FINAL REPORT

- publishable -

Contract N°: *ERK6-CT1999-00018*

EUROTROUGH II

Extension, Test and Qualification of EUROTROUGH from 4 to 6 Segments at Plataforma Solar de Almería

PROJECT COORDINATOR: Instalaciones Inabensa, S.A.

Project Partners:

INABENSA, SOLUCAR	**Sevilla, Spain**
IBERDROLA	**Madrid, Spain**
FLABEG Solar International	**Cologne, Germany**
Schlaich Bergermann und Partner	**Stuttgart, Germany**
CIEMAT	**Madrid, Spain**
DLR	**Cologne, Germany**
SOLEL	**Jerusalem, Israel**

REPORTING PERIOD: from October 2000 to December 2002
PROJECT START DATE: 1.10.2000 DURATION: 27 months
Date of Issue of this Report: April 2003

Project funded by the European Community
under the Non Nuclear Energy Programme (1998-2002)

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1 Executive Summary

Figure 1: EUROTROUGH-II prototype in test operation in summer 2002 at PSA.

The project **EUROTROUGH II** – “Extension, Test and Qualification of EUROTROUGH from 4 to 6 Segments at Plataforma Solar de Almería” has successfully demonstrated the feasibility of large solar parabolic trough collectors with an aperture area of 817.5m² per unit and has contributed to further cost reduction of this technology for large-scale solar electricity generation.

Under the actual global developments towards sustainable technology, clean energy and CO_2-emission reduction, a number of challenging solar thermal power projects are coming up. The successful outcome of the EUROTROUGH II qualification positions the European labs and industry in the leading field of high performance parabolic trough technology. The overall objective of the programme was to lower the generation costs of solar thermal electricity. The consortium partners are developing projects for 50 MW solar power plants in Spain and Greece. They will exploit the results of the EUROTROUGH II project to equip the solar fields with commercial scale EUROTROUGH collector loops.

With its performance of 60% annual thermal collection efficiency the EUROTROUGH II can collect at a site with 2300 kWh/m² annual direct normal radiation a 1300 thermal kWh per year.

Within the EUROTROUGH-II project the focus was mainly on the objective to extend the total collector length from today’s 100m state-of-the-art to 150m to reduce the number of drive pylons, tracking mechanisms, controllers and flexible joints of a solar field accordingly by 33% without performance losses.

The EUROTROUGH-II project included design, construction, test and evaluation for the extended parabolic trough collector design in order to qualify the performance of one representative half of a 150m EUROTROUGH-II collector. The focus of R&D was in the theoretical and experimental analysis of the performance of such a 150m parabolic trough collector under various insolation and wind load conditions and its comparison with the current LS3 and the 100m EUROTROUGH version.

Following tasks were accomplished:

- Development of concepts for 150m EUROTROUGH units, collectors and entire fields, the detailed design and engineering of the 2 segment extension at PSA and the detailed engineering for the LS-3 oil loop modification at PSA are finished; finite-element-method (FEM) for mechanical analysis of the collector support structure under dead and wind loads, and ray-tracing tools predicted effects of the structural design on optical performance.
- Workshop drawings and specifications are ready;
- Engineering, procurement and manufacturing of materials and components for the test loop extension, its documentation, assembly and start-up are finished;
- Collector manufacturing with the new design (EUROTROUGH-II) was finished; the extended prototype was assembled and started-up at PSA;
- Development of measurement methodology and procedures, identification of sensors, configuration of data acquisition system, test program definition are finished;
- Optical characterisation techniques of flux density measurement and photogrammetry for efficiency analysis were introduced;
- Thermal and mechanical testing of the EUROTROUGH-II prototype was successfully finished and evaluated;
- Techno-economic case studies have been performed;
- The final reports and technology implementation plan are prepared.
- Information from the project is available in the web: www.eurotrough.com.

The development of the EUROTROUGH collector, performed in two stages, supported by additional activities of several of the project partners, has been finished. With the effort of European industry and research partners and the financial contribution of the European Commission, the aim of a European solar parabolic trough collector has been reached.

2 Objectives of the project

The project EUROTROUGH II – "Extension, Test and Qualification of EUROTROUGH from 4 to 6 Segments at Plataforma Solar de Almería" successfully demonstrated the feasibility of 817.5m² large parabolic trough collector units with improved performance and reduced costs for large solar fields.

2.1 Socio-economic Objectives and strategic aspects

Solar energy is one of the sustainable and long term energy sources of the world. The current status of technological development allows first solar applications in niche markets for solar thermal systems and photovoltaics in small system sizes. One of the promising perspectives of the concentrating solar thermal power technology is large-scale power production from solar radiation. The EU directive for renewable energy systems 2001/77/EC passed the European Commission and will help towards market introduction with political means. The technological development of the solar power generation has its key players in Europe, basically in Spain, Germany, and Israel. The systematic analysis of the existing technology and stepwise improvement in parallel to the market introduction strategies were tasks of the partners in this project.

Under the actual global developments towards sustainable technology, clean energy and CO_2-emission reduction, a number of challenging solar thermal power projects are coming up. The successful outcome of the EUROTROUGH-II collector qualification results in EU-leadership in low-cost parabolic trough technology and has provided the project partners with the extended prototype to demonstrate their capability in this field when bidding in upcoming requests for proposals of Worldbank/GEF projects in the framework of the solar initiative. The overall objective of the programme was to lower the generation costs of solar thermal electricity. The consortium partners are developing projects for 50 MW solar power plants in Spain and Greece. They will exploit the results of the EUROTROUGH II project to equip the solar fields with commercial scale EUROTROUGH collector loops.

2.2 Scientific/Technological Objectives

Within the EUROTROUGH-II project the focus was mainly on the objective to extend the total collector length from today's 100m state-of-the-art to 150m to reduce the number of drive pylons, tracking mechanisms, controllers and flexible joints of a solar field accordingly by 33% without performance losses.

The EUROTROUGH-II project included design, construction, test and evaluation for the extended parabolic trough collector design in order to qualify the performance of one representative half of a 150m EUROTROUGH-II collector. The focus of R&D was in the theoretical and experimental analysis of the performance of such a 150m parabolic trough collector under various insolation and wind load conditions and its comparison with the current LS3 and the 100m EUROTROUGH version.

Technical goals of the project were improvements to the concentrating solar parabolic trough technology:

- Track with one central drive 6 instead of 4 collector segments of 12m length on each side, thus extending the collector unit length by 50%.
- Reduce installation cost below 200 €/m^2
- Have same or less average wind induced optical losses due to bending and twisting of the 150m EUROTROUGH collector as the 100m state-of-the-art LS-3
- Reach a maximum angular deviation of the most outward collector element of 6 mrad or less from the optimum tracking position for wind speeds up to 7 m/s.
- Reduce critical stress to mirror facets by a factor of 2.
- Demonstrate a thermal collector peak efficiency of 60% at a normal incident design radiation of 850W/m^2.

3 Scientific and Technical Description of the Results

The main result of the EUROTROUGH-II project is the solar parabolic trough collector shown in Figure 1 and Figure 2. Specific details of the results are

1. The ET150 collector design, the concept, workshop drawings, engineering
2. The ET150 prototype collector at PSA
3. The test and qualification results
4. Tracking controller, mirror fixation technique, and optical analysis tools

These results have been achieved during the 27 months of duration of the project. The work was based on the specific technological experience of the partners, and on the first phase, the "EuroTrough"-project, performed in the 4th Framework Programme between 1998 and 2001, and on the work programme of the EUROTROUGH-II project.

This parabolic trough collector for solar energy technology is the key element of large-size solar fields for solar power generation and process heat. Such solar fields are in preparation in various locations in Southern Europe and outside Europe for solar thermal power plants, e.g. the two ANDASOL projects in Spain, each with 50 MW of electric capacity.

Figure 2: EUROTROUGH-II prototype on termination of the assembly at PSA (Milestone M3) in March 2002. Structural elements (torque box, pylons, cantilever arms) are visible.

Results achieved during the EUROTROUGH-II project are in particular the performance improvements and cost reductions thanks to the extension of the collector length from 100m to 150m per unit, and more detailed experience with design issues and performance characteristics.

Further topics of the project were cost analysis, new absorber tubes, and case studies for technology implementation.

WP1 Coordination

Lead: Inabensa

The Spanish company Inabensa (belonging to Abengoa) coordinated this project. The coordination work package included information exchange, organisation of meetings, termination of reports, contact with the European Commission, and further financial and administrative aspects.

In addition to kick-off and final meeting a total of six project progress meetings were held. These meetings, together with specific task meetings served for the information exchange and update on work contents and schedule to the most recent status.

Regular progress and management reports, including mid-term and final reports, part of them confidential, as well as the Technology Implementation Plan (TIP) have been prepared in collaboration with the project participants and distributed to partners and European Commission.

WP2 – Development of concepts for 150m EUROTROUGH units, collectors and entire fields, the detailed design and engineering of the 2-segment extension at PSA and the detailed engineering for the LS-3 oil loop modification at PSA

Lead: SBP

The tasks of the second work package were based on the design and installation experience of the previous prototype at PSA. The results from the final design review and construction experience lead to major and minor modifications in the parabolic trough collector design. The concepts are result of an intense discussion of the involved experts from industry and research participants.

The main results of the working package WP 2 are the collector manufacturing drawings for the prototype extension at PSA. The issued workshop drawings include the lessons learnt from the production and assembly of the previous prototype at PSA, and the extension of the collector from 100 to 150 meters. Further developments have been made towards weight reduction with lighter steel profiles, easier assembly (cost reduction), and elimination of deficiencies.

On that base the detailed design was elaborated and the following deliverables were worked out: Specifications and Schedule of Quantities ET II (Deliverables D2 and D3), including:

- General system description
- Complete set of drawings
- Material and part list EUROTROUGH II
- Installation procedures
- Quality Control Measures
- Tender Documents, Piping Diagrams for Loop Modification

Additional effort was necessary for strong version collector design at the field edges (high wind loads). The wind tunnel tests showed that collector elements at the edge of the field have to withstand much higher load than collectors in the inner field.

Therefore the inner field (95% of the hole field) requires a “light” design, which is named the “field design”. For the edge of the field two possibilities were considered:

1. Increase of strength of torque box and pylons
   - Increase profile sections
   - Increase of steel grade
2. Reduction of loads
   - Wind fence
   - Reduction from 12 to 8 SCE per drive at the edge

The following decision was taken for preliminary field layout:

Field: Design with 12 SCE per drive combined with stronger drive pylons.

Field edges:
- Drive and Middle Pylons (stronger profiles) from ET I project
- 8 SCE per drive
- SCE design as provided in deliverable D2. Higher loading compensated with a decrease of the alarm wind speed

Advantages:
- Same mass as field version
- Same center of gravity
- Same SCE construction

Disadvantage:
- No uniform field layout
- Additional drive pylon

Within this working package, Flabeg Solar has evaluated the influence of deviations due to different wind loads on the performance of a collector field. High wind loads would cause bending and twisting of the collector structure, leading to decreased system efficiency.

The analysis of the design parameters influencing the efficiency of a concentrating solar collector shows, that optical quality of the concentrator is crucial to achieve cost effectiveness. Certain design parameters kept unchanged in this project: mirror reflectivity and receiver absorption have reached high quality in the industrial production for existing parabolic trough plants. Concerns in this project were related to the structural stiffness under dead load and wind load, and special attention of this work package and the interdisciplinary collaboration was on tolerances of the manufacturing and assembly.

High precision is reflected in high specific cost, while low precision results in low efficiency. Optimisation between both extremes was made in this project with structural analysis (finite element method FEM), and consecutive ray-tracing analysis. Basing on a number of load cases calculated by SBP engineers, DLR calculated in the design phase the improvements in optical intercept (percentage of reflected rays captured by the absorber tube) due to the design changes and weight reduction in the steel support structure of the trough modules. With the reduced deviations of concentrator facets mounting, an improvement in optical efficiency could be achieved. It turned out that the structural improvements significantly increased the collector efficiency for operation conditions.

The test loop at PSA had to be adapted to the requirements of the extended collector. More powerful pump and cooler capacity, piping modifications and control were designed.

WP3 Procurement and manufacturing of all materials and components for the EUROTROUGH collector extension, its assembly and erection, its permit, start-up, acceptance and cost monitoring.

Lead: Inabensa

After termination of the conceptual design and of the manufacturing drawings in the first year, the second year comprised the procurement and manufacturing for the extension of the collector at PSA.

Basing on the drawings prepared by SBP the steel parts were manufactured by Inabensa in the workshops. DLR took over the supervision and checks during the manufacturing. Reflector panels were made by Flabeg, and the absorber tubes by SOLEL.

The assembly jigs had to be modified according to the changed concept and geometry, and had to be checked.

The assembly was finished in March 2002, marking the milestone for the mid-term review by the European Commission.

The procurement of all materials and installation for the prototype installation at PSA was finished. This included also measurement equipment and further materials necessary for assembly start-up and testing.

All the material has been delivered to PSA and installed. This work was mainly performed by Inabensa. Additional effort on measurement and data acquisition was by Ciemat and DLR.

Within this working package, Flabeg Solar supplied the solar reflectors needed for the extension of the EuroTrough test-loop from 50 m to 75 m. Besides 50 conventional LS-3 reflectors, 20 special test-reflectors were provided to the Plataforma Solar. The new reflectors are designed by Flabeg Solar in order to reduce mirror breakage under high wind-loads.

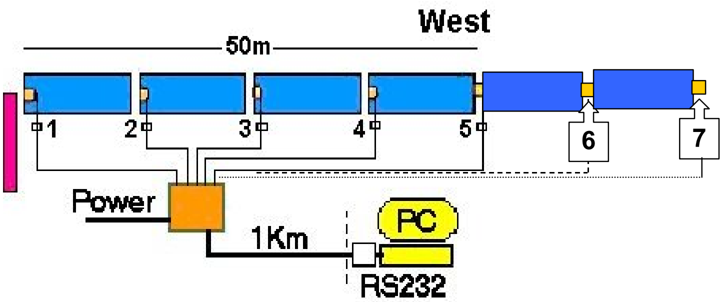


Figure 3: Schematic view of the SIMADISS-II angular measurement system installation at the EuroTrough collector

To perform the mechanical testing related to collector torsion of the new collector, Ciemat has acquired the equipment for the system based on angular encoders. Absolute angular encoders were chosen as they offered the highest resolution in the market (17 bits/turn or 0.003º/bit) and give absolute angular positions. Seven of these encoders were installed in the loop (one at every collector support; Figure 3). Several electronic devices for data reading and treatment have been manufactured, installed into metallic boxes and connected to a remote PC. The whole system is called SIMADISS-II.

Based on the performance and cost assumptions established during the first phase of the project, formats and procedures for a comprehensive cost evaluation were established by Flabeg Solar. In a second step, the manufacturing and erection cost of the collector extension were monitored in detail.

The following sections summarise the results of this assessment for the main cost items, the metal support structure cost and the installation requirements. The outcome of further evaluations were directly included into the evaluation of the solar field cost (see WP 4).

Collector weight analysis

The costs of the metal support structure are the major single cost item within the collector system. Since these costs are mainly determined by the kg price of the structural elements used, the weight of the EuroTrough II collector structure was evaluated in detail.

Like the LS-3 structure, one ET100 SCA (Solar Collector Assembly) collector consists of 8 SCE's (Solar Collector Elements) with a total length of 100 m. A first prototype of the ET100 collector structure was already manufactured, assembled and evaluated within the first phase of the project (see Final EuroTrough Phase I Report). However, the concept of the structural elements was reviewed during the second project phase, which resulted in a redesign of the structural elements.

Despite the weight savings for the ET100 collector, the main objective during the second project phase was the extension of the Solar Collector Assembly (SCA) to a total length of 150 m. Therefore, the final weight of the ET150 structure was analyzed in detail, as well.

Erection cost analysis

Besides the weight reduction, optimization of the erection procedure was a main objective of the EuroTrough collector design. Though anticipated higher before, only a small decrease in erecting time could be achieved during phase one of the EuroTrough project. One reason for this was the time-consuming installation procedure for the reflector brackets. Therefore, the design was changed during the second project phase in order to lower the installation time.

Since collector installation cost are a major cost item within the calculation of the solar field cost, installation time and manpower requirements for the EuroTrough collector were analysis in detail. For this, an itemized list of the different erection steps needed was established by FLABEG Solar. In a second step, this work was reviewed and accomplished by INABENSA and DLR, who were responsible for collector erection during phase one and phase two of the EuroTrough project. Finally both, erection steps and manpower requirements, were scaled up to full solar field size by FLABEG Solar and INABENSA.

The overall erection time could be reduced by about 20% . A main reason for this is the reduction of the mirror installation time, which could be reduced by 30% in the second project phase.

Obtaining the legalisation of the EUROTROUGH-II loop according to Spanish law and regulations was foreseen in the project planning. For this purpose the required documentation has been prepared in collaboration with Iberdrola and submitted to the Technological Development and Employment Department of the Autonomous Government of Andalucía. Within the documentation handed in, the hydraulic pressure test, carried out as part of the start-up and acceptance procedures of the ET system, was included.

WP4 Development of measurement methodology and procedures, identification of sensors, configuration of data acquisition system, test program definition and execution, operation and maintenance and evaluation.

Lead: CIEMAT

Figure 4: Extended prototype collector (ET150) in operation at Plataforma Solar de Almería

After the preliminary test campaign in the first year, the second project year included the main test program on the collector prototype at PSA.

These tests included:

- Thermal performance tests under numerous operating conditions, varying tracking offset, temperature and irradiation.
- Mechanical tests applying a torque load to the collector structures to measure the torsion of the frame work structure
- Stress measurement at the mirror fixing pads

- Optical analysis (photogrammetry) and raytracing, to analyse the achieved precision of the collector assembly
- Flux measurement in the focal region of the collector

Significant efforts during this period have been on operation and maintenance of the loop.

The operation itself has had no major differences in comparison with previous periods since the loop and control configuration both basically remain the same. The operation of the whole system with the two modules of the extension has not supposed a change in the operation methodology although some trials were carried out during the preoperational test with the more powerful pump and cooler.

Normal temperature levels in operation have been 100, 150, 200, 250, 300 and 350°C while the oil pump is set usually to 7.2 m^3/h. Only when very low temperatures are needed, higher flows are set. No vaporisation problems occurred since the inert gas pressure was always set to a minimum of 2 bar over the maximum oil vapour pressure.

The tracking control system already existing at the EUROTROUGH loop has been adapted to the needs of the new 150m EUROTROUGH collector. Named EuroTrack2000, this local control abandons the traditional tracking control with solar sensors, and implements the innovative concept of positioning the collector accurately knowing the position of the Sun (by means of astronomic calculation algorithms and the determination of the set point for the perfect orientation of the collector) and the angular position of the collector (by means of an absolute optical encoder).

Thermal testing

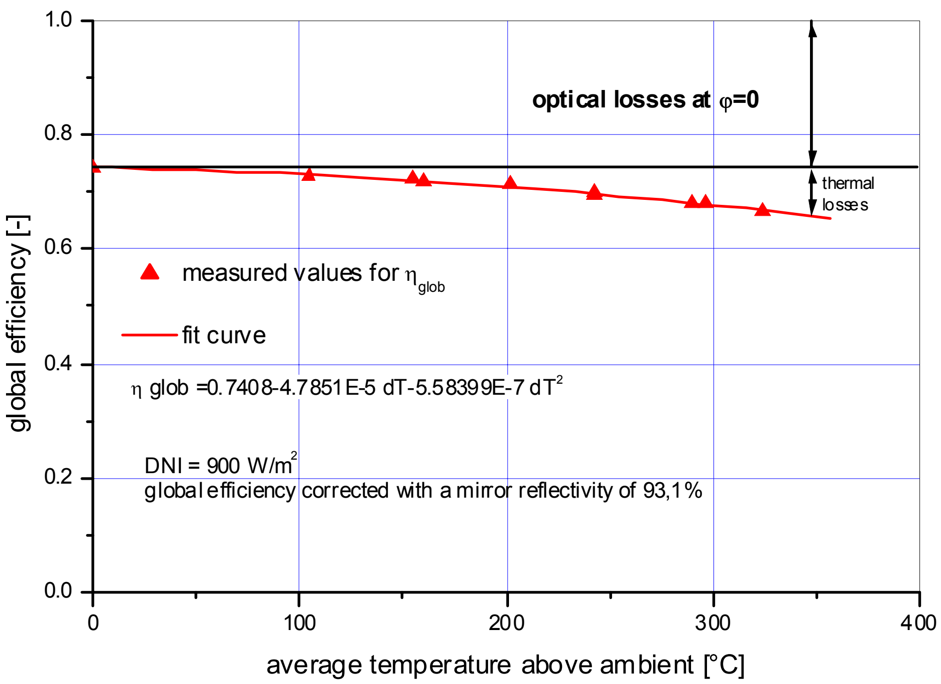


Figure 5: Measured global efficiency of the EUROTROUGH-II Collector at PSA at normal irradiation

The first test series served for the determination of the base case: the previously prepared EUROTROUGH collector with its 50m-prototype. The results showed the success of the development work of the previous project and served for comparison of the achievements in the EUROTROUGH-II project.

After the construction of the collector extension (prototype length 75 m) and change of the absorber tubes to the new Solel UVAC-tube prototypes, the new test series were executed to confirm the improvements. Because the prototype was not renewed, but only extended, the test results of this project represent a mixture of qualities of the previous design and the current design. Nevertheless, the results show improvements. The presented graphs are an extract of the results from the test evaluation.

The graphs refer to the tests performed in the second test campaign in 2002 with the 75m long extended prototype.

These tests were performed with clean mirrors, a direct solar radiation of about 900 W/m^2 at solar noon and a volumetric flow of 13-14 m^3/h. Because no thermal losses exist for a fluid temperature of 0 K above ambient temperature the global efficiency is equal to the optical peak efficiency in this point. An optical peak efficiency of 74.1% is reached. The higher the temperature above ambient the more is the decrease of the global efficiency due to thermal losses of the receiver. At 350 K above ambient a global efficiency of 65.6% is measured. The polynomial fit curve is given in Figure 5.

Optical peak efficiency

The optical peak efficiency is a fixed value and does not depend on the collector operation conditions (see test report). Only the cleanness conditions of the mirrors and the glass tube affect the optical performance. Due to the fact that the mirror reflectivity is a realistic indicator for the collector cleanness state, the optical peak efficiency dependence from the mirror reflectivity was measured.

The determination of the optical peak efficiency by experiments was done according to the test reports. The maximum optical efficiency of 74.1% was measured after a cleaning of all collector mirrors and glass tubes.

Thermal losses

Thermal losses were measured in several tests at different average collector temperatures above ambient.

Incident angle modifier

Several tests at different incident angles were done in order to find the dependence of the incident angle modifier from the incident angle.

A better thermal performance of the EUROTROUGH-II collectors was measured for both cases: the focussed collector and the non-focussed collector. This fact was expected because the emission coefficient in the infrared range of the EUROTROUGH II absorber tubes (SOLEL UVAC) is not as high as the emission coefficient of the EUROTROUGH I absorber tubes (SOLEL HCE).

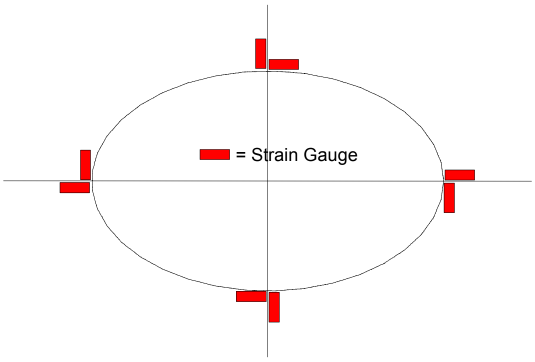
Actually, the thermal losses of the focused EUROTROUGH II collector are about 20% lower than the thermal losses of the focused EUROTROUGH I collector. The thermal losses of the non-focused EUROTROUGH II collector are about 30% lower than the thermal losses of the non-focussed EUROTROUGH I collector.

Mechanical testing

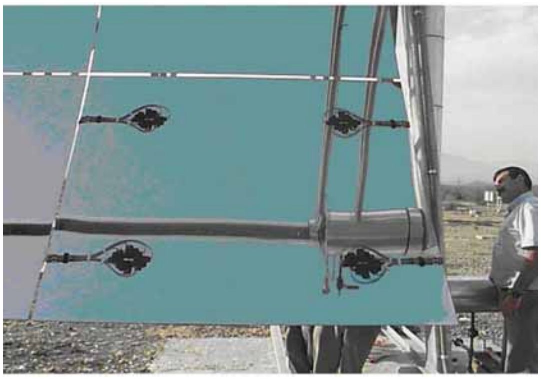
One of the main objectives of this task was to determine, experimentally, the structural deformations and deviations of the EUROTROUGH-II collector under real and simulated wind load conditions. A complete system for measuring collector torsion, called SIMADISS-II, has been developed and constructed by the Technical Department of the PSA.

Another main objective of this task was the identification of the maximum wind loads that the mirror facets can stand without suffering destructive vibrations and/or deformations.

In order to obtain real measured data of stress levels in the glass mirror surface, Ciemat instrumented a facet with several strain gauges. As critical tensions were expected in the glass mirror close to the pads one mirror facet was equipped with 8 strain gauges (Figure 6a) on its front side at every pad position. As every facet has 4 pads, a total of 32 strain gauges were installed. VISHAY strain gauges, model CEA06-250-350, were used with a *quarter-bridge* connection.



(a)



(b)

Figure 6: (a) Strain gauges positioning around mirror pad. (b) Final installation view

The instrumented facet was mounted at one of the outer edges of the collector EUROTROUGH I (Figure 6b) before mounting the two modules for the extension in EUROTROUGH II. All the wires were connected to the DAS by means of IMP Solartron electronic cards. Each of these cards supports ten strain-gauge channels and can read them one time per second.

Optical assessments

The optical quality has been identified as a major parameter for the efficiency of the parabolic trough collector. After manufacturing difficulties, long procedures for adaptation of jigs and accurate assembly procedures, it was still not obvious, whether the specified accuracy from the drawings had been fulfilled during the manufacturing or not.

Since the beginning of the project, based on the manufacturing experience of the previous project phase, the possibility of 3-dimensional geometry evaluation of the fabricated collector was planned. In a collaboration project at PSA with an expert from Australian National University from the field of concentrating solar technology, the methodology of Photogrammetry has been applied. Photogrammetry is a photographic technique using triangulation for the measurement of marked measurement points in the object space. Digital photography and modern computer analysis tools are used. Engineering consultants for this application offer their service for standard tasks, but not for the surface of concentrating collectors. Previous investigations had shown the applicability of photogrammetric characterisations to solar concentrators over a large range of physical dimensions (M. Shortis, G. Johnston).

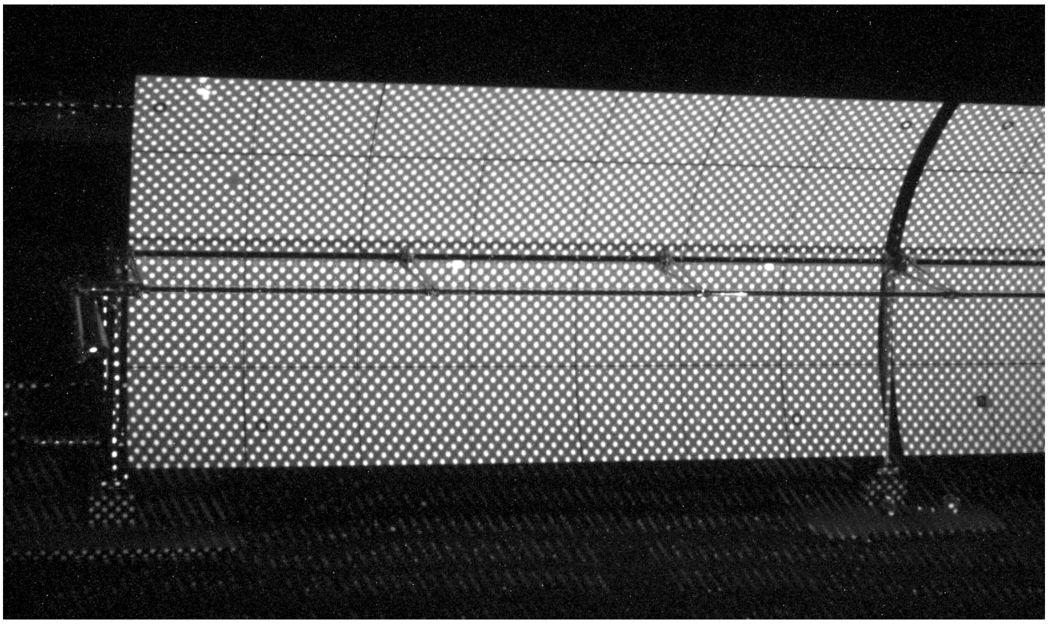


Figure 7: Photo of a EuroTrough collector segment with circular targets for photogrammetric assessments.

The photogrammetric studies of the EuroTrough prototypes existent at the end of the EuroTrough-I project phase was performed at PSA in March 2001 as part of the project activities.

The resolution of the photogrammetric method made it very suitable for the characterisations of the EuroTrough parabolic trough concentrators. The spatial accuracy of the 3D-measurements for a trough module was in the order of 0.2 mm, although the overall accuracy of any characterisation was very dependent on the stability of the camera during the photography. Investigations undertaken on single facets demonstrated object-space resolutions down to approximately 10 micron.

Figure 7 shows a typical photo of one collector module, targeted with more than 3000 circular dots for surface characterisation. The results of the analysis were compared to the ideal parabolic shape of the design and gave information about the accuracy achieved in the assembly of the modules and about the deformation due to sag under dead load. The findings lead to some specific design improvements. The method is being further improved and applied in follow-up activities of the consortium partners.

Flux density measurement

Parabolic trough collectors concentrate the solar radiation on a long focal line. The achieved concentration factor is related to the diameter of the absorber, and to the efficiency of the collection. Deficiencies in precision, deviations of the geometry, e.g. due to wind load can provoke spillage of radiation past the absorber tube. The measurement of the solar flux density is common in solar tower applications, where the focus is small and compact, for the analysis of the energy in the focal region. For the parabolic troughs this task is quite difficult. The reasons for the difficulties are the low concentration and thus the large dimensions of the focus over the whole collector length, and the large rim angle of the radiation with a short focal length. Due to the presence of the absorber tube in the focus, a measurement of the radiation in the focus is impossible. Analysis of the flux density in the vicinity of the absorber is the only opportunity to gather information about the focus. During this project it was deducted that the radiation, which is not intercepted with the absorber tube – the lost amount of energy – is a quantity that can be measured in a specific configuration.

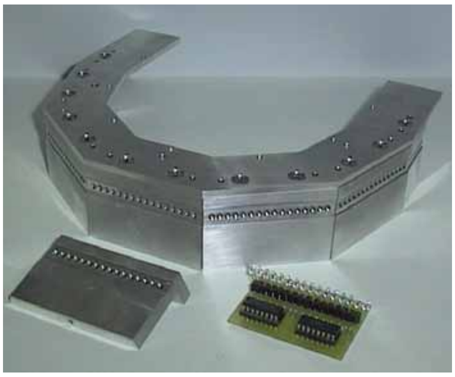
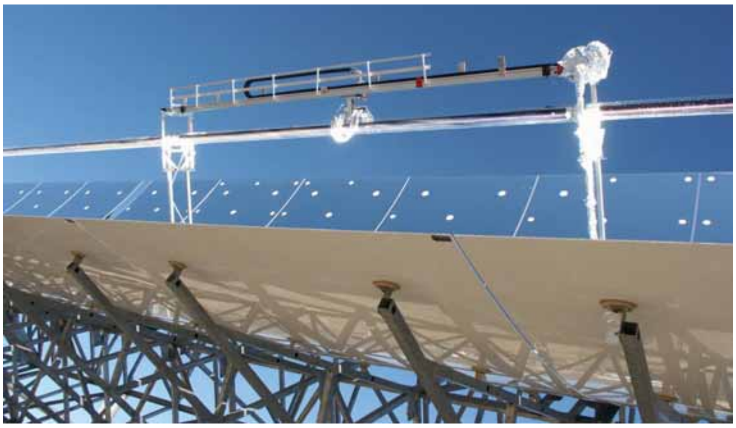



Figure 8: Diode array (left) and carriage assembly on the EUROTROUGH collector (right)

This configuration has been developed and applied by DLR in the EUROTROUGH-II project. Two arrays of photodiodes on a moving carriage around the absorber tube measure the amount of incoming radiation and the amount of radiation spilled behind the absorber tube. Figure 8 shows the tailored diode array and its assembly on the absorber of the EUROTROUGH collector. A patent has been applied for.

Evaluation of Solar Field Performance and Cost

The main objective of Phase two of the EuroTrough project was to further improve the collector design of phase one. This effort should further reduce the solar field cost and consequently lower cost of solar thermal electricity generation. Within this working package, the findings of the prototype manufacturing, erection and evaluation were summarized and scaled up to full solar field size. This work was mainly carried out by applying the FLABEG Solar's performance and cost models. For this both, the performance model and the cost model had to be largely modified and extended in order to incorporate the EuroTrough collector system with a total length of 150m.

a) Solar Field Performance Evaluation

In conjunction with the work carried out within WP 2.1 “Conceptual Design”, structural and ray-tracing analyses of the EuroTrough collector were performed by SBP and DLR to determine the effect of wind load on the optical quality of the collector. From these analyses equations were developed, which gives the effect of the wind speed and velocity and the collector position on the intercept factor. The FLABEG performance model was adopted to consider these effects and the new correlations were incorporated in the model.

The detailed performance analyses showed that the EuroTrough collector performs only 0.6% below the ideal performance of a perfect collector, which is not effected by any wind loads. The economic analysis shows that about 6% of the metal support structure cost can be invested to make the EuroTrough collector more rigid so that wind loads would not effect the performance.

b) Solar Field Cost Evaluation

Based on the cost monitoring carried out within working package 3.5, the investment costs of the EuroTrough collector were analysed in detail. There are two reasons for the cost reduction: First, the reduced amount of components needed for a 150 m system (like the hydraulic systems, control units, sensors etc.) and secondly, the cost reduction of single components used for the EuroTrough collector system. E.g. the total cost of the metal parts needed for the one EuroTrough SCA with 100 m length could be reduced by 15%. The main reason for this being the lighter structure (between 13 and about 16% as explained above) and, with this, lower material and manufacturing costs.

As in phase one of the project, no cost reduction could be achieved for the 100 m EuroTrough hydraulic drive system. However, since the EuroTrough hydraulic drive system is also capable to supply higher forces, the higher number of SCE’s needed for the 150 m SCA will no increase the hydraulic system cost any further.

According to the evaluation of manpower needed for the collector erection, installation cost could be reduced by 19.5% for the 100 m, respectively 22.4% for the 150 m system.

Other piping & civil works costs are similar for both - LS-3 and EuroTrough - 100 m collector systems. For the 150 m EuroTrough collector, the reduced number of SCA interconnections was accounted for.

Because of the overall reduction of the metal support structure weight and the more condensed packing, freight and transport cost are reduced for both EuroTrough systems.

Besides the reduction of investment cost, addition operation and maintenance cost savings are expected for the EuroTrough solar field. The main reasons for this are the easier mirror cleaning and less complex realignment requirements due to the new HCE support. Furthermore, the new reflector attachments and the reduced number of components (e.g., drives systems and interconnecting piping) needed due to the longer collector length will lead to lower maintenance and replacement requirements.

WP5 Techno-economic case studies, definition of exploitation and technology implementation plan.

Lead: Inabensa

Results of the techno-economic case studies for EuroTrough application

FSI has conducted two case studies applying the 150m EuroTrough design, one for a site in Europe with private project financing under a legal framework that give premiums to renewable electricity, the other for a site in a developing country with a GEF grant covering the incremental costs. These case studies are complementary to the one addressed in the previous project EuroTrough.

IBERDROLA has provided cost data for conventional equipment and components, as well as their performance characteristics. Solúcar has obtained competitive offers for those elements, of which high numbers are required in a solar field.

Case Selection

For the first case a parabolic trough solar power plant located in the Andalusian province of Granada (Spain) with a 50MW steam cycle and no thermal storage was selected. In the following this steam cycle plant will be referenced as “Guadix” The detailed description is in chapter *Spain*, the parameter for the analysis are given in chapter *Evaluation and comparison.*

For the second case an Integrated Solar Combined Cycle System (ISCCS) designed for a site in south of Mexicali in Baja California Norte in Mexico was selected, which is supported by the Global Environmental Facility. For detailed description see chapter *Mexico* and for the parameters see chapter *Evaluation and comparison*.

Descriptions of the selected power plant

a) Spain

Solar Steam Cycle Configuration

The schematic drawing below illustrates the solar steam cycle configuration as used in the Californian Solar Electricity Generating Systems (SEGS), showing the solar field, where solar radiation is concentrated and collected, the storage system as option and the power conversion system.

In the direct operation mode, the HTF is circulated through the solar field where it is heated and supplied through a main header to the heat exchangers located in the power block, where superheated steam is produced at a temperature of 370°C and a pressure of 100bar. After passing through the HTF side of the heat exchangers, the cooled HTF is then re-circulated through the solar field to repeat the process. In this way, the HTF fluid acts as the heat transfer medium between the solar field and the power block of the steam cycle, heating up in the solar collectors and cooling down while producing steam for the steam generator. The superheated steam is then fed to the high-pressure (HP) casing of a conventional steam reheat turbine. The steam is reheated before being fed to the low-pressure (LP) casing. The spent steam from the turbine is condensed in a conventional steam condenser and returned to the heat exchangers via condensate and feed-water pumps to be transformed back into steam. With this process, the collected and concentrated solar radiation from the solar field is converted into electricity and afterwards fed to the general power supply.

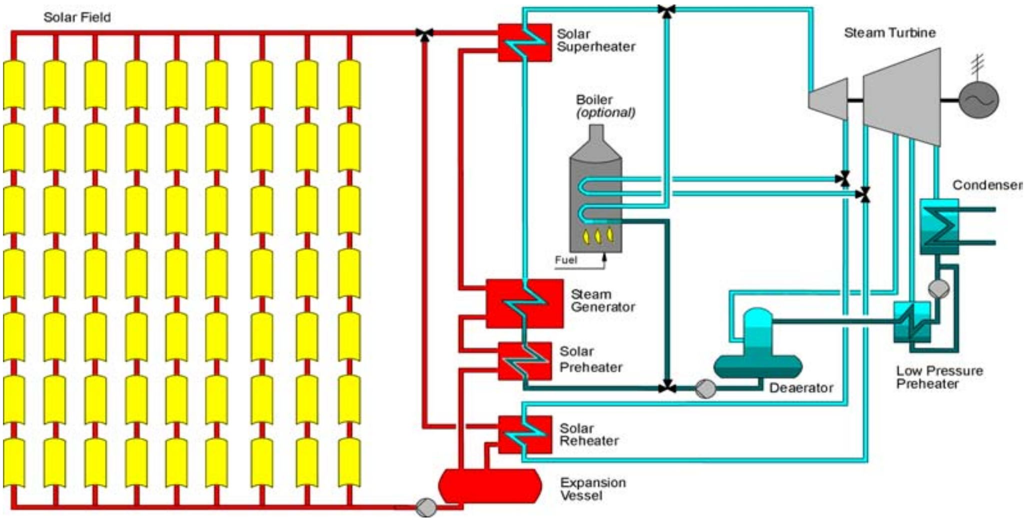


Figure 9: Process Flow Diagram of the SEGS Project with Parabolic Trough Solar Field

<u>Description of the Site</u>

For this study it was assumed to implement the Guadix plant in the high valley of Marquesado de Zenete in the Andalusian province of Granada. The Marquesado de Zenete is a wide valley north of Sierra Nevada, approximately 60 kilometres south-east of Granada (see attached map) elevating from 900 to 1100m. It is one of the most elevated and extended plateaus on the Spanish peninsula, with an average altitude of its municipalities of more than 1000m above sea level. It connects the Guadalquivir valley with the Mediterranean Sea.

b) Mexico

<u>Integrated Solar Combined Cycle Configuration</u>

The plant concept investigated for the integration of solar energy, known as the Integrated Solar Combined Cycle System (ISCCS), is derived from a conventional combined cycle design in which the exhaust heat from the combustion turbine generates steam in a heat recovery steam generator (HRSG) to drive a steam turbine connected to a generator, with supplemental heat input from the solar field to increase the steam to the steam turbine. The ISCCS combines mature gas turbine/steam turbine technology with mature solar parabolic trough technology.

A combined cycle plant operates on the Brayton cycle, and modern combined cycle plants can achieve thermal efficiencies over 55%. This compares to a fossil-fired project where fuel is fired in a boiler to produce steam to drive a Rankine cycle plant at an efficiency on the order of 40%. Solar-produced steam can be used more effectively in a combined cycle, and the heat rate of the combined cycle plant may be improved by the use of solar.

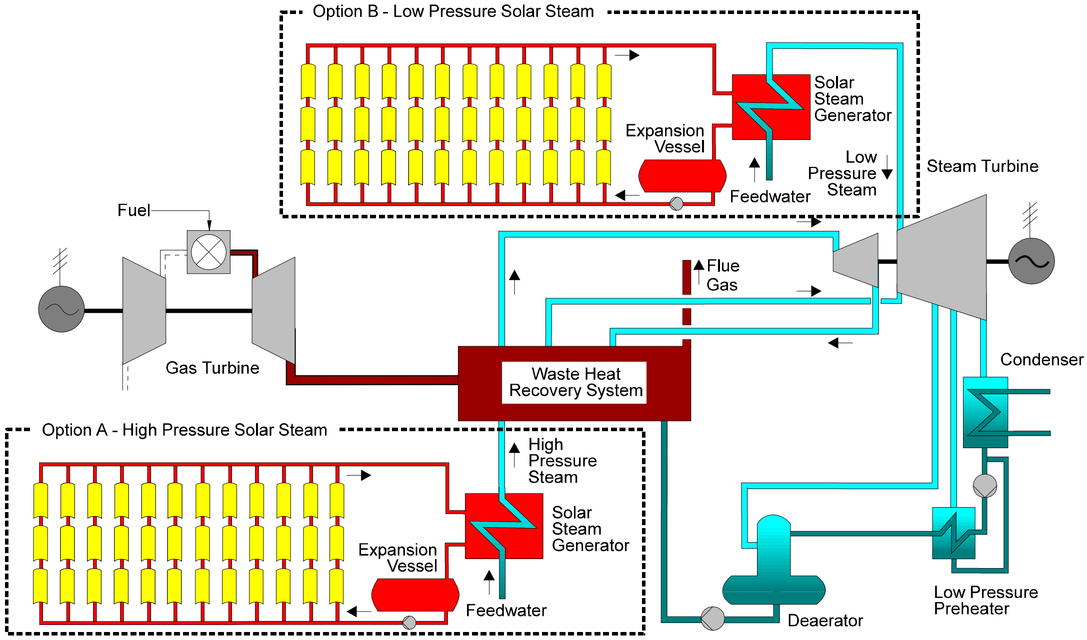


Figure 10: Process Flow Diagram of the ISCCS Project with Parabolic Trough Solar Field

Description of the Site

Solar radiation in the Baja California Norte region is excellent. An extensive review of existing data was undertaken for the area to select typical data for performance projections, making use of available Typical Meteorological Year (TMY) data and satellite data developed by NREL and others. From this, a typical year of direct normal insolation (DNI) consisting of hourly radiation data was established for the study.

Guided by CFE preferences, a site was chosen close to the Cerro Prieto geothermal plant facility south of Mexicali in Baja California Norte.

The overall slope of the land is less than 1%, lessening the cost of grading.

Cooling water, makeup water, and general use water are anticipated to be provided from the spillover from the existing Cerro Prieto geothermal plant cooling system.

Case analysis

a) Methodology

As key figures the levelized life-cycle cost, or **L**evelized **E**lectricity **C**ost (LEC) are used to characterize the economic viability of a power project.

In general, levelized life-cycle cost is the present value of a resource's cost (including capital, financing and operating costs) converted into a stream of equal annual payments. By levelizing costs, resources with different lifetimes and generating capacities can be compared.

In power projects, the LEC's are computed from three main cost parameters:

- cost of investment
- cost of Operating and Maintenance (O&M)

- cost of fuel

b) Evaluation and comparison

Using the described model and the input from the partners as well as the data of the EuroTrough II design with 150 m length the costs of the projects have been collected.

Cycle design studies

A detailed lay out study using the Gate cycle code was performed by IBERDROLA. Improvements and design optimisations are suggested. This could be used to perform further iterations in the economical analysis. The complete cycle design study is in the appendix.

Technology Implementation Plan

Coordinated by Flabeg Solar, a detailed Technology Implementation plan was developed by the partners of the EuroTrough consortium during phase one of the project. Based on this document, an updated Technology Implementation plan was prepared by Flabeg Solar for the second phase of the project. The final version of the Technology Implementation plan has been submitted to the European Commission via Cordis-Server in electronic database format (eTIP). Results will become available on the Server (www.cordis.lu).

4 Results and Conclusions

The development of the EUROTROUGH collector, performed in two stages, supported by additional activities of several of the project partners has been finished. With the effort of European industry and research partners and the financial contribution of the European Commission, the aim of a European solar parabolic trough collector has been reached.

The prototype of the EUROTROUGH collector has been prepared, started-up, operated and evaluated in detail at the Spanish Plataforma Solar de Almería (PSA). The further results of this project were the design and engineering documentation and workshop drawings for EUROTROUGH collector manufacturing and assembly. The qualification at PSA included thermal tests, mechanical analysis, optical assessment and design improvements as results of the prototype experience.

During the project the designers and scientific partners have shown special activities in the field of optical and mechanical analysis and qualification of the collector design. The eager search for highly efficient, robust and mature technology has brought up side results concerning finite-element-analysis (FEM), ray-tracing, flux density measurement, and photogrammetric structure analysis, here mechanical analysis of the collector support structure under dead load, wind load, and the effects on optical performance.

The results of the case studies and cost analysis will help with the next steps during technology implementation in the international energy market.

Current status of the technology

The EUROTROUGH design has been initiated in the 90s, well ahead of other new developments in the solar power market. Meanwhile, companies like NEVAG, Germany, DukeSolar (now: SolarGenix), USA, and Solarmundo, Belgium, have been reporting on solar collector development activities. It can be stated, that the EUROTROUGH collector is the most successful development in terms of proven performance, reliability and costs.

In general the interest in solar power is increasing on European and international level. The EUROTROUGH collector design has the potential to play a key role in the deployment of solar power worldwide.

The feed-in law with tariffs for solar thermal electricity has been approved in Spain in August 2002. An incentive premium of 12 cts per kWh will be granted for solar thermal power plants up to 50 MW nominal power. This incentive has launched the development of the largest solar thermal power plants in the world, the two AndaSol projects with 510’120m² solar field each; the first project AndaSol-1 will receive financial support from the 5th Framework Program under Contract NNE5-2001-00560. The Solar Millennium group as developer of the AndaSol projects has foreseen to implement the EuroTrough technology, which has been further enhanced and qualified for commercial operation in 2003 with the financial support of the German Ministry and the participating industrial partners in the full size SKALET Demonstration loop at Kramer Junction.

Contribution to EU policies

European cohesion between favoured and less favoured regions was enhanced by the EuroTrough consortium: Light weight structural engineering of SBP Germany was manufactured and assembled with the experience INABENSA/SOLUCAR at the unique facilities of Ciemat's Plataforma Solar de Almería in the less favoured region of Andalucía (Spain). Power plant engineering know-how of the German engineers is complemented by the users perspective of a Spanish utility interested in building a commercial parabolic trough plant in Spain. A key component, the solar reflector, comes from FLABEG in Germany. SOLEL, Israel, developed and delivered the absorber. The R&D expertise of the Spanish CIEMAT and the German DLR seamlessly joins at the PSA. European cohesion will continue in the envisaged commercialisation phase of parabolic trough plants. Solar electricity implementation in Southern European member countries will contribute with its significant investment and job creation to the regional development.

It has been demonstrated in California, that parabolic trough systems are among the most cost effective renewable power technologies. The parabolic trough technology is now ready for more widespread application. The industrial development of a European parabolic trough technology had a strategic role for the competitiveness of European solar equipment suppliers in the upcoming solar thermal projects initiated by the Worldbank's Solar Initiative and the Global Environmental Facility (GEF). It was a strategic step for the European industry to become fully capable to design, manufacture and offer the presently most mature and competitive solar thermal technology - parabolic troughs. The fulfilment of the objectives of the present project succeeded in improved competitiveness of European industry and stimulates follow-up initiatives in technology development and implementation.

The Kyoto objectives imply for EU a short-term reduction of CO_2-emissions. This is the driving force for the development of new technologies, innovation and associated measures. The EU directive 2001/77/EC for doubling the share of renewable energy systems to 12 % in 2010 will help towards market introduction with political means. This solar power technology fulfils the exigencies of the European White Paper of 1997 and of the European directive 2001/77/EC to introduce renewable energy for greenhouse gas mitigation in an efficient and environmentally and socio-economically compatible and beneficial way in Southern Europe and elsewhere in the world. With the opening and deregulation of the internal community electricity market, a trans-national competition among renewable electricity producers will take place, where a producer from anywhere in the community will be able to sell his green power to a costumer at any other location in the community.

With the EuroTrough-II project results, the partners have committed themselves to contribute significantly to the social objectives the EU: The realisation of EuroTrough projects will contribute to improve the quality of life in the region, by creating new job opportunities, improving the local energy infrastructure, avoiding emissions, protecting the climate and environment, preserving the fossil fuel resources and reducing import needs.

The erection and operation of the AndaSol projects in Southern Spain will create numerous job opportunities in the region and permanent qualified jobs. The production of collectors requires massive investments in fabrication facilities for high production volumes. After successful market introduction, the industrial partners will operate production lines of the solar field and storage components in Europe. Assembly and erection will be close to the utilisation areas in the Mediterranean and will enhance co-operation with the Southern Mediterranean neighbours. 400 direct jobs are created with a production capability of 500'000m²/year in Europe; another 1000 construction jobs are created in the client countries for the erection of these systems. This will contribute to improve the economic and social conditions of the less developed regions in Europe and its Mediterranean neighbours.

A EuroTrough solar field can supply 2000 to 4000 (with storage) full load hours per year to a steam cycle. With EuroTrough technology, each square meter of solar field can produce up to 1200 kWh of thermal energy per year or over 400kWh of electricity per year. Taking into account the average European CO_2 emissions of 1 kg per kWh electric, there results a cumulative saving of 10 tons of carbon dioxide per each square meter of solar field over its 25 year lifetime. This emission avoidance protects our climate and preserves our environment. Similarly, EuroTrough preserves the fossil energy resources: Taking into account the average European conventional power plant efficiency of 40%, there results a cumulative saving of 2.5 tons of fossil fuel per square meter of solar field over its 25 year lifetime.

5 Acknowledgements

The financial support of the European Commission under the 5th Framework Programme, Contract No. ERK6-CT1999-00018, and of the involved partner institutions is gratefully acknowledged.

Thanks to the construction team from Sevilla, the operation and maintenance teams of the EUROTROUGH-Facility at PSA, and to the administration staffs involved in each of the participating organisations.

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