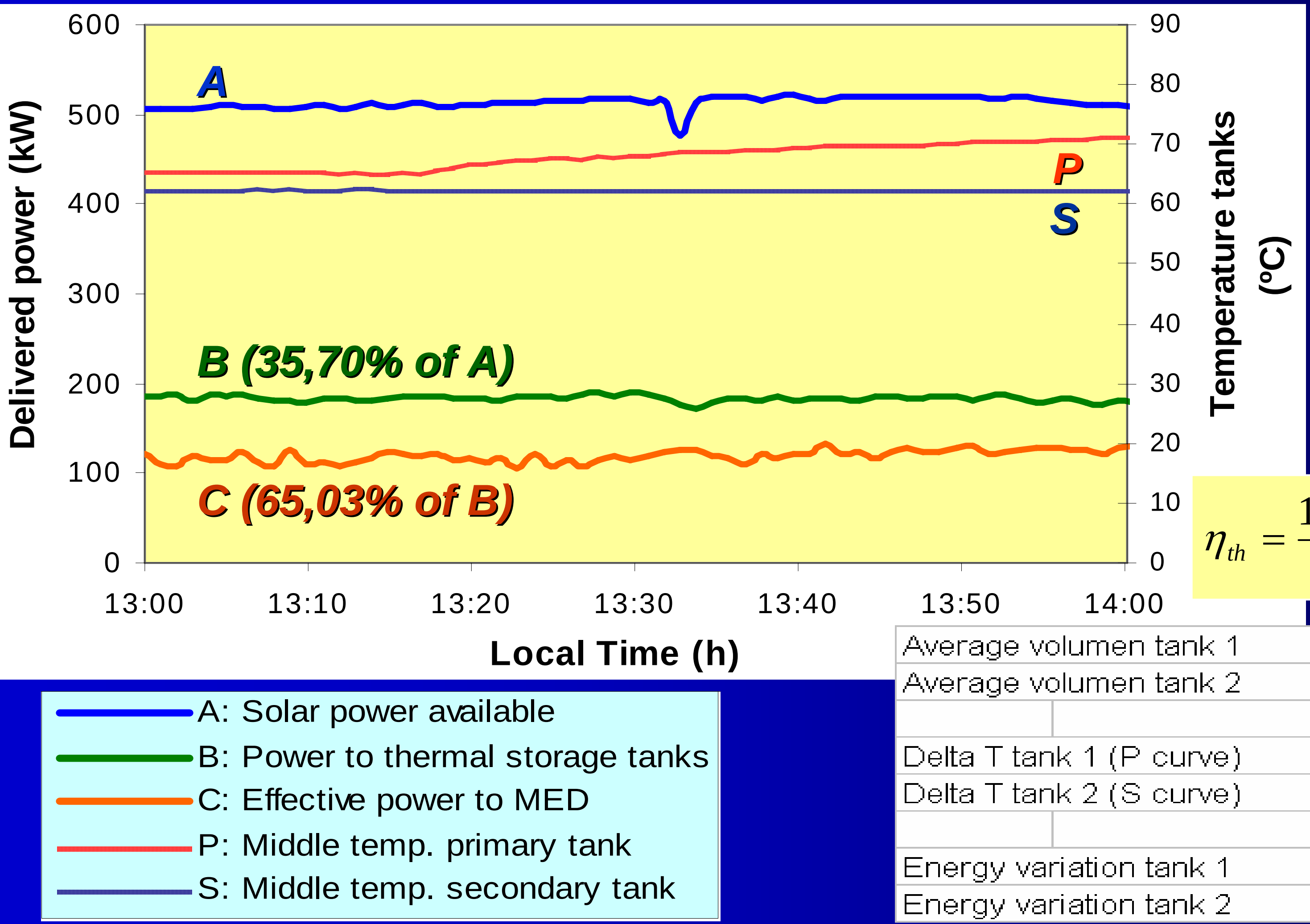


OVERALL EFFICIENCY ANALYSIS



OVERALL THERMAL EFFICIENCY

Test date: 16/02/2006



$$\int_{13:00}^{14:00} A(t)\,dt = 571{,}23\ kWh$$

$$\int_{13:00}^{14:00} B(t)\,dt = 186{,}28\ kWh$$

$$\int_{13:00}^{14:00} C(t)\,dt = 121{,}13\ kWh$$

$$\eta_{th} = \frac{121{,}13 + 64{,}70 - 2{,}10}{186{,}28} = 98{,}64\ \%$$

Average volumen tank 1	9.801,04	L		
Average volumen tank 2	9.811,45	L		
Delta T tank 1 (P curve)	5,77	ºC		
Delta T tank 2 (S curve)	-0,19	ºC		
Energy variation tank 1	236.805,58	kJ	64,70	kWh
Energy variation tank 2	-7.686,60	kJ	-2,10	kWh

INDEX

1. BACKGROUND ACTIVITIES ON SOLAR DESALINATION AT PSA
2. THE AQUASOL PROJECT
3. FIRST EXPERIMENTAL RESULTS
4. CONCLUSIONS

CONCLUSIONS & PERSONNAL REFLECTIONS

1. Water scarcity is a global problem which will become **<u>of capital importance during the 1st half of current century</u>** → Seawater desalination is, in many cases, the only alternative to achieve a sustainable development.
2. Today, the cost of desalination systems based on RES is clearly higher than conventional ones, being **<u>Solar Energy</u>** is the most promising one.
3. However, the current environmental and oil mixed scenarios (wide consensus of “oil peak” achievement in less than 30 years) makes extremely unlikely that **<u>Solar Desalination</u>** will not play a major role in the coming years.
4. At then end, it will not only be **<u>necessary</u>** to achieve environmental sustainability, but also **<u>inevitable</u>** to guaranty water supply security.
5. Main current inconveniences of Solar Desalination: **<u>higher investment costs</u>** (25% - 50% higher) and **<u>necessary land surface</u>** (1 Ha = 2000 m3/day).
6. Main objectives of AQUASOL projects were: reduction of either **<u>investment costs</u>** and **<u>exploitation costs</u>** of Solar Desalination based on MED technology, as well as **<u>environmental impact</u>** of brine produced.
7. First experimental results are **<u>very promising</u>** due to the high flexibility achieved

CONCENTRATING SOLAR POWER

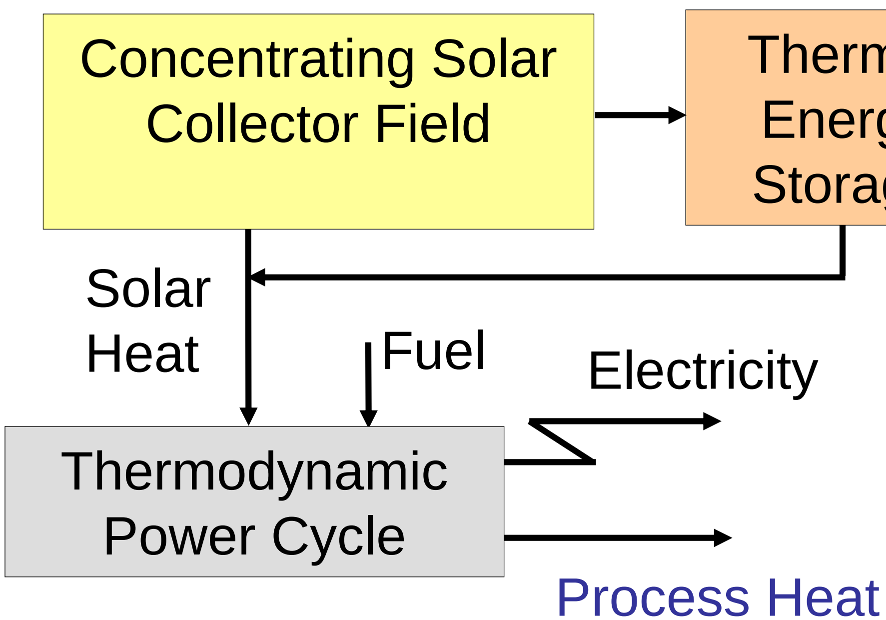
in the Trans-Mediterranean Renewable Energy Co-Operation: Electricity and Fresh Water

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
German Aerospace Center
DLR

Stefan Kronshage, Franz Trieb (DLR, Stuttgart)

Concentrating Solar Power – The Principle

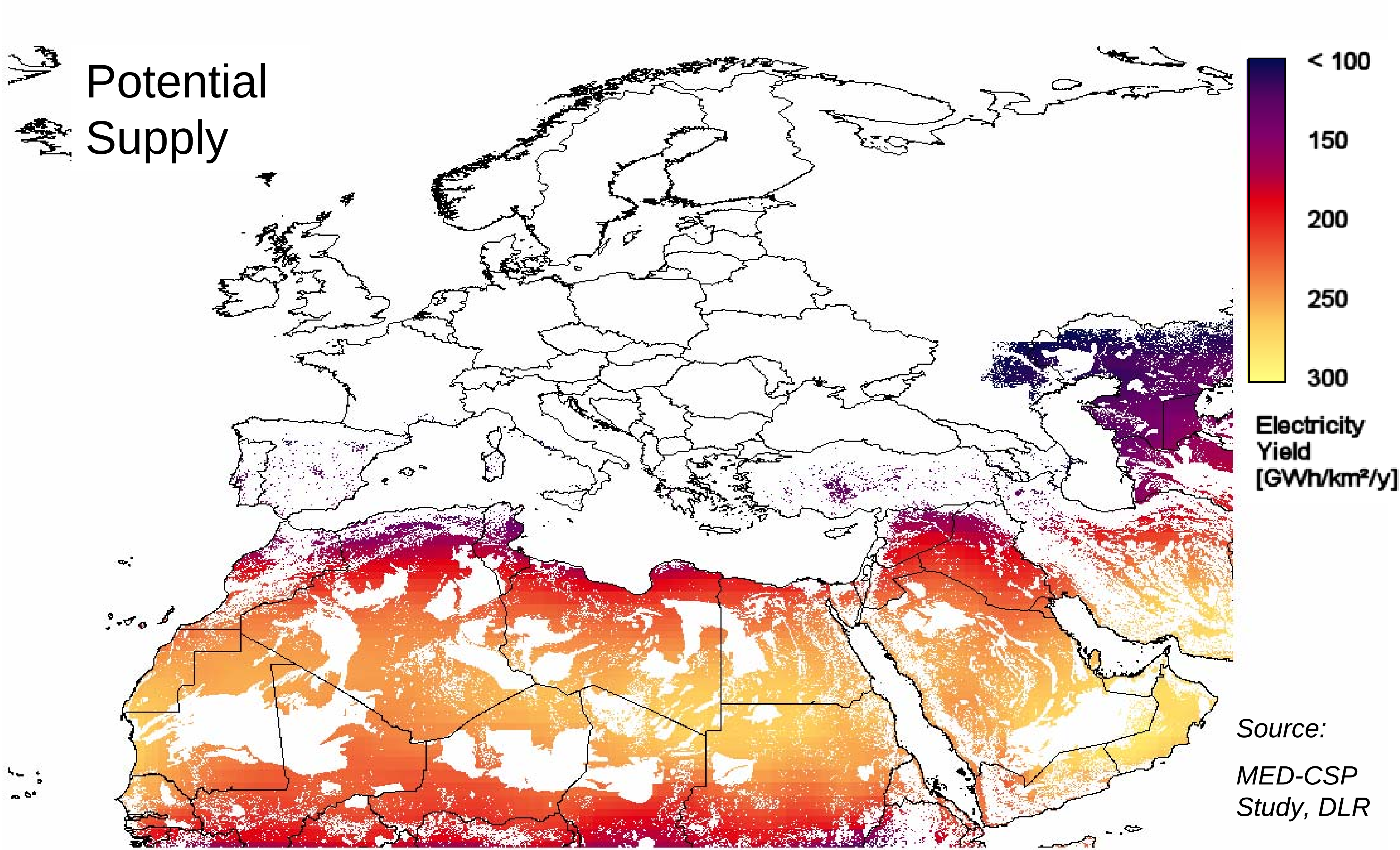
- heat generation by concentrating solar irradiance
- power generation by steam cycle turbine



- concentrated solar energy as “Solar Fuel”
- steam temperature of 400 – 500 °C
- secured capacity, power on demand
- additional process heat

Electricity in EU-MENA

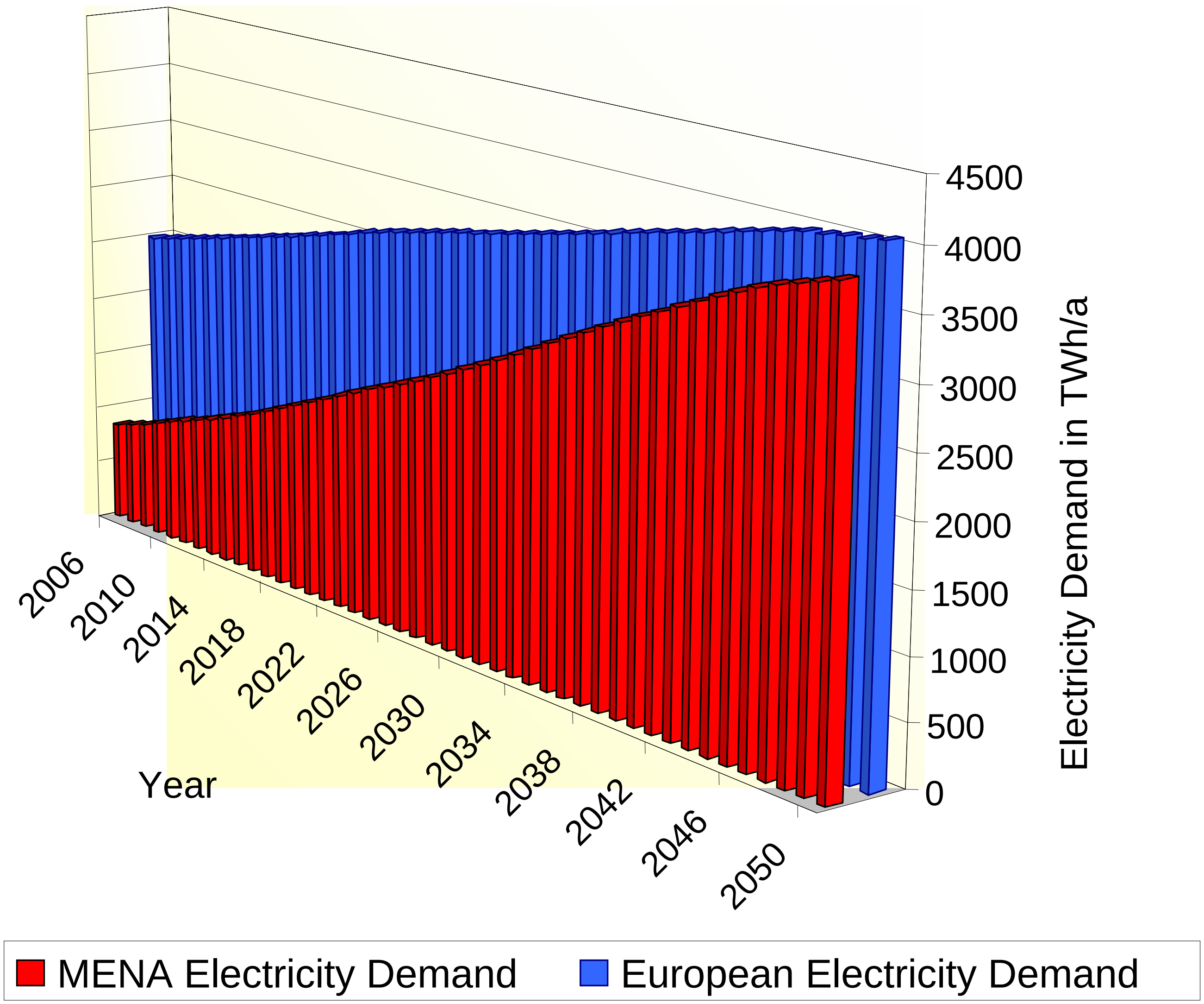
Potentials for Solar Thermal Electricity



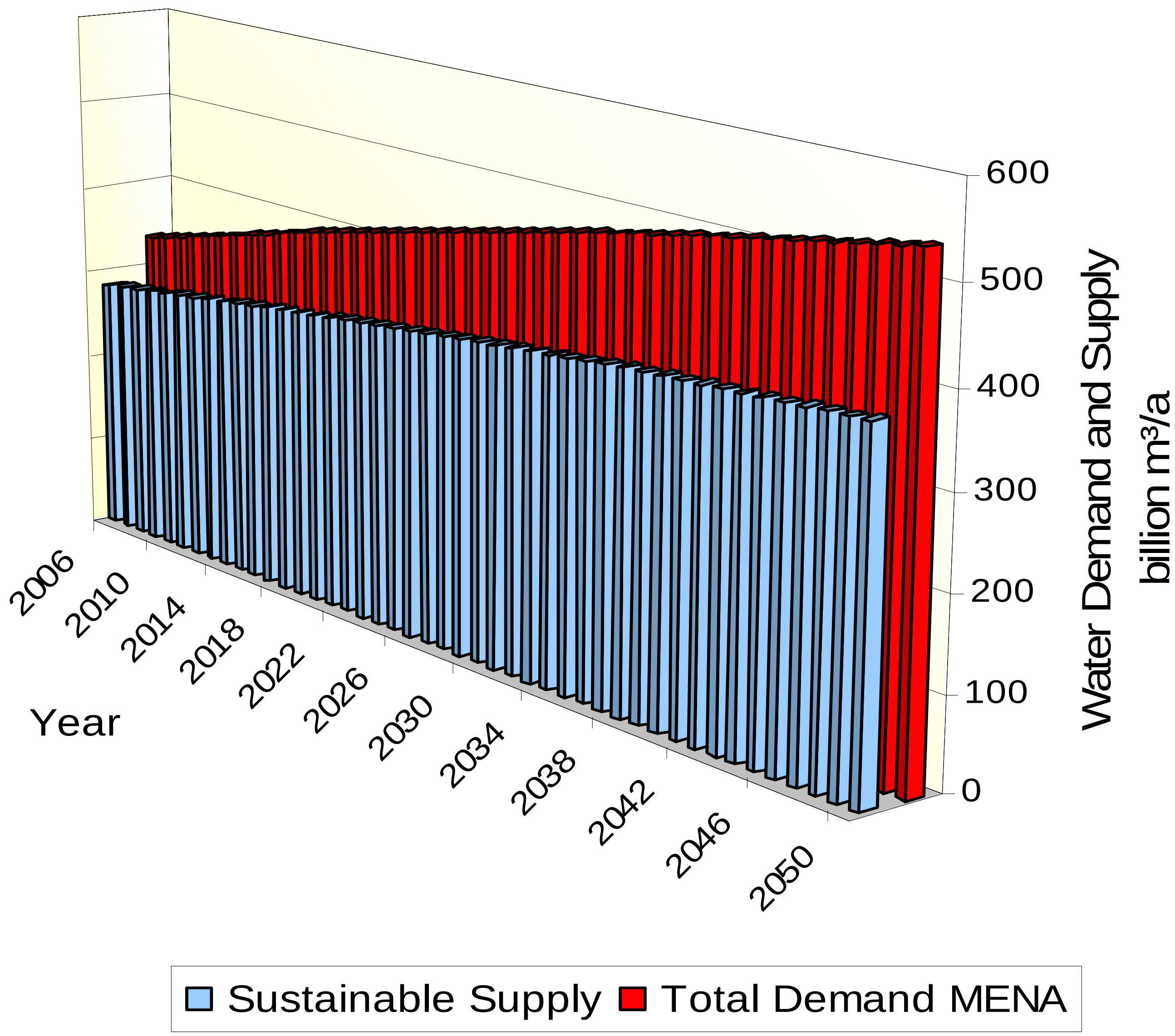
Source:

MED-CSP Study, DLR

Electricity Demand in MENA

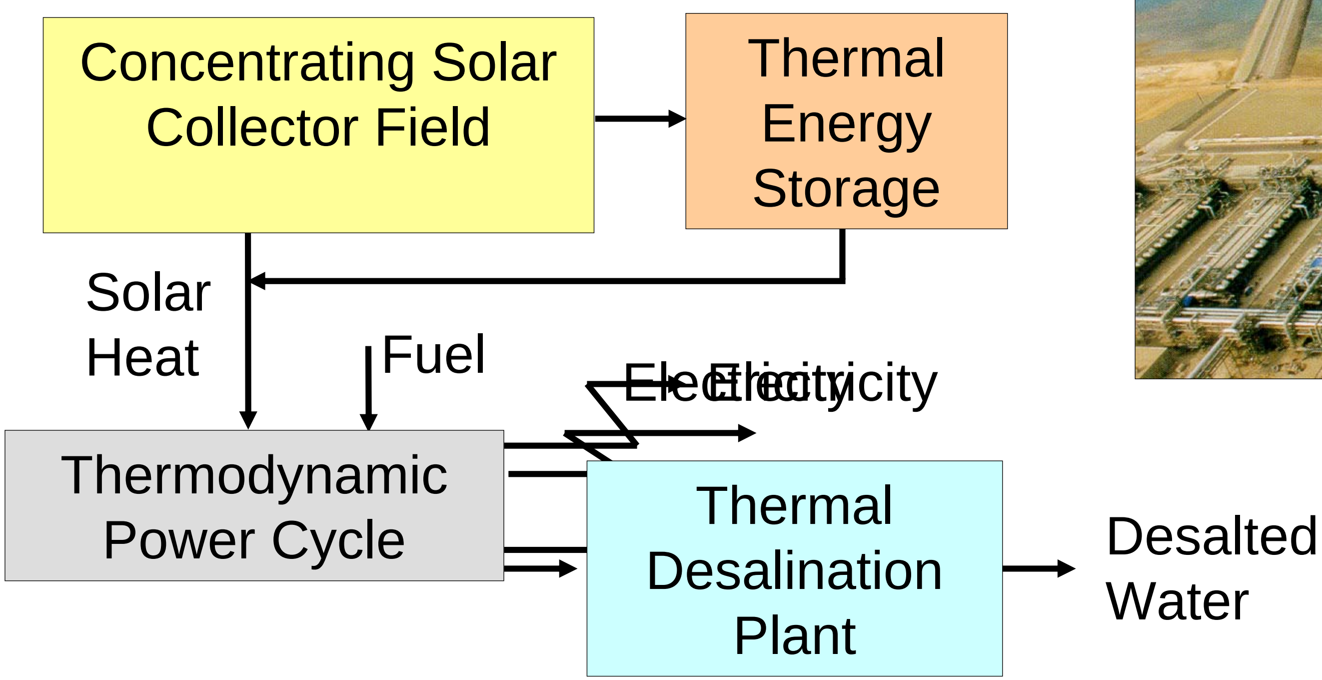


Fresh Water Balance in MENA



Co-Generation of Electricity & Desalted Water

- waste heat for efficient thermal water desalination
- ca. 1000 m³/day desalted water per MW_e installed capacity



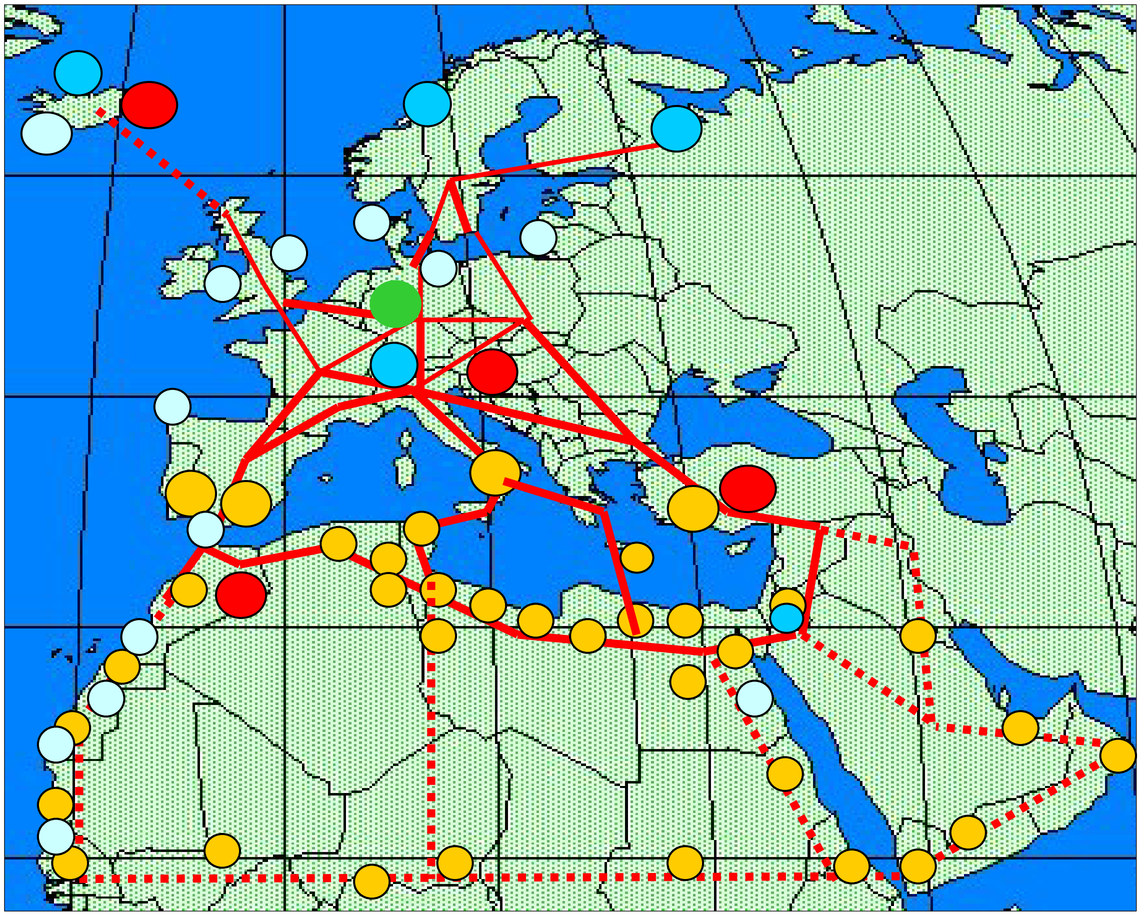
Trans-Mediterranean Renewable Energy Co-Operation (TREC)

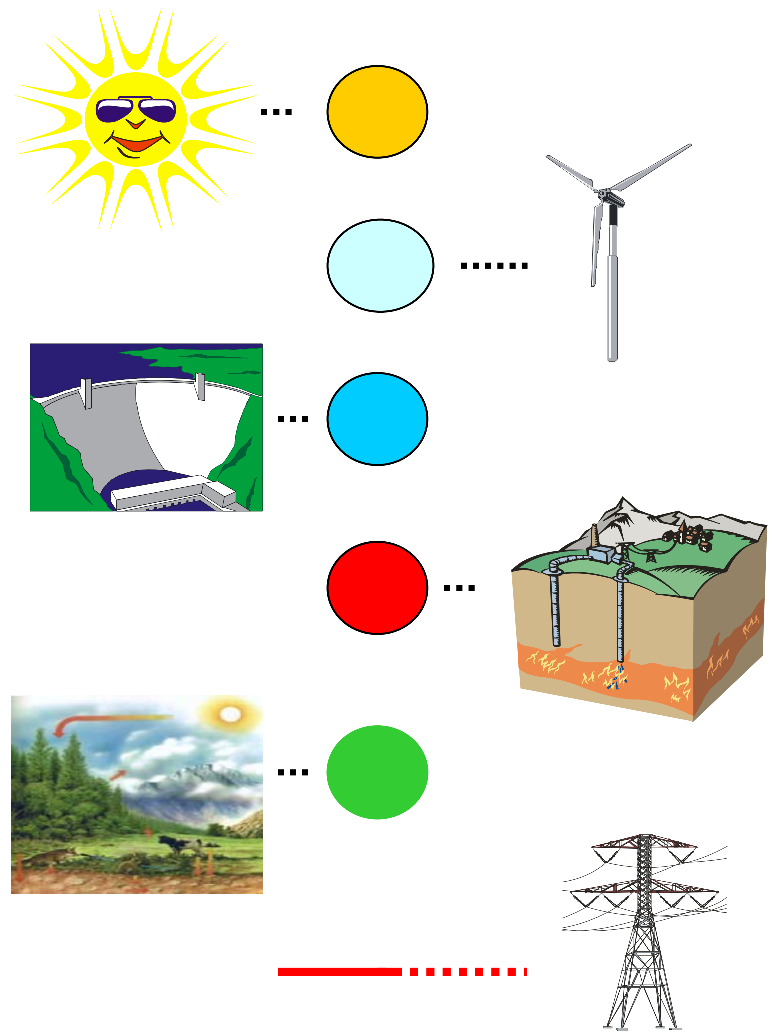
⇨ Combined Solar **Electricity** Generation and **Water** Desalination in MENA

- covering local electricity demand with "clean" electricity
- exporting "clean" electricity to EU
- providing substantial amounts of fresh water in MENA

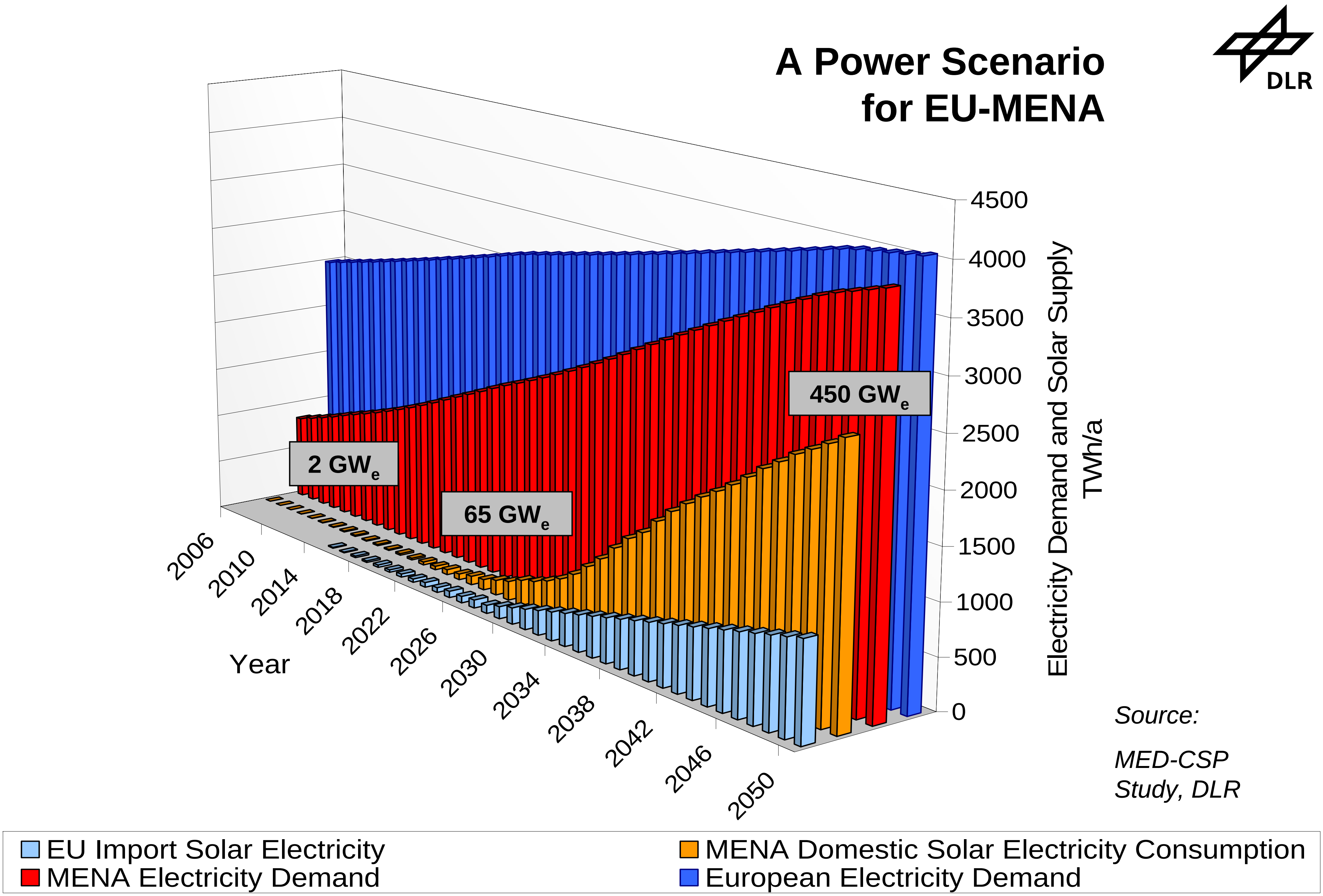
⇨ Trans-Mediterranean Interconnecting Grid (HVDC)

Trans-Mediteranean Interconnecting Grid

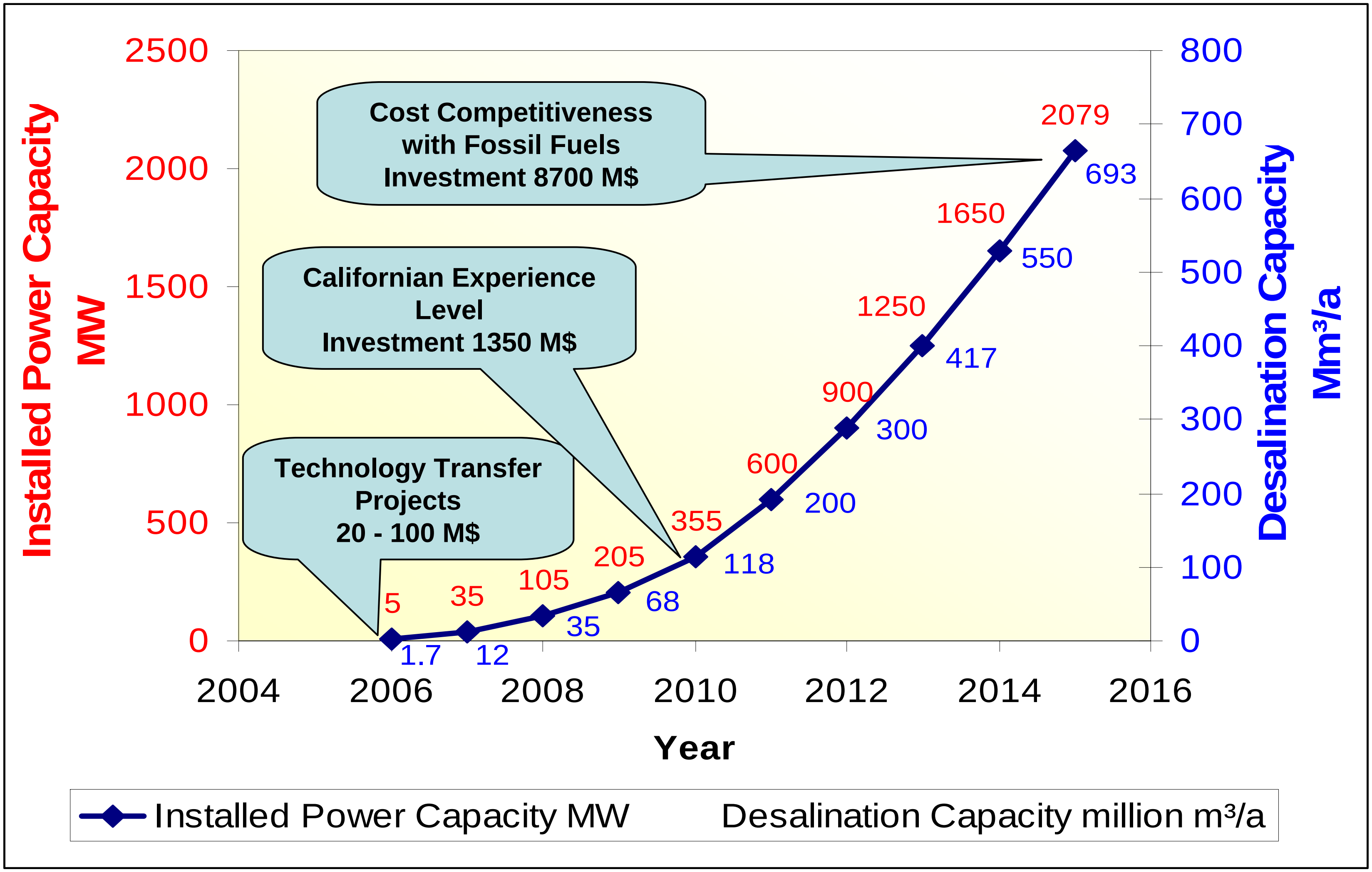




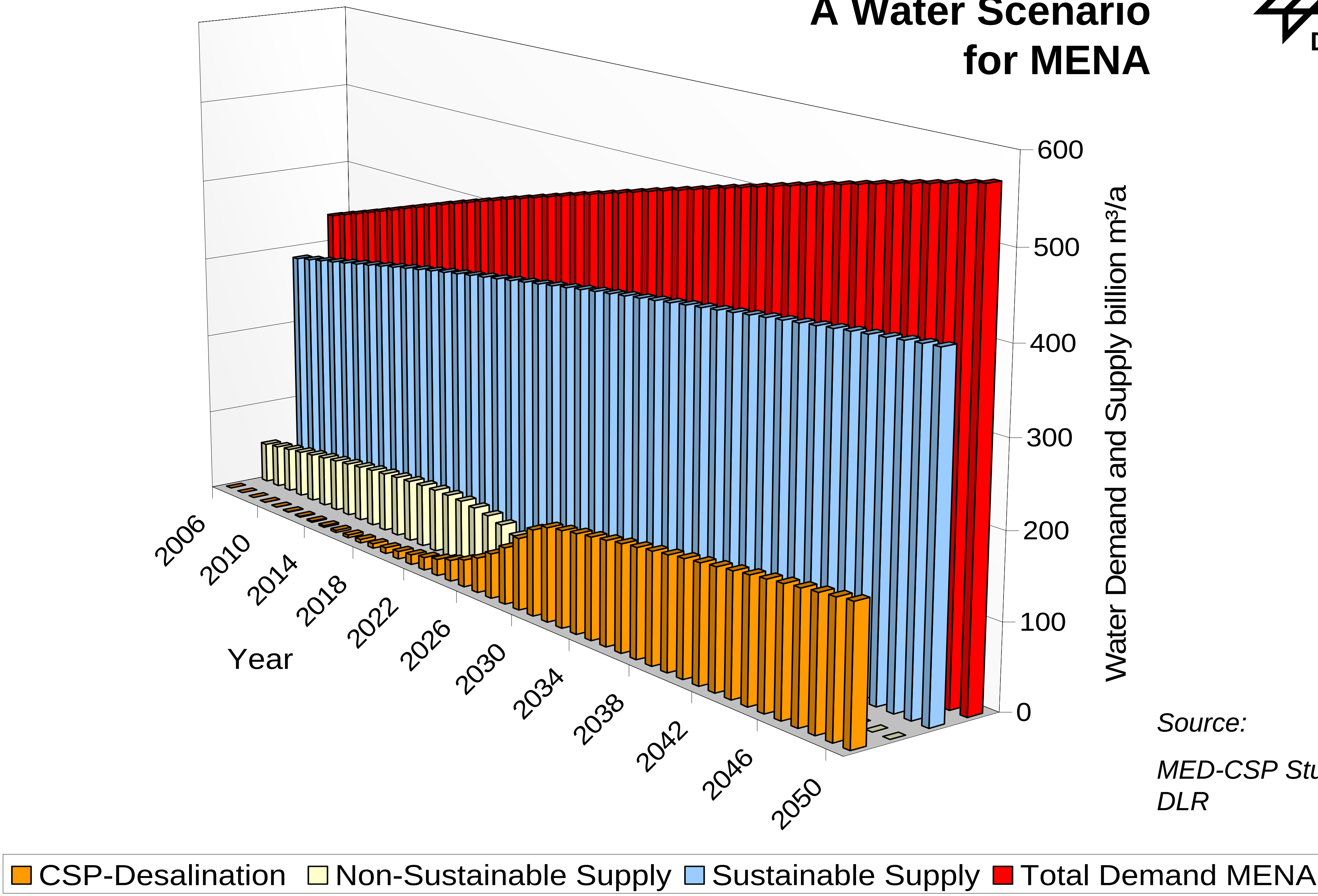
Source: TREC


A Power Scenario
for EU-MENA
DLR
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Electricity Demand and Solar Supply
TWh/a
450 GWe
2 GWe
65 GWe
2006
2010
2014
2018
2022
2026
2030
2034
2038
2042
2046
2050
Year
Source:
MED-CSP
Study, DLR
EU Import Solar Electricity
MENA Domestic Solar Electricity Consumption
MENA Electricity Demand
European Electricity Demand

How to start: the first 10 years



A Water Scenario for MENA



Source:

MED-CSP Study, DLR

Target for 2030:
Common market and grid infrastructure for renewable energy among the countries surrounding the Mediterranean Sea

Conclusions

- CSP provides a **sustainable solution** for clean energy and water security in EUMENA.
- **Low and stable prices** for power and water.
- **Additional labour, industry and trade** and reduced conflict potential on water and energy.
- **Incentives and attractive conditions** are required to mobilise private investment into CSP in MENA.

To Do's

- **Technology transfer** from EU to MENA
- **Mobilize EU and MENA governments** to support/adopt CSP initiative

What is gained after 2015 ?

- A sustainable solution for energy and water security in EUMENA and world wide.
- Low and stable prices for power and water and relief from long-term subsidies.
- Additional labour, industry and trade and reduced conflicts on water and energy.

What is required until 2015 ?

- A Trans-Mediterranean Partnership for Energy and Water Security in EUMENA.
  - Investment Volume: 10 Billion $
  - Return on Investment: average 6 %
  - Purchase Guarantees for: 20 TWh/y + 1 Bm^3/y

The inevitable need for seawater desalination means an additional burden for the national economies in MENA. There is no economically feasible solution for water security in MENA based on desalination with fossil or nuclear energy.

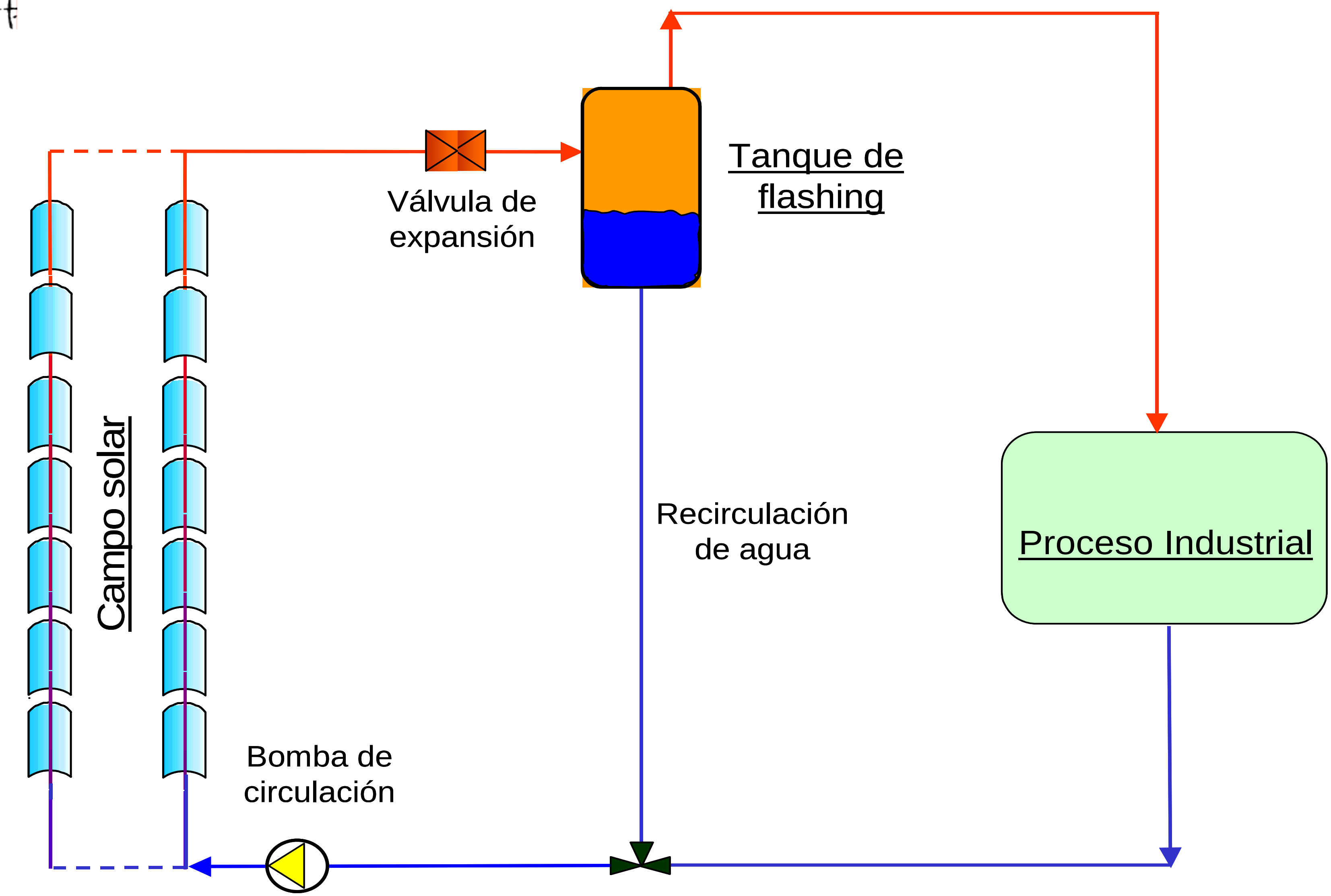
CSP offers a sustainable solution and at the same time relief for the national economies:

- lower cost of primary energy
- lower external costs of energy
- income from export of solar electricity
- income from export of saved fuels
- income from emission trading

STEAM FOR INDUSTRIAL PROCESSES

Solar Steam Generation

- Indirect Process
  - ➔Flashing
  - ➔Boiler plus heat exchanger
- Direct Process
  - ➔Direct Steam Generation: DISS



Parabolic Trough for Industrial Process Heat

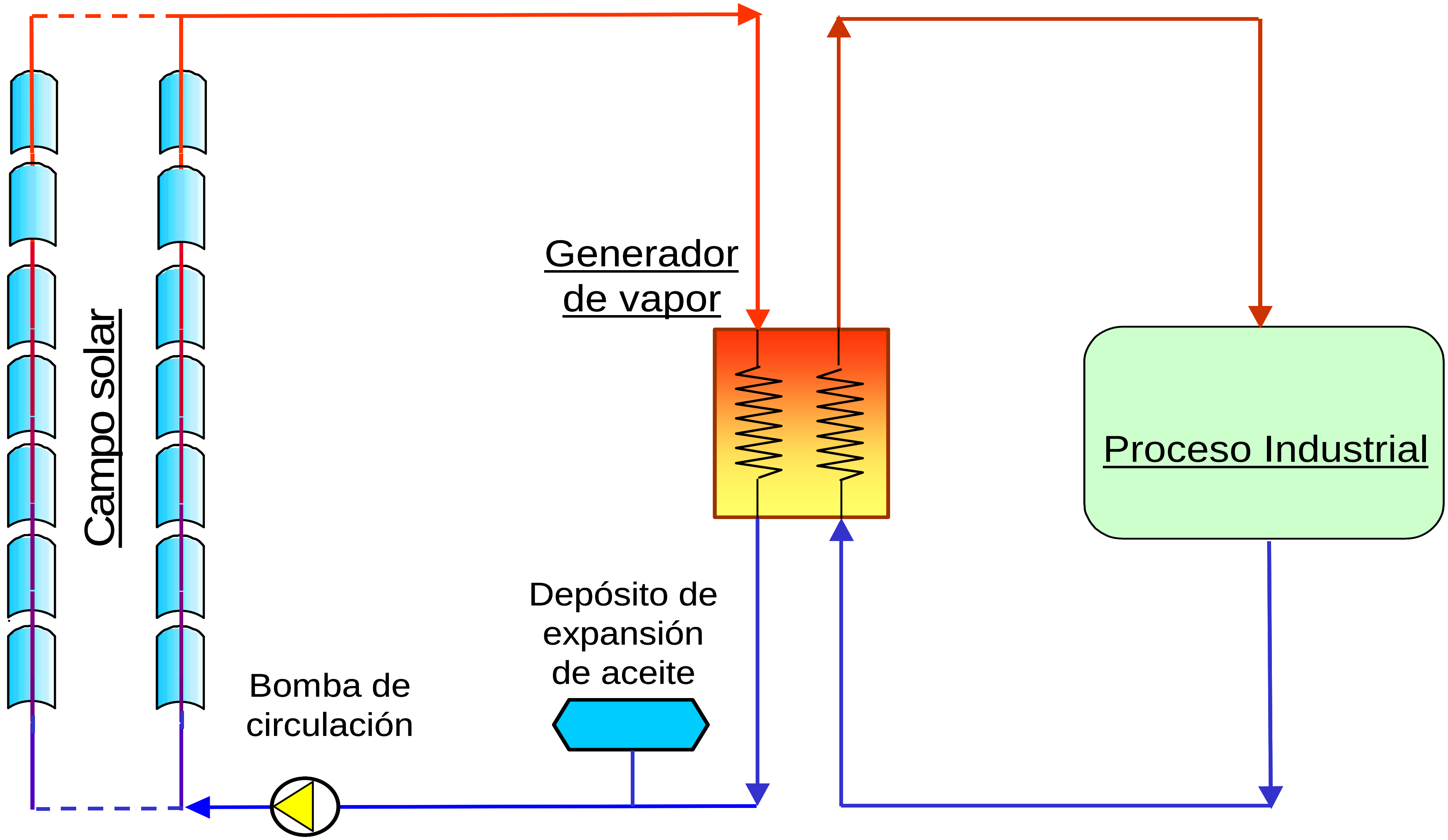
Flashing

Working Fluid = Water

- **Pros**
  - ➔No heat exchanger
  - ➔Simpler design
  - ➔Lower cost
- **Cons**
  - ➔High thermal losses
  - ➔High pressure drop
  - ➔Low working pressures

El Nasr (Egypt) (Dec, 2003)

Turkey (Dec, 2003)



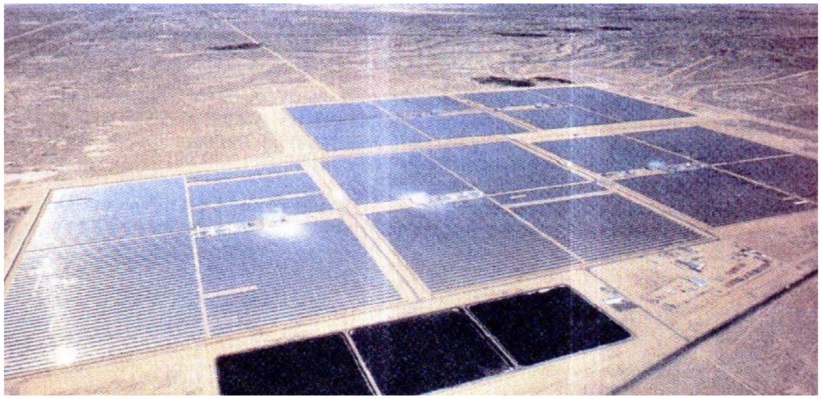
Parabolic Trough for Industrial Process Heat

Boiler plus Heat Exchanger

Working Fluid = Thermal Oil

- **Pros**
  - ➔ **Well-known technology**
- **Cons**
  - ➔ High cost
  - ➔ Risk of oil spillage
  - ➔ High pressure drop

Beith Shemesh (~Jerusalem)

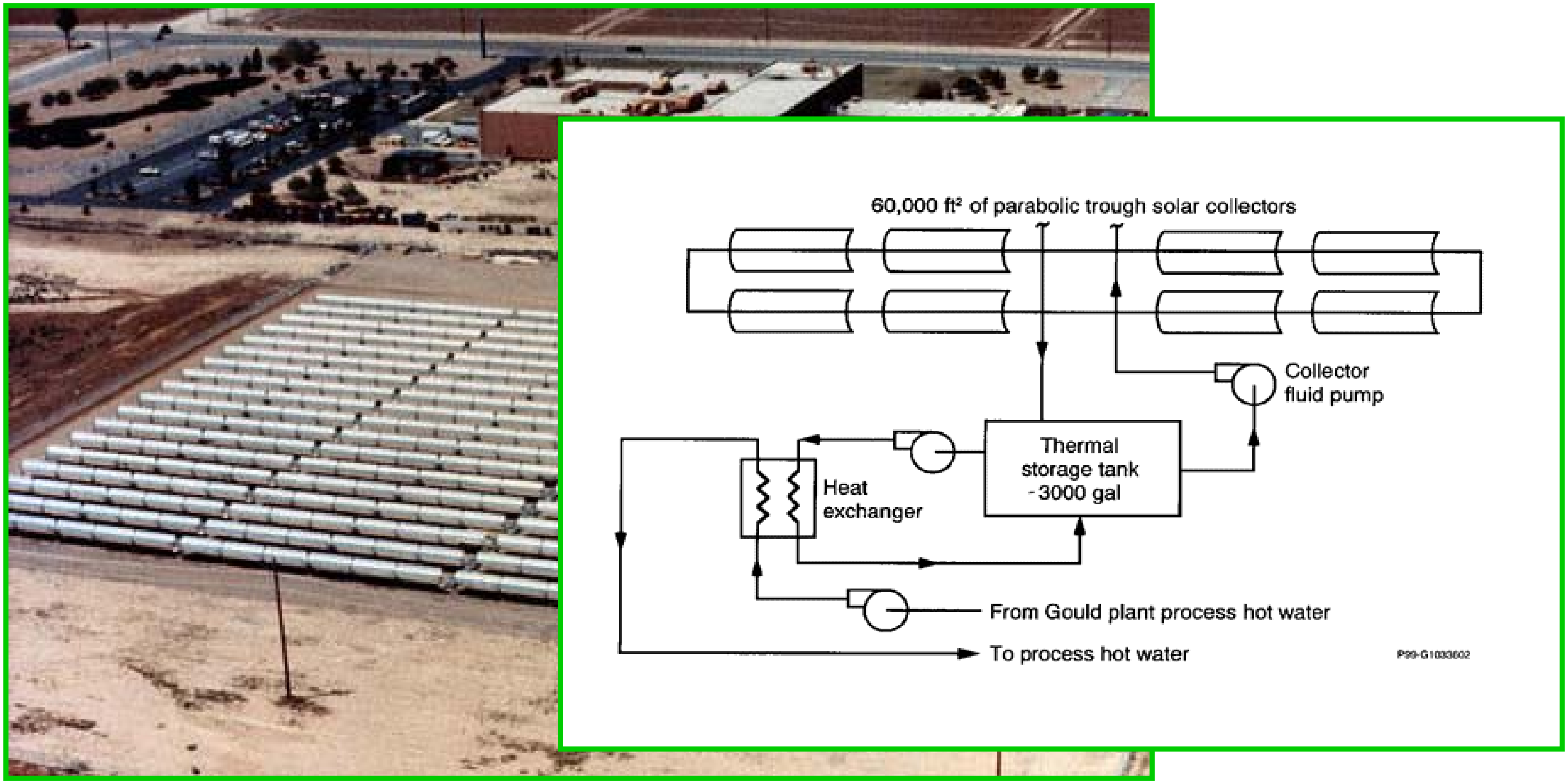


SEGS Plants (California) 340MW$_e$

• Gould Electronics, Chandler, Arizona (1982)

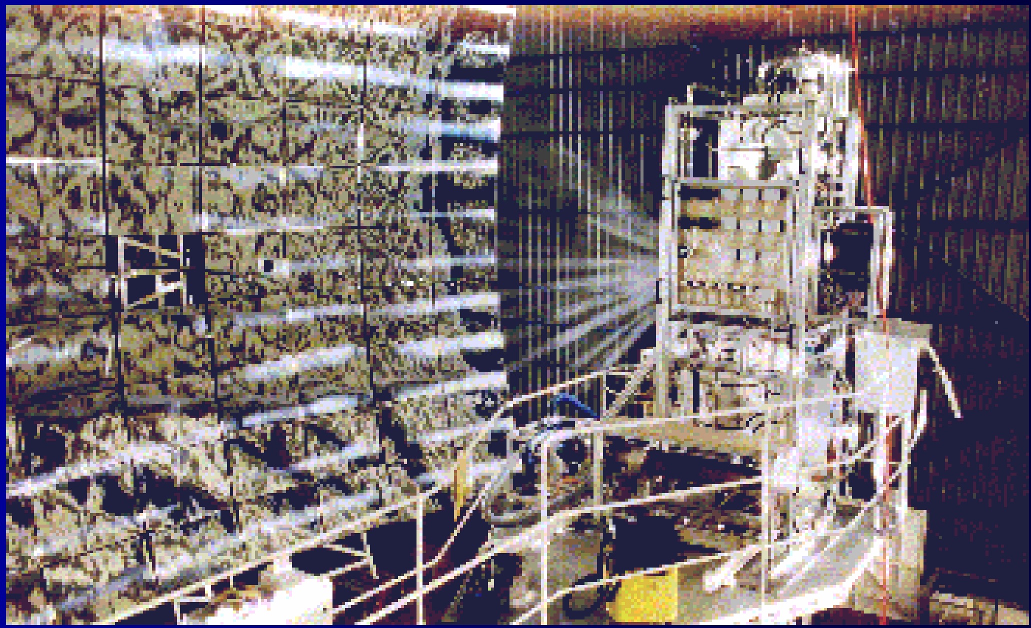
432 units of ‘T-700 Solar Kinetics Inc’ (5617m²); thermal oil

‘Cu’ sheet production factory



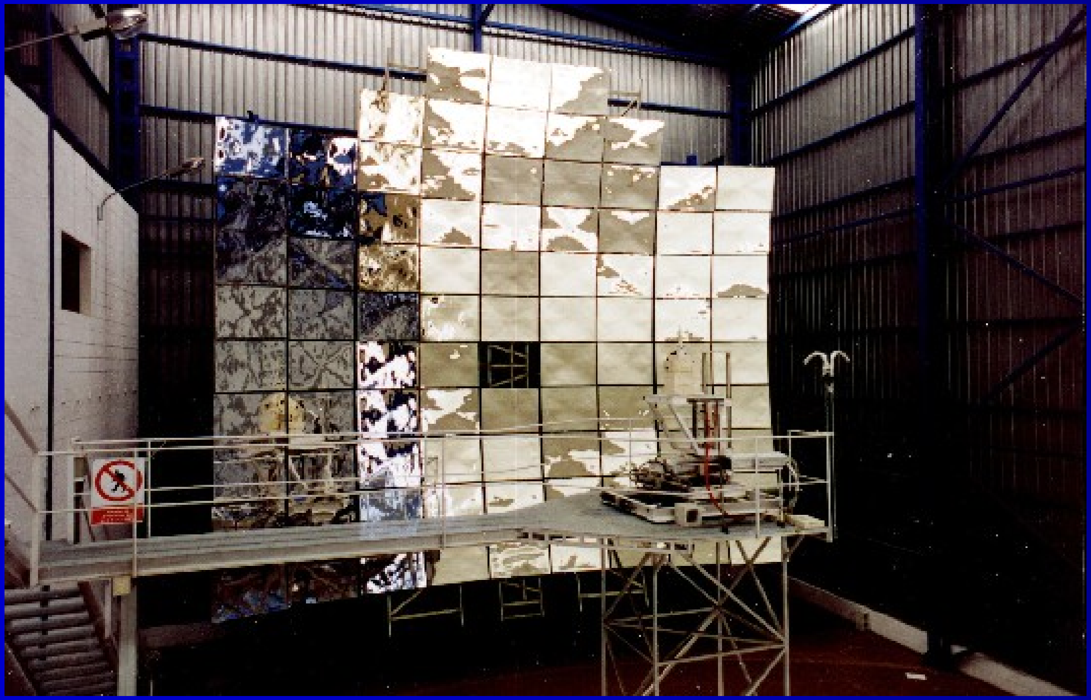
HIGH TEMPERATURE PROCESSES

SOLAR FURNACE



- ✓ **Tool for achieving high flux and high temperatures (T > 2000 ºC).**
- ✓ **Peak flux: 3000 suns. Power: 58 kW. Concentrating area: 98,5 m^2.**
- ✓ **Focus diameter: 23 cm. Gaussian energy profile.**
- ✓ **Up to now, thermal materials surface treatment applications.**
- ✓ **New applications: high temperature chemical processes, industrial process heat.**

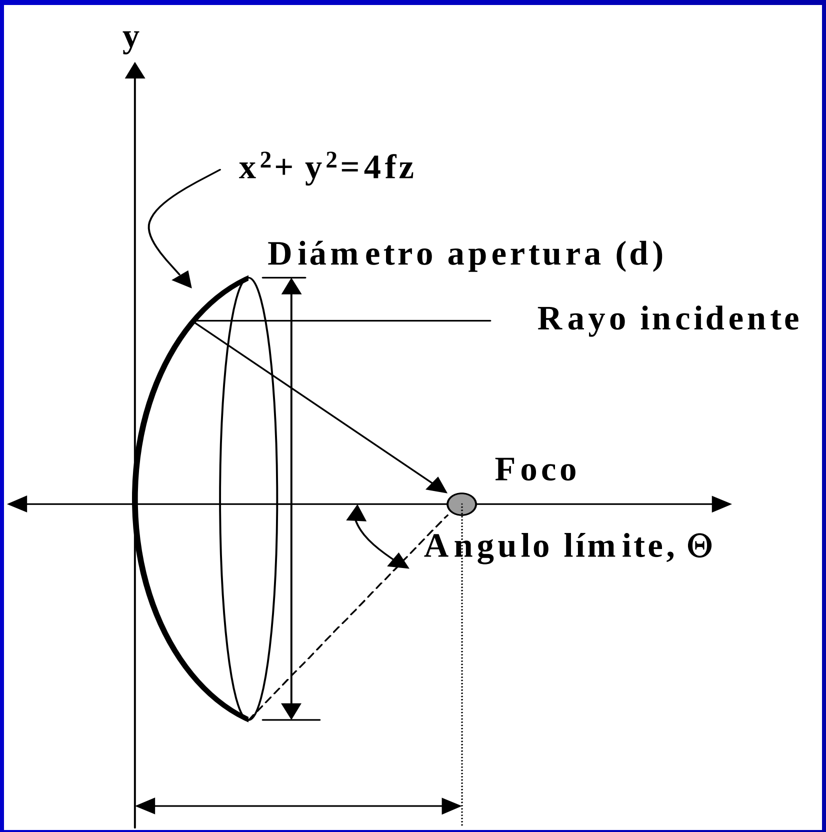
Main components of a Solar Furnace



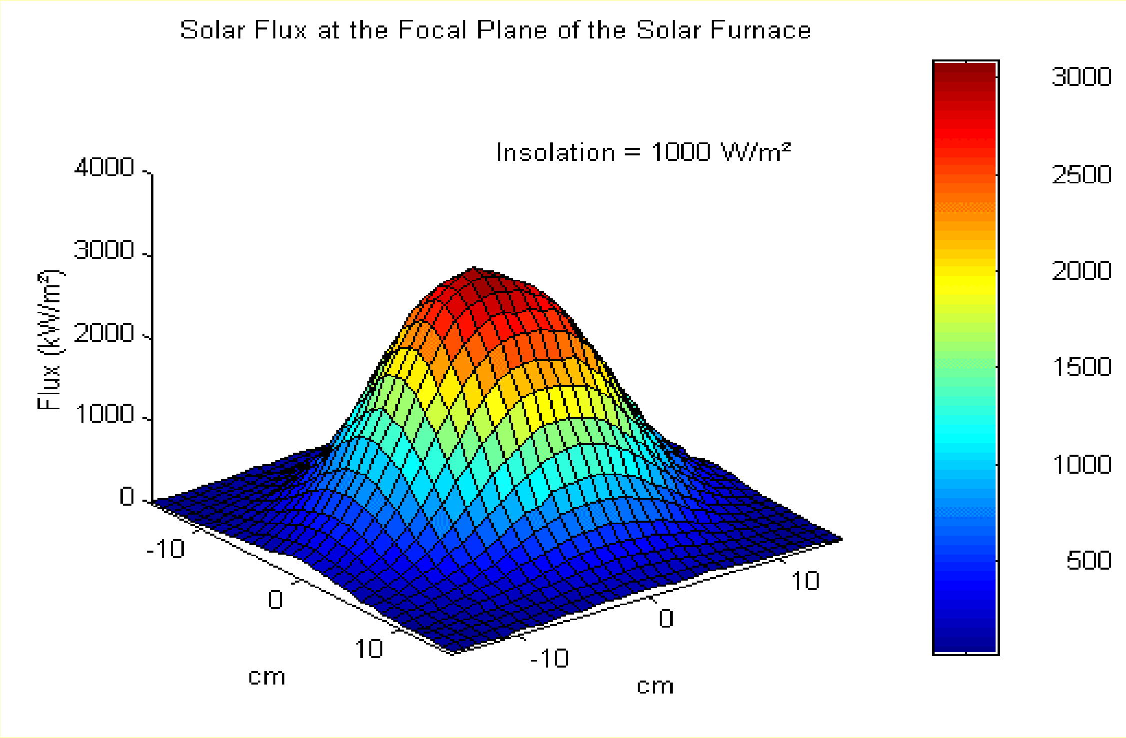
Parabolic Dish

Flat Heliostat

The Flux Map at the Focal Point



FLUX MAP AT SOLAR FURNACE FOCUS



Solar System Integration: what to be considered ?

- Temperature level that determinates concentration needs, and therefore, sun tracking requirements of the solar system

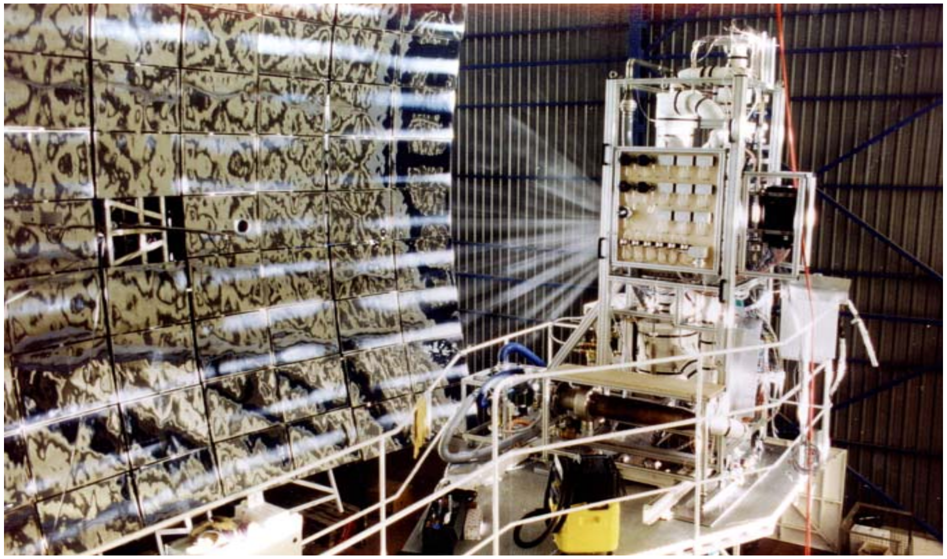
- Synergy betwen heat transfer means of the industrial process and the uses in the solar system.

- Consumption profile of the industrial process related to high levels of solar insolation.

High Temperature Solar Processes (above 400ºC)

Main industrial states/sectors sensitive to be treated by high temperature solar process heat involve synthesis processes, production of chemical commodities and high temperature material and waste treatments, such as:

- **Metalurgical** Industry
- **Chemical** Industry
- **Ceramic** Industry
- **Glass** Industry
- **Cement** and **lime** industry
- High temperature **waste** treatment



Main research lines in High Temperature Solar Process Heat:

- Production of ***syngas*** by reforming or solar gasification of fossil fuels (800-1500K)
- Conversion of ***biomass*** and other ***carbonaceous materials*** by different solar thermochemical routes into bio-oils, charcoal, and syngas
- Production of ***fullerenes*** and ***carbon nanotubes*** by sublimation of graphite above 3000 K or by catalytic thermal decomposition of hydrocarbons
- Production of ***metallic carbides*** and ***nitrides*** by solar carbothermic reduction of metal oxides
- Production of ***zinc***, ***iron***, ***magnesium***, and other metals by carbothermic reduction of their metal oxides
- Decomposition of ***limestone***, the main endothermic step in the production of cement, at 1300 K
- Solar thermal detoxification and recycling of ***waste materials***
- Solar ***Hydrogen thermochemical*** production

Technical and economical evaluations *about some of these processes indicates that* ***high temperature solar process heat generation*** *could be feasible in medium/long term.*

Geneve, 31 March, 2006

DEVELOPMENT OF A HEAT SUPPLY SYSTEM BASED ON CONCENTRATED SOLAR ENERGY: TESTING AND CHARACTERIZATION OF ITS APPLICATION TO SEVERAL HIGH-TEMPERATURE INDUSTRIAL AND WASTE REMOVAL PROCESSES

PSA - CIEMAT takes part in diferent national and international projects about solar thermochemical hydrogen production as well as other high-temperature industrial production and waste treatment processes.

Related to high-temperature materials and waste treatment processes, nowdays is being developed **SolarPro Poject**, funded by the Spanish Ministry of Science and Technology in the frame of the National Plan for R&D+i (Reference: REN2003-09247-C04-01) and cordinated by PSA - CIEMAT.

The **purpose** of SolarPRO is to demonstrate the technological feasibility of using solar thermal energy as the energy supply system for production processes and waste treatments having the common denominator of high temperature .

Some **industrial processes** of high scientific and technological interest have been selected for this from the positive results in SolarPRO I, with several different research groups highly specialized in these processes as partners.

Geneve, 31 March, 2006

Processes

- Ceramics processes
- Materials treatment
- Powder metallurgical processes
- Waste treatment

Reactors

- Test bed for volumetric receiver or Process chamber with volumetric receiver
- Rotary Kiln
- Fluidized bed

DEVELOPMENT OF A HEAT SUPPLY SYSTEM BASED ON CONCENTRATED SOLAR ENERGY: TESTING AND CHARACTERIZATION OF ITS APPLICATION TO SEVERAL HIGH-TEMPERATURE INDUSTRIAL AND WASTE REMOVAL PROCESSES

Objetives:

1. Design of **pre-industrial prototypes** to provide solar heat to high-temperature industrial processes and remote modular systems to certain processes based on the parabolic concentrator concept with associated reactor.

2. Acquire enough data and experience to **optimize solar energy equipment design** and **operating procedures** to the applications tested.

3. **Modelling** and **control** of selected processes and validation with real data from the experiments.

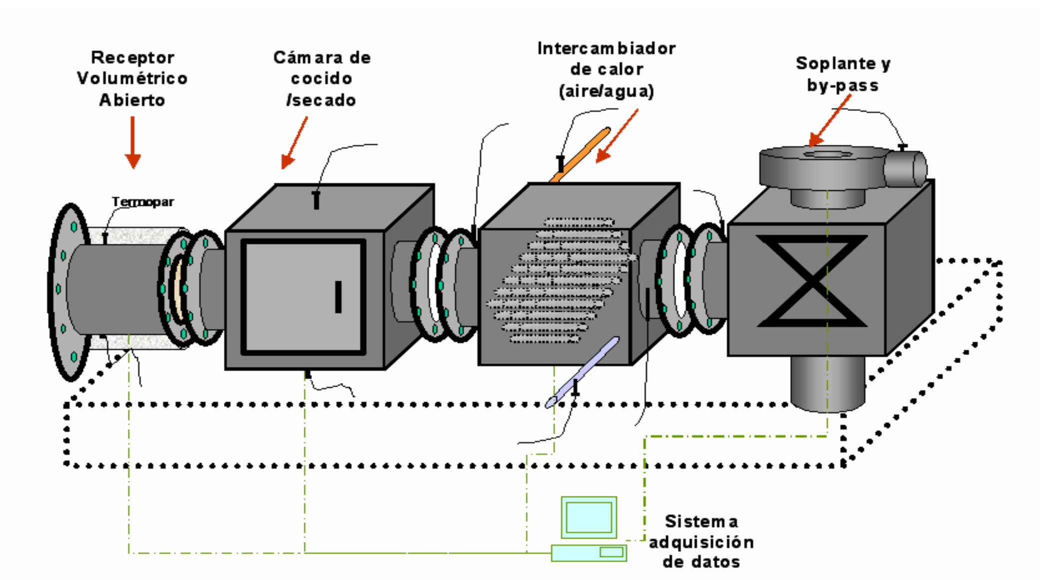
4. **Identification of potential new processes** that could use solar process heat as the energy supply.

5. Arrive at conclusions that will assist in later **system scale-up**

Geneve, 31 March, 2006

DEVELOPMENT OF A HEAT SUPPLY SYSTEM BASED ON CONCENTRATED SOLAR ENERGY: TESTING AND CHARACTERIZATION OF ITS APPLICATION TO SEVERAL HIGH-TEMPERATURE INDUSTRIAL AND WASTE REMOVAL PROCESSES

Typical industrial ceramics processes – INSTITUTO DE TECNOLOGÍA CERÁMICA (ITC)		
Drying of the 'raw' pieces	100ºC < T < 200ºC	· Drying chamber and baking with volumetric receiver
'Third firing', for certain kinds of decoration	800ºC < T < 900ºC	· Drying chamber and baking with volumetric receiver
Firing of ceramic tiles	800ºC < T < 1150ºC	· Drying chamber and baking with volumetric receiver



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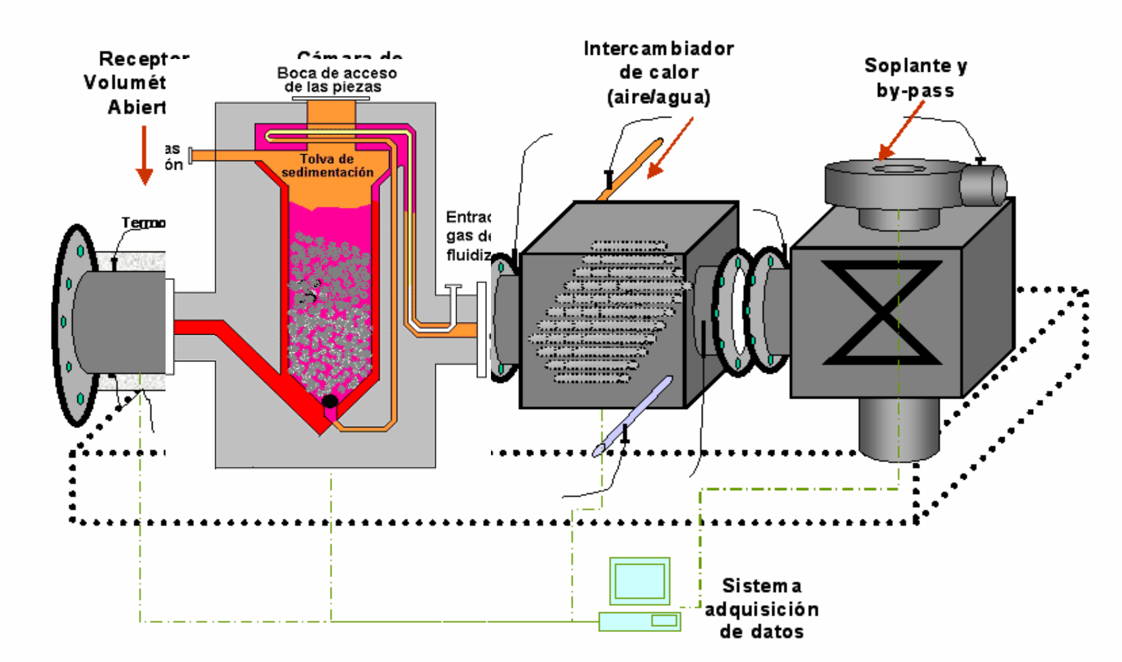
Powder metallurgical processes – UNIVERSIDAD DE SEVILLA		
Metal sintering processes	T~ 1000ºC	· Controlled-atmosphere processing chamber



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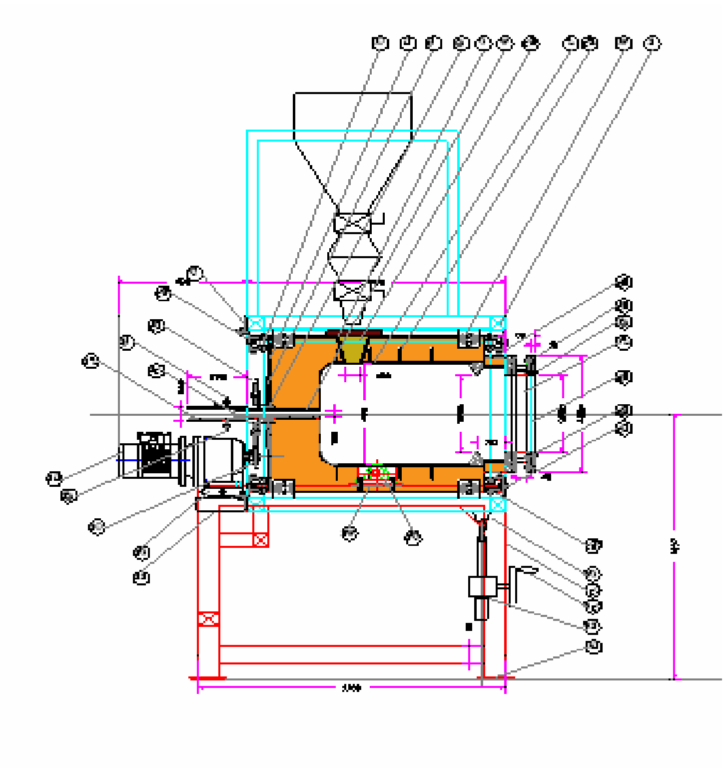
Waste treatment – UNIVERSIDAD POLITÉCNICA DE CATALUÑA		
Processes for eliminating heavy metals from polluted soils	T< 630ºC	· Adapted **Rotary kiln.**



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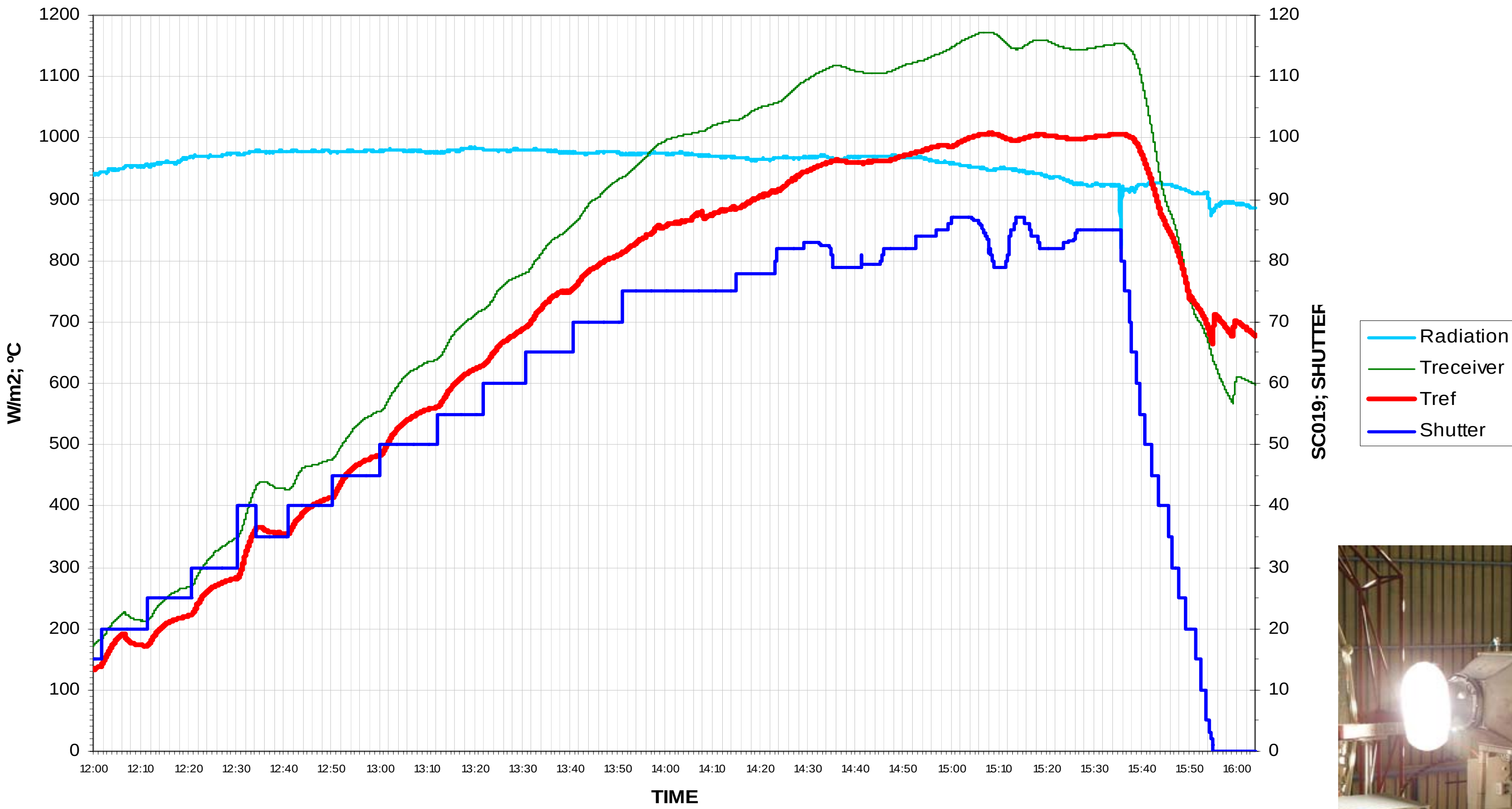

Geneve, 31 March, 2006

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Plataforma Solar de Almería

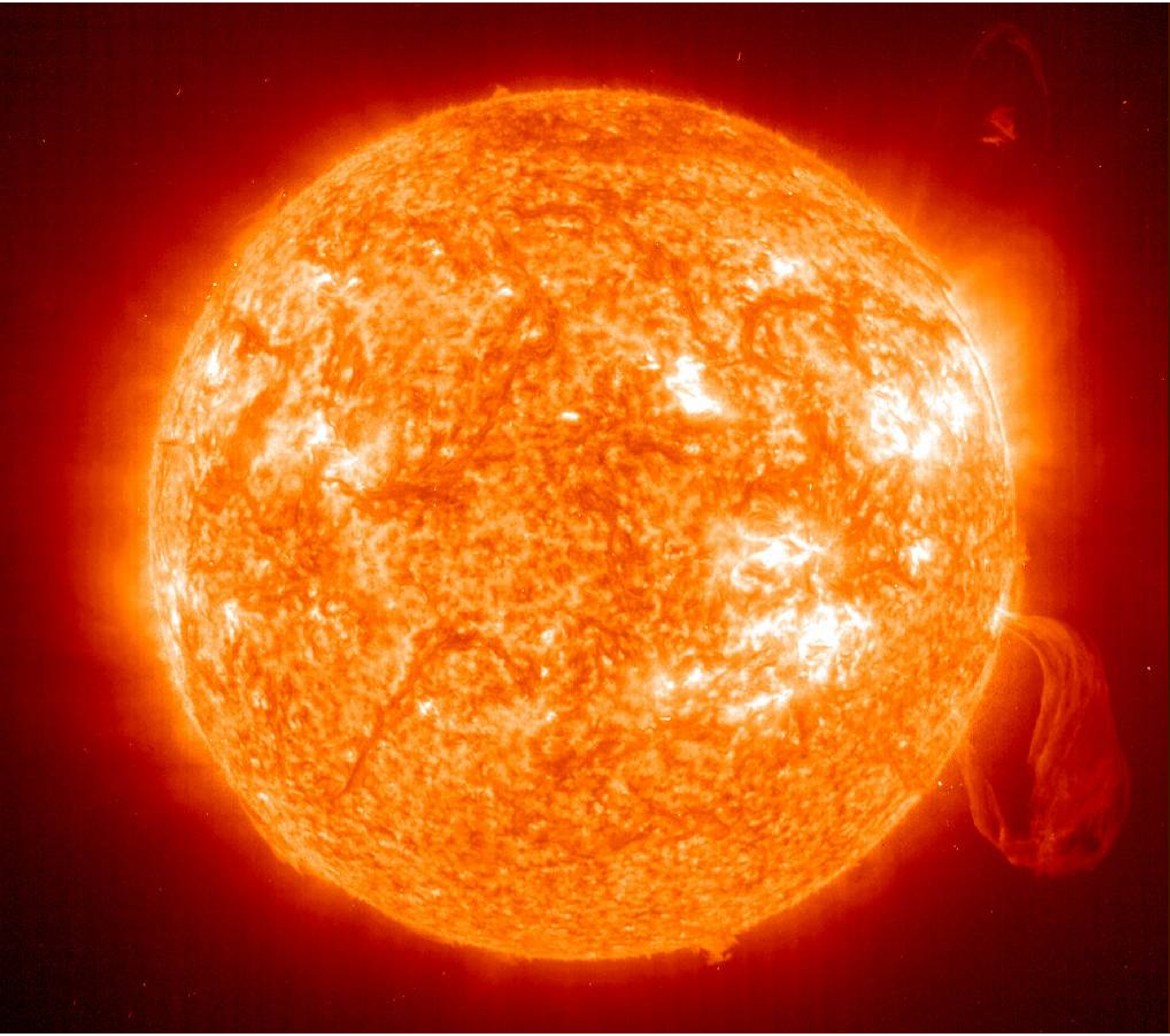
ACKNOWLEDGEMENTS

The following colleagues have kinldy contributed to this presentation:

- PSA-CIEMAT: Dr. Julián Blanco, Dr. Sixto Malato, Dra. Pilar Fernández, Dra. Esther Rojas, Ms. Inmaculada Cañadas and Dr. Eduardo Zarza.

- DLR-Stuttgart: Dr. Franz Trieb and Dr. Stefan Kronshage.

- AEE-INTEC: Dr. Werner Weiss



Thank you very much for your attention