

Final Report  
May, 2004

**Installation and monitoring  
of parabolic type concentrating  
Solar Cookers**

**Presented by Golo Pilz  
on behalf of the  
Global Hospital and Research Centre (GHRC)  
and the World Renewal Spiritual Trust (WRST)**

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# 1 Responsibilities

The body responsible for the project is the

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*Eng. Jürgen Birnbaum ( cand. M.sc.Energy Systems) for doing the major part in energy calculations.*

J. M. Engineering, Ahmedabad, *for supplying receivers and tanks*.

and many others too numerous to mention who have tirelessly helped with setting up and maintaining the system, data collection and processing and the preparation of this final document.

### 3 Summary

Solar cooking is one of the most interesting applications in the field of renewable energies. During the last twenty years many designs and concepts have been developed and tested, especially in the field of family cooking. Solar cooking boxes and small concentrators are available in most developing countries to help reduce the consumption of costly kerosene, gas or firewood. However, the problem of heat storage has not yet been satisfactorily solved and this is one of the reasons that solar cookers are not yet in everyday use.

In 1995, the World Renewal Spiritual Trust (WRST) and the Brahma Kumaris tested with the help of GTZ, Germany, two parabolic concentrators for institutional cooking at the Academy for a Better World in Mt Abu, Rajasthan, India.

The concentrator was originally designed by Wolfgang Scheffler, a pioneer in solar cooking, and is meanwhile manufactured in various places in India. Since then the parabolic dish has undergone several improvements.

As a result of positive tests at the end of 1995, a proposal for a solar steam cooking system for 1000 people was forwarded to GTZ. The proposal was approved at the beginning of 1996 and successfully installed in 1997 at the Academy in Mt Abu.

The steam cooking system in the Gyan Sarovar academy uses 24 concentrators of 7,2 m<sup>2</sup> size to focus the sunlight on 12 receivers. The collected energy is transferred to a solar steam generator by means of a primary water circulation line. From there, steam is transferred by pipe to the kitchen, for cooking and preparation of tea.

In case of low solar radiation or extra demand, a highly efficient back-up steam generator, fuelled by kerosene, provides steam.

The system has been operating from the beginning without any major problem and has reached the theoretically calculated maximum steam output of 600 kg steam per day. The daily availability of the system is good. The whole solar cooking system is being operated and maintained by two local staff members.

In view of the positive experiences with the steam cooking system in Mt. Abu, the Brahma Kumaris/ WRST complex in Shantivan, Talheti, Abu Road

considered introducing a similar but bigger system for its premises. In November 1997 the planning and design for a solar steam cooking system for 20,000 meals per day started.

The system in Shantivan consists of 84 parabolic concentrators and is designed to generate 3500 kg steam per day. The surface of the parabolas has been increased from 7.2 to 9.2m<sup>2</sup> and a new receiver has been designed and successfully tested. The steam is generated in a header pipe above the receivers and the whole system works without a pump by means of a thermo siphon.

The combination of the solar steam cooker with a conventional back-up system (generating steam with kerosene) provides 24 hours of steam on demand. This has created wide acceptance of the system by the kitchen staff.

As the Shantivan Complex has nearly 200,000 visitors per year from all over India and abroad the demonstration and distribution of information is excellent. As the system is modular in size and application, several companies and institutions have already shown interest in the technology.

Since then, the Brahma Kumaris and WRST Solar Department have continuously developed and improved the solar steam cooking system.

Meanwhile further Systems have been installed successfully in the Brahma Kumaris Yellapur Complex (10 dishes), the Brahma Kumaris Om Shanti Retreat Complex, in Maneswar near New Delhi (20 dishes) and the BK Headquarters in Mt. Abu (6 dishes).

For the Global Hospital and Research Centre (GHRC) the dish size has been increased to 12.6 m<sup>2</sup>. Furthermore the overall design has been modified. Instead of a Header pipe above all the receivers, a steam tank has been introduced in order to increase efficiency and reduce heat losses.

In the GHRC system a new tracking system has been introduced and all the dishes are connected by means of stiff aluminium square tubes. The dishes are tracked by one DC motor and a gear system.

## 4 Goals

The main goal of the project is the transfer of technology, the demonstration of such a system with an improved design and the evaluation of the efficiency of a solar steam system of this size under practical conditions.

GHRC, being located in Mt. Abu itself, will be the first Hospital to be equipped with a solar steam cooking system and also make use of this steam for additional purposes like sterilization and laundry. The hospital has 100 beds and conducts regular seminars for Hospital administrators/doctors and nurses and thus a good demonstration effect of the system can be expected.

Another important aspect of the project is the adaptation of all the improved and redesigned components such as the increased dish of 12,6 m<sup>2</sup>, new steam tank, layout of steam generators and tracking system.

### **Areas of special interest in this project are:**

- Increased dish size / improved layout
- Improved steam storage / new tracking system
- Standardization of the overall design

It is necessary that all the experience of the previous projects will be used to further improve the manufacturing process and ensure that all improvements and positive results of the project will directly enter the manufacturing process.

The WRST/Brahma Kumaris have already established a vast expertise in the field of solar community cookers through the previous solar steam cooking projects in Mt. Abu, Taleti, Yellapur and Delhi and its collaboration with MNES, the IIT Delhi, the company HTT, the Institute für Solare Energie Versorgungs Technik (ISET) and the GTZ.

As Brahma Kumaris have networked extensively with various partners it will be easy to communicate the experience of this project to all the interested organizations.

By this, all future manufacturers and users of the solar dish cooking system will greatly benefit from the outcome of this project.

## 5 Project Description

**The Title of the Project is**  
**“Installation and Monitoring**  
**of parabolic type concentrating Solar Steam System”**

The Project duration is one year

Wolfgang Scheffler of Switzerland originally developed this type of parabolic concentrator in the '80s. Since then the parabolic dish has undergone several improvements. The solar steam system at the Global Hospital and Research Centre is basically a further development of the solar steam cooking system of the Brahma Kumaris at Om Shanti Retreat Centre in Delhi.

As the solar radiation in Mt. Abu is excellent, a system of this size is expected to generate approximate 900 kg of steam per day.

This will be used as per the following formula:

300 kg steam for food cooking (600 meals per day)

300 kg steam for sterilizer (2 –3 shifts per day)

300 kg steam for laundry

In this latest version, the parabolic concentrator is oval in shape and has a total increased reflective area of 12,6 m<sup>2</sup>. The parabola is fitted to a rotating support which itself rests on a stand and the entire construction is made out of mild steel. The parabolic dish reflects the sunlight by means of rectangular pieces of mirror glass with an optical reflection close to 88%. The glass has been procured in India. The sunlight is concentrated onto the round receivers of 35 cm in diameter, at a distance of 5,2 meters from the end of rotating support. A single disk has a maximum output of ~4.8 kW at 1000 W/m<sup>2</sup> solar radiation and can reach temperatures up to 1000° C in the focus.

In the solar cooking system in GHRC, a total number of 20 parabolic concentrators have been installed in two separate modules of 5 pairs each and are reflecting sunlight on a total of 10 receivers. The design is such that one parabola reflects from a higher position to the front side of the receiver and another mirror reflects from a lower position to the rear of the receiver.

The dishes are arranged in an accurate east-west alignment and tracking is done by a central system by means of 2 winches, 2 DC motors, an electronic timer and a small 12V- 35W PV system. In the evening, the system has to be reset manually to the morning position.

For the solar system at GHRC the well proven standard shell type reflector out of MS, dia 35 cm has been used. The steam is generated directly in both the steam tanks with a volume of 1400L each. As the receivers are working as per the thermo-siphon principle there is no need of any circulation pump. Through its design and dimension the Steam tanks are working as steam generators, temporary steam storage and feed water reservoir.

To avoid any scaling in the entire system, water softening and filtration provides demineralised water to the system. Insulated pipes transfer the generated steam to the various loads, while Steam traps and a pressure reduction station ensure good steam. The steam is used for cooking, sterilization and laundry.

The idea behind this new design is to minimize electrical loads like pumps, and to economise on piping and better overall design. In case of low solar radiation, two highly efficient kerosene-fuelled steam generators function as a back-up system.

The system is protected against excess pressure by safety valves and an automatic shut down mechanism. The status of the whole plant is monitored by temperature and pressure metres and a digital 3-channel data logger

## **6 Project Progress**

After finalizing all aspects of the project, work started in March 2003 with the construction of a workshop and the procurement of materials and major components were ordered.

In April 2003, manufacturing of the parabolas, the rotating support and the stand started in the new workshop.

In May 2003, the layout of the master lines and of the 20 mirrors on the site was carried out.

In July 2003, the feed water pump and the glass were purchased.

Civil work for the platform started in August 2003.

Between October 2003 and January 2004, installation of the parabolic concentrators took place, while simultaneously the glass was cut into size and fitted onto the dishes.

From November to December 2003 the feed water pipeline and steam pipeline were welded together by a certified welder.

In December 2003 the tracking system was fitted and tested and all the electrical connections, the control unit and the insulation had been completed.

From January 2004 onwards, the flushing of all the pipes, pressure tests and electrical tests took place.

The system was successfully tested at the end of January 2004.

## **7 Technology Transfer and Demonstration**

The Global Hospital and Research Centre has an excellent infrastructure including a conference hall and attached nursing training school. The Hospital functions as the prime medical centre for the whole mountain range and also conducts a wide range of conference and training programs throughout the year.

The Hospital is an ideal place for the dissemination of the renewable energy philosophy. Many people with different backgrounds, such as industrialists and administrators, have already shown interest in the system. There are regular guided tours to the solar steam system and information material is available on site.

## **8 Results and Evaluation**

For the evaluation and testing of the solar steam system, a tailored measuring system was necessary. A system was designed and installed by Golo Pilz and Thorsten Ludwig (Dr. Phys.).

The solar steam system came into full use straight after its first test runs in December 2003. The system was monitored for a period of 2 month.

### **8.1 Technical Description**

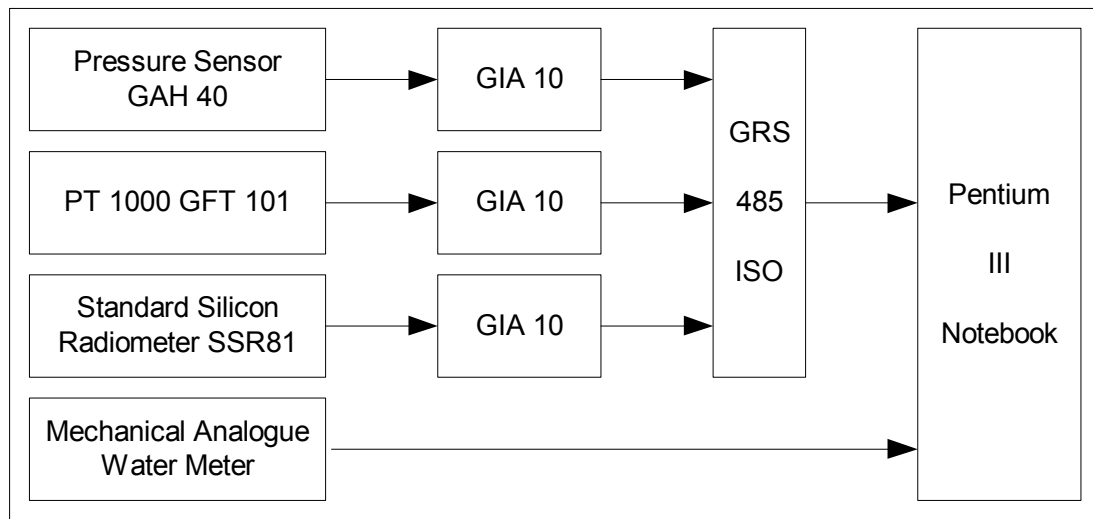
#### **8.1.1 Abstract**

A computer-based measuring program was carried out from February to April 2004 in order to analyse, evaluate and optimise the solar steam generating system. As key parameters the pressure, temperature as well as solar radiation and total steam output have been recorded.

#### **8.1.2 Introduction**

After the great success of all the previous solar cookers, it was decided to build a similar system at the Global Hospital and Research Centre in Mt. Abu. The GHRC system profited from the experience gained by all the previous systems. A detailed measuring program was carried out since the newly developed 12,6 m<sup>2</sup> dish, the new steam tank layout and new tracking system came into use in the GHRC system. The following text should give the reader a detailed description of the agenda and the devices use.

### 8.1.3 The measuring system



**Picture 1: Schematic drawing of the measuring system**

Standard sensors for temperature, pressure and radiation were used for data acquisition. The sensors were read out with the digital Gia 10 of Greisinger. For data logging the Gias have been connected via serial ports and via a GPIB bus with a Pentium III Notebook.

#### **The Sensors:**

##### **Pressure Sensor GAH 40**

A thin-film (DMS) pressure transducer from Greisinger with a pressure range of 1 to 16 bars was used. The sensor has a 4–20mA standard output. It is powered by a 12V-DC power supply. The error is less than 1%.

##### **PT 1000 GFT 101**

A platinum resistor-type sensor was used to measure the temperature. Because of its higher accuracy the 1000  $\Omega$  type came into use. The temperature response of metal resistors is so well known, that for many decades the platinum resistor has been the international standard for temperature definition from the Kelvin range all the way up to 1000°C.

##### **Standard Silicon Radiometer SSR 81**

To measure the intensity of the sunlight we used a standard silicon radiometer SSR 81 from Zenit. The standard silicon radiometer has

temperature compensation with a built-in temperature sensor KTY 81/120. The calibrated output is 67mV at 1000 W/m<sup>2</sup>.

In addition the SLM018c solar power-measuring unit made by Mac solar, was used to measure solar radiation as a back up.

### **Interfaces:**

#### **GIA 10**

The GIA 10, made by Greisinger, is a universal microprocessor based controller and indicator. It has various connections for norm signals like 0-20mA, 4-20mA, 0-1 volt and 1-10 Volt, temperature sensor KTY87 –205 and PT 1000. Also frequency and counting functions can be carried out. The GIA 10 offers a standard RS 485 interface.

#### **GRS 485 ISO**

The GRS 485 made by Greisinger is a RS 485 into RS 232 signal converter. It converts the incoming signals from the Greisinger GIA 10 (pressure/solar/temperature) in to RS 232 Signal and hence allows direct connection and online logging and the reading of data.

#### **RS 232**

The RS 232 is a standard PC serial port. The advantage is that only two wires are necessary while the disadvantage is a high error rate when run without handshaking or data control.

### **8.1.4 Software**

The software EBS9M – Recorder and EBS9M - Convert supplied by Greisinger were used to read out, log and convert the data.

The data has been saved as ASCII files.

For data processing and analysis we used standard programs like Excel, ProEngineer and Math Lab.

#### **Excel**

For some worksheet calculations we used this Microsoft standard worksheet program. It allows to convert ASCII files into Excel sheets and to create graphs from the data. Additionally the data can be integrated, averaged and much more. A wide selection of fit functions and analysing tools allows the

user to do a detailed analysis of his data. All graphs in this report were created with Excel.

### **ProEngineer WILDFIRE**

Pro Engineer is a professional 3 D Computer Aided Design (CAD) program.

The program is specially used for construction drawings

### **Math LAB**

Math Lab is a program used for data analysis and technical graphics.

## **8.1.5 Data acquisition**

Data collection was going on continuously from January to April 2004, in which time the system was in full use. The data read out was then further processed and the data streams were put together with Excel, and further analysed. All graphics were done with Excel program.

## **8.1.6 Manual data collection:**

### **Steam output**

The feed water intake was manually recorded everyday at fixed times by a mechanical analogue water meter to estimate the steam output.

## **8.2 Results**

### **8.2.1 Solar radiation:**

As per the measurements it appears, that Mt. Abu is among the places in the world, which receives highest solar radiation.

The total global radiation has been measured and by means off mathematical calculation the indirect sunlight has been determined and subsequently subtracted from the total radiation.

Table 1: Different ratios of direct solar radiation 25.03.04

| <b>25.04.2003</b>                              |              |          |          |          |          |
|--|--------------|----------|----------|----------|----------|
| time   | 10.00        | 11.00    | 12.00    | 13.00    | 14.00    |
| calculated solar radiation [W/m <sup>2</sup> ] | 947,737      | 949,495  | 953,072  | 953,989  | 951,668  |
| measured solar radiation [W/m <sup>2</sup> ]   | 1080,000     | 1080,000 | 1080,000 | 1070,000 | 1070,000 |
| Ratio  | 0,878        | 0,879    | 0,882    | 0,892    | 0,889    |
| <b>average Ratio</b>                           | <b>0,884</b> |          |          |          |          |

As the sample day of 25<sup>th</sup> in Table 1 indicates, the diffused radiation is around 11,6% of the global solar radiation.

For further details see Calculations in Appendix II.

### 8.2.2 Steam Energy

For the calculation of steam energy, the output of the 18<sup>th</sup>, 25<sup>th</sup> and 28<sup>th</sup> of May has been measured by the amount of daily feed in water.

Table 2: Produced steam energy for various days

| day                                  | 18.03.2004    | 25.03.2004    | 28.03.2004    |
|--------------------------------------|---------------|---------------|---------------|
| average steam pressure [bar]         | 4,251         | 3,668         | 5,557         |
| amount of water used [l]             | 740           | 910           | 600           |
| amount of water used [kg]            | 717,87        | 882,79        | 582,06        |
| water enthalpy [kJ/kg]               | 607,210       | 589,225       | 654,967       |
| steam enthalpy [kJ/kg]               | 2737,846      | 2732,679      | 2742,951      |
| work energy [kJ/kg]                  | 2130,636      | 2143,454      | 2087,985      |
| work energy [kWh/kg]                 | 0,592         | 0,596         | 0,580         |
| <b>total daily work energy [kWh]</b> | <b>425,21</b> | <b>526,04</b> | <b>337,86</b> |

Table 2 shows, that on 18<sup>th</sup> - 717,87 kilo steam and on 25<sup>th</sup> a maximum of 882,79 kilo steam and on 28<sup>th</sup> a minimum of 582,06 kilo steam has been produced.

For further details see Calculations in Appendix II.

### 8.2.3 System efficiency

To accurately assess the system efficiency we calculated the energy potential of the steam energy and set it into relation to the received direct solar radiation. The energy content of the steam was calculated at the averaged daily pressure.

Table 3: System efficiency

| day                                      | 18.03.2004   | 25.03.2004   | 28.03.2004   |
|--|--------------|--------------|--------------|
| total daily steam energy [kWh]           | 425,21       | 526,04       | 337,86       |
| total daily direct solar radiation [kWh] | 1506,50      | 1598,81      | 1340,34      |
| <b>efficiency [%]</b>                    | <b>28,23</b> | <b>32,90</b> | <b>25,21</b> |
| <b>average efficiency [%]</b>            | <b>28,78</b> |              |              |

The average efficiency of the steam system is at the moment 28,78%. The best result was on 25.3 with 32,90% and the minimum was on 28.3 with 25.21 %.

For further details see Calculations in Appendix II.

### 8.2.4 Diesel savings and CO<sub>2</sub> reduction:

The diesel saving and the CO<sub>2</sub> reduction on various days is calculated as shown in Appendix II. The calculated values are presented in table 4.

Table 4: Diesel saving on various days

| day                                     | 18.03.2004    | 25.03.2004    | 28.03.2004    |
|---|---------------|---------------|---------------|
| total daily produced steam [kg]         | 717,87        | 882,79        | 582,06        |
| steam produced per liter diesel [kg/l]  | 10,00         | 10,00         | 10,00         |
| <b>saved amount of diesel [l]</b>       | <b>71,79</b>  | <b>88,28</b>  | <b>58,21</b>  |
| <b>reduction of CO<sub>2</sub> [kg]</b> | <b>157,93</b> | <b>194,21</b> | <b>128,05</b> |

### 8.2.5 Performance of the system:

The 3 steam pressure graphs in Appendix I show the diurnal variation of pressure. These graphs indicate the direct relation between the load management and energy input through the sun. Each day shows a significant difference. Still there is a certain pattern to each day, which shows the pattern of usage. First we have the initial build up of pressure. From around 9.30am the valves are opened and the steam is used. Then, between 11.00am – 2.00pm, depending on demand and solar radiation, the pressure varies greatly. Usually from 3.00pm onwards solar radiation is declining and in accordance with the load the pressure drops significantly.

## 9 Discussion

The accuracy and stability of the sensors and the measuring system was good. The solar steam system works very reliable. On a sunny day the solar system is generating first steam from 9.30am onwards. The daily pressure graph (see appendix I) clearly shows that up to the point where the steam is used, the pressure builds up steadily and ultimately shows signs of saturation close to the maximum operating pressure of 10 bars. It is interesting to note the response of the system to load. In this case the rise in pressure is slower or the pressure drops with a speed relative to the load.

In order to run the system in higher a efficiency range, it is advised to avoid higher steam pressure and use the steam before it reaches 6 bars of system pressure.

It has been found that in full sunshine the solar steam system in GHRC matches the full load with ease.

It seems that the measured maximum of 882 kilo of steam is still not the maximum capability of the system. It has been found that one module receives partial shadow from 1.00pm onwards through branches of a nearby tree.

It is expected that by further trimming of these branches, improved load management and better focusing the output of the system can be increased towards a maximum of 1000kg of steam per day.

## 10 Conclusion

Such types of solar steam generating systems are suitable for institutional cooking and industrial steam requirements. Here it can be a cheap way to produce low-pressure saturated steam.

On a sunny day the output and storing capability of the system was excellent so that at times the steam could be stored over night and in the morning sufficient steam was available. During such periods the back-up system could be switched off completely.

The solar steam system has been in operation for last 3 months. In the monsoon season, usually a period of 10 weeks, it is not practical to run the solar steam system because of continuously cloudy conditions. In this period the steam is totally provided by the back-up system. The rest of the year is excellent and Mt. Abu reaches a maximum of nearly 2000 kWh/m<sup>2</sup> per year because of its desert like climatic conditions.

The mechanical stability and output of the newly developed 12,6 m<sup>2</sup> dish is excellent and fulfils all promises.

The newly designed tracking system works excellently and is worthy to be replicated in future systems. The reflectivity of the mirror glass obtained from India is around 88 % and due to the extra backside coating a lifetime of around 8-10 years is expected.

The overall handling of the system is easy and operation and maintenance is already in the hands of trained hospital staff.

Mt. Abu 12.5.2004

Golo Pilz  
Project Coordinator

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## **12 Appendix**

- I Data
- II Calculations
- III Drawings
- IV Photos

## **I. Data**

## II. Calculations

### II.I Solar radiation

The measured data also includes the diffused radiation. So the direct solar radiation is calculated by mathematic formulas and then compared to the measured values. The difference between the values is the diffused solar radiation.

#### II.I.I Calculation of the direct solar radiation

For the calculation of the direct solar radiation some data are necessary, which are shown next.

|        |                                       |         |
|--------|---------------------------------------|---------|
| $\Phi$ | <i>latitude of Mount Abu</i>          | 24°36 N |
| $L$    | <i>geographic length of Mount Abu</i> | 72°43 E |
| $L_0$  | <i>geographic length of India</i>     | 84° E   |

The whole calculation is based on the data of 25.03.04. So all values are taken for this particular day.

The first step is to calculate the solar time (formula 1).

$$\text{solar time} = \text{normal time} + 4 \cdot (L_0 - L) + EOT \quad (1)$$

|       |                                       |       |
|-------|---------------------------------------|-------|
| $EOT$ | <i>equation of time</i>               | [min] |
| $L$   | <i>geographic length of Mount Abu</i> |       |
| $L_0$ | <i>geographic length of India</i>     |       |

To solve formula 1 the equation of time has to be solved (formula 2).

$$EOT = -7,66 \cdot \sin(x) - 9,87 \cdot \sin(2 \cdot x + 24,99) + 3,83 \cdot \sin(x) \quad (2)$$

with formula 3:

$$x = 0,9856 \cdot N - 2,72 \quad (3)$$

$x$  [°]

$N$  *Number of days*

The Number of days in formula 3 are counted from the 1. January. So for the 25.03.04, N becomes 85.

As a next step the hour angle has to be calculated (formula 4).

$$\omega = 15 \cdot \left(12 - \frac{1}{60} \cdot \text{solar time}\right) \quad (4)$$

$\omega$  *hour angle* [°]

*solar time* [min]

Then the declination angle could be calculated (formula 5). This explains at which latitude the position of the sun actually is.

$$\delta = -23,45 \cdot \cos\left(\frac{360}{365,25} \cdot (N + 10)\right) \quad (5)$$

$\delta$  *declination angle* [°]

$N$  *Number of days*

For the calculation of the direct radiation also the solar altitude angle (formula 6) and the solar azimuth angle (formula 7) is needed. The solar altitude angle explains the position of the sun on the horizon.

$$\alpha_s = \frac{1}{\sin(\sin(\Phi) \cdot \sin(\delta) + \cos(\Phi) \cdot \cos(\delta) \cdot \cos(\omega))} \quad (6)$$

$$\gamma_s = \frac{1}{\cos\left(\frac{\sin(\alpha_s) \cdot \sin(\Phi) - \sin(\delta)}{\cos(\alpha_s) \cdot \cos(\Phi)}\right)} \quad (7)$$

|            |                              |     |
|------------|------------------------------|-----|
| $\alpha_s$ | <i>solar altitude angle</i>  | [°] |
| $\Phi$     | <i>latitude of Mount Abu</i> | [°] |
| $\delta$   | <i>declination angle</i>     | [°] |
| $\omega$   | <i>hour angle</i>            | [°] |
| $\gamma_s$ | <i>solar azimuth angle</i>   | [°] |

With the help of the solar altitude angle the relative mass of air can be calculated. The mass of air describes the way of solar radiation through the atmosphere.

$$air\ mass = \frac{1}{\sin(\alpha_s)} \quad (8)$$

|            |                             |     |
|------------|-----------------------------|-----|
| $\alpha_s$ | <i>solar altitude angle</i> | [°] |
|------------|-----------------------------|-----|

With the mass of air the different transmission factors for absorption, scattering and extinction can be derived. In all the following calculations the difference in the mass of air depending on the height of Mount Abu is not included, because the difference is negligible.

By travelling through the atmosphere solar radiation is getting scattered, absorbed or extinct and partly loses its energy. How much energy is lost, is described by the transmission factors.

As first the transmission factor of the Rayleigh scattering by molecules of the air is calculated.

$$\tau_{Ra} = e^{-(0,0903(1,0+air\ mass - air\ mass^{1,01}) \cdot air\ mass^{0,84})} \quad (9)$$

|             |  |
|-------------|--|
| $\tau_{Ra}$ | <i>transmission factor for Rayleigh scattering</i> |
|-------------|--|



To get the direct solar radiation on a plane orientated to the sun the transmission factors has to be added (formula 15) and then multiplied by the solar constant  $E_{SC}$  (formula 16).

$$\tau = \tau_{Ra} + \tau_{O3} + \tau_{Ga} + \tau_{Wa} + \tau_{Ae} + \tau_{Ci} \quad (15)$$

$\tau$  overall transmission factor

$$S_{D,90^\circ} = E_{SC} \cdot \tau \quad (16)$$

$S_{D,90^\circ}$  direct solar radiation on  $90^\circ$  to sun surface  $\left[ \frac{kW}{m^2} \right]$

$$E_{SC} = 1367,00 \frac{W}{m^2}$$

This calculated value is now compared with the measured value. The difference between the both is the diffused radiation. To calculate the direct radiation of all measured data the ratio between the measured solar radiation and the calculated direct solar radiation is necessary (formula 17).

$$R = \frac{S_{D,90^\circ}}{S_M} \quad (17)$$

$R$  ratio of direct solar radiation

$S_M$  measured solar radiation  $\left[ \frac{W}{m^2} \right]$

$S_{D,90^\circ}$  direct solar radiation on  $90^\circ$  to sun surface  $\left[ \frac{W}{m^2} \right]$

This ratio is calculated for different measured values. To get a good result of the ratio the average of all calculated values is taken (formula 18).

$$\bar{R} = \frac{\sum^n R}{n} \quad (18)$$

$\bar{R}$  average ratio of direct solar radiation

$R$  ratio of direct solar radiation

$n$  number of ratios

With the average ratio all measured data are multiplied to get the direct solar radiation.

### II.I.II Example 25.03.04

In the example the direct radiation at Mount Abu (11.00 o'clock) is calculated.

Formula 3:

$$x = 0,9856 \cdot N - 2,72 = 0,9856 \cdot 85 - 2,72 = 81,056$$

Formula 2:

$$\begin{aligned} EOT &= -7,66 \cdot \sin(x) - 9,87 \cdot \sin(2 \cdot x + 24,99 + 3,83 \cdot \sin(x)) \\ &= -7,66 \cdot \sin(81,056) - 9,87 \cdot \sin(2 \cdot 81,056 + 24,99 + 3,83 \cdot \sin(81,056)) = -0,197 \end{aligned}$$

With formula 3 and formula 2, formula 1 can be calculated:

$$\begin{aligned} solar\ time &= normal\ time + 4 \cdot (L_0 - L) + EOT = 660 + 4 \cdot (-84 - (-72,43)) + (-0,197) \\ &= 613,5\ min \end{aligned}$$

Formula 4:

$$\omega = 15 \cdot \left(12 - \frac{1}{60} \cdot solar\ time\right) = 15 \cdot \left(12 - \frac{1}{60} \cdot 613,5\right) = 26,691^\circ$$

Formula 5:

$$\delta = -23,45 \cdot \cos\left(\frac{360}{365,25} \cdot (N + 10)\right) = -23,45 \cdot \cos\left(\frac{360}{365,25} \cdot (85 + 10)\right) = 1,487$$

Formula 6:

$$\begin{aligned} \alpha_s &= \frac{1}{\sin(\sin(\Phi) \cdot \sin(\delta) + \cos(\Phi) \cdot \cos(\delta) \cdot \cos(\omega))} \\ &= \frac{1}{\sin(\sin(24,36) \cdot \sin(1,487) + \cos(24,36) \cdot \cos(1,487) \cdot \cos(26,691))} = 55,572^\circ \end{aligned}$$

Formula 7:

$$\gamma_s = \frac{1}{\cos\left(\frac{\sin(\alpha_s) \cdot \sin(\Phi) - \sin(\delta)}{\cos(\alpha_s) \cdot \cos(\Phi)}\right)} = \frac{1}{\cos\left(\frac{\sin(55,572) \cdot \sin(24,36) - \sin(1,487)}{\cos(55,572) \cdot \cos(24,36)}\right)}$$

$$= 67,293^\circ$$

Formula 8:

$$air\ mass = \frac{1}{\sin(\alpha_s)} = \frac{1}{\sin(55,572)} = 1,212$$

Formula 9:

$$\tau_{Ra} = e^{-(0,0903 \cdot (1,0 + air\ mass - air\ mass^{1,01}) \cdot air\ mass^{0,84})} = e^{-(0,0903 \cdot (1,0 + 1,212 - 1,212^{1,01}) \cdot 1,212^{0,84})} = 0,932$$

Formula 10, for the thickness of the ozone layer normally 0,32cm are taken:

$$\tau_{O_3} = 1 - \frac{0,1611 \cdot d_{O_3} \cdot air\ mass}{(1,0 + 139,48 \cdot d_{O_3} \cdot air\ mass)^{0,3035}} = 1 - \frac{0,1611 \cdot 0,32 \cdot 1,212}{(1,0 + 139,48 \cdot 0,32 \cdot 1,212)^{0,3035}} = 0,981$$

Formula 11:

$$\tau_{Ga} = e^{-(0,0127 \cdot air\ mass^{0,26})} = e^{-(0,0127 \cdot 1,212^{0,26})} = 0,987$$

Formula 12, for  $d_{wa}$  normally three is taken:

$$\tau_{Wa} = 1 - \frac{2,496 \cdot d_{wa} \cdot air\ mass}{6,385 \cdot d_{wa} \cdot air\ mass \cdot (1,0 + 79,03 \cdot d_{wa} \cdot air\ mass)^{0,683}}$$

$$= 1 - \frac{2,496 \cdot d_{wa} \cdot air\ mass}{6,385 \cdot d_{wa} \cdot air\ mass \cdot (1,0 + 79,03 \cdot d_{wa} \cdot air\ mass)^{0,683}} = 0,872$$

Formula 13, for the horizontal visibility 100km is a standard value:

$$\tau_{Ae} = e^{air\ mass^{0,9} \cdot \ln\left(0,97 - \frac{1,265}{VIS^{0,66}}\right)} = e^{1,212^{0,9} \cdot \ln\left(0,97 - \frac{1,265}{100^{0,66}}\right)} = 0,893$$

Formula 14, the  $d_{Ci}$  for a cloud free sky is normally 0,01:

$$\tau_{Ci} = e^{-(air\ mass \cdot d_{Ci})} = e^{-(1,212 \cdot 0,01)} = 0,988$$

Formula 15:

$$\tau = \tau_{Ra} + \tau_{O3} + \tau_{Ga} + \tau_{Wa} + \tau_{Ae} + \tau_{Ci} = 0,932 + 0,981 + 0,987 + 0,872 + 0,893 + 0,988 = 0,695$$

Formula 16:

$$S_{D,90^\circ} = E_{SC} \cdot \tau = 1367,00 \frac{W}{m^2} \cdot 0,695 = 949,495 \frac{W}{m^2}$$

Formula 17, at the 25.03.04, 11.00, the measured radiation was 1080 W/m<sup>2</sup>:

$$R = \frac{S_{D,90^\circ}}{S_M} = \frac{949,495 \frac{W}{m^2}}{1080 \frac{W}{m^2}} = 0,879$$

Formula 18 is calculated in the next chapter, because there are the given of all calculated times from the 25.03.04.

### II.I.III Different ratios of direct solar radiation

The different ratios of direct solar radiation for the 25.03.04 are all calculated by the calculation described above. The result is shown in table 1.

Table 1: Different ratios of direct solar radiation 25.03.04

| <b>25.04.2003</b>                              |              |          |          |          |          |
|--|--------------|----------|----------|----------|----------|
| time   | 10.00        | 11.00    | 12.00    | 13.00    | 14.00    |
| calculated solar radiation [W/m <sup>2</sup> ] | 947,737      | 949,495  | 953,072  | 953,989  | 951,668  |
| measured solar radiation [W/m <sup>2</sup> ]   | 1080,000     | 1080,000 | 1080,000 | 1070,000 | 1070,000 |
| Ratio  | 0,878        | 0,879    | 0,882    | 0,892    | 0,889    |
| <b>average Ratio</b>                           | <b>0,884</b> |          |          |          |          |

**The diffused radiation is around 11,6% of the global solar radiation.**

## II.II Steam energy

For the calculation of the steam energy the measurements from 18.03.04, 25.03.04 and 28.03.04 are used. In the following chapters it is explained how to calculate the data to get the graphs shown in appendix.

### II.II.I Theoretically calculations

As a first step we have to calculate average steam pressure:

$$\bar{p} = \frac{\sum_1^i p_1 + p_2 + \dots + p_i}{i} \quad (19)$$

|           |                                   |       |
|-----------|-----------------------------------|-------|
| $\bar{p}$ | <i>average pressure</i>           | [bar] |
| $p_1$     | <i>first pressure measurement</i> | [bar] |
| $p_i$     | <i>last pressure measurement</i>  | [bar] |
| $i$       | <i>number of measurements</i>     |       |

After this step we have to calculate the enthalpy of water and steam at this pressure. Therefore we need the enthalpy of water and of steam at 3,4bar and 6bar.

Enthalpy of water: - at 3,4bar  $h'_{3,4} = 579,90 \frac{kJ}{kg}$

- at 6bar  $h'_6 = 640,40 \frac{kJ}{kg}$

Enthalpy of steam: - at 3,4bar  $h''_{3,4} = 2730 \frac{kJ}{kg}$

- at 6bar  $h''_6 = 2756 \frac{kJ}{kg}$

With this values and the next formula the enthalpy of water and steam at every pressure between 3,4 and 6bar could be calculated.

$$h = \left( \frac{h_6 - h_{3,4}}{2,6} \right) \cdot (6 - \bar{p}) + h_{3,4} \quad (20)$$

|           |                                     |                                |
|-----------|-------------------------------------|--------------------------------|
| $h$       | <i>enthalpy at desired pressure</i> | $\left[ \frac{kJ}{kg} \right]$ |
| $h_6$     | <i>enthalpy at 6bar</i>             | $\left[ \frac{kJ}{kg} \right]$ |
| $h_{3,4}$ | <i>enthalpy at 3,4bar</i>           | $\left[ \frac{kJ}{kg} \right]$ |
| $\bar{p}$ | <i>average pressure</i>             |                                |

With this values the work enthalpy, which is necessary to produce the steam, can be calculated.

$$Q_1 = h'' - h' \quad (21)$$

|       |                       |                                |
|-------|-----------------------|--------------------------------|
| $Q_1$ | <i>work enthalpy</i>  | $\left[ \frac{kJ}{kg} \right]$ |
| $h''$ | <i>steam enthalpy</i> | $\left[ \frac{kJ}{kg} \right]$ |
| $h'$  | <i>water enthalpy</i> | $\left[ \frac{kJ}{kg} \right]$ |

To convert the work enthalpy in work energy (from kJ/kg to kWh/kg), the formula (21) must be multiplied by 0,000278.

$$Q_2 = Q_1 \cdot 0,0278 \cdot 10^{-3} \quad (22)$$

|       |                    |                                 |
|-------|--------------------|---------------------------------|
| $Q_2$ | <i>work energy</i> | $\left[ \frac{kWh}{kg} \right]$ |
| $Q_1$ | <i>work energy</i> | $\left[ \frac{kJ}{kg} \right]$  |

Now the work energy per kg water is calculated. The whole energy, which is produced by the solar steam system, has to be calculated by multiplying formula (22) with the amount of water (in kg), which was used at that day (formula 23). How to calculate that is shown in formula (24).

$$m_w = V_w \cdot \rho_w \quad (23)$$

$$\begin{array}{lll} m_w & \text{mass of water} & [kg] \\ V_w & \text{volume of water} & [l] \\ \rho_w & \text{density of water} & \left[ \frac{kg}{l} \right] \end{array}$$

The density of water is at every temperature different. For our system an average water temperature of 65° is assumed. For this temperature the density is calculated.

$$\rho_{w,65^\circ} = \frac{\rho_{w,100^\circ} - \rho_{w,50^\circ}}{25} \cdot 15 + \rho_{w,50^\circ} \quad (24)$$

$$\begin{array}{lll} \rho_{w,65^\circ} & \text{density of water at } 65^\circ C & \left[ \frac{kg}{l} \right] \\ \rho_{w,100^\circ} & \text{density of water at } 100^\circ C & \left[ \frac{kg}{l} \right] \\ \rho_{w,50^\circ} & \text{density of water at } 50^\circ C & \left[ \frac{kg}{l} \right] \end{array}$$

Now the total amount of energy produced by the solar steam system can be calculated.

$$Q_t = Q_2 \cdot m_w \quad (25)$$

$$\begin{array}{lll} Q_t & \text{total amount of energy} & [kWh] \\ Q_2 & \text{work energy} & \left[ \frac{kWh}{kg} \right] \\ m_w & \text{water mass} & [kg] \end{array}$$

### II.II.II Example 25.03.2004

From the measurements all the data for  $p_1, p_2$  up to  $p_i$  and  $i$  are available. So it is possible to calculate formula (19).

$$\sum_1^i p_1 + p_2 + \Lambda + p_i = 2552,853 \text{ bar} \quad (26)$$

$$i = 696 \quad (27)$$

insert (26) and (27) in (19):

$$\bar{p} = \frac{\sum_1^i p_1 + p_2 + \Lambda + p_i}{i} = \frac{2552,853 \text{ bar}}{696} = 3,668 \text{ bar}$$

As next step formula (20) for water and steam is calculated:

$$h' = \left( \frac{h'_6 - h'_{3,4}}{2,6} \right) \cdot (6 - \bar{p}) + h'_{3,4} = \left( 640,40 \frac{\text{kJ}}{\text{kg}} - 579,90 \frac{\text{kJ}}{\text{kg}} \right) \cdot (6 - 3,668) + 579,90 \frac{\text{kJ}}{\text{kg}} = 607,10 \frac{\text{kJ}}{\text{kg}}$$

$$h'' = \left( \frac{h''_6 - h''_{3,4}}{2,6} \right) \cdot (6 - \bar{p}) + h''_{3,4} = \left( 2756 \frac{\text{kJ}}{\text{kg}} - 2730 \frac{\text{kJ}}{\text{kg}} \right) \cdot (6 - 3,668) + 2730 \frac{\text{kJ}}{\text{kg}} = 2737,846 \frac{\text{kJ}}{\text{kg}}$$

With this values it is possible to calculate (21),(22):

$$Q_1 = h'' - h' = 2737,846 \frac{\text{kJ}}{\text{kg}} - 607,10 \frac{\text{kJ}}{\text{kg}} = 2130,636 \frac{\text{kJ}}{\text{kg}}$$

$$Q_2 = Q_1 \cdot 0,278 \cdot 10^{-3} = 2130,636 \frac{\text{kJ}}{\text{kg}} \cdot 0,278 \cdot 10^{-3} = 0,596 \frac{\text{kWh}}{\text{kg}}$$

Now formula (24) is calculated:

$$\rho_{w,100^\circ} = 0,9581 \frac{\text{kg}}{\text{l}}$$

$$\rho_{w,50^\circ} = 0,9881 \frac{\text{kg}}{\text{l}}$$

$$\rho_{w,65^\circ} = \frac{\rho_{w,100^\circ} - \rho_{w,50^\circ}}{25} \cdot 15 + \rho_{w,50^\circ} = \frac{0,9581 \frac{\text{kg}}{\text{l}} - 0,9881 \frac{\text{kg}}{\text{l}}}{25} \cdot 15 + 0,9881 \frac{\text{kg}}{\text{l}} = 0,9701 \frac{\text{kg}}{\text{l}}$$

The next step is to calculate the water mass (23):

$$m_w = V_w \cdot \rho_w = 910 \text{ l} \cdot 0,9701 \frac{\text{kg}}{\text{l}} = 882,79 \text{ kg}$$

With formula (22) and (23) the total amount of energy produced at 25.03.04 is:

$$Q_t = Q_2 \cdot m_w = 0,596 \frac{kWh}{kg} \cdot 882,79 kg = 526,14 \frac{kWh}{kg}$$

### II.II.III Produced steam energy for various days

The steam energy is calculated for three different days with different direct solar radiation and different average pressure. The calculated data are shown in table 2.

Table 2: Produced steam energy for various days

| day                                  | 18.03.2004    | 25.03.2004    | 28.03.2004    |
|--------------------------------------|---------------|---------------|---------------|
| average steam pressure [bar]         | 4,251         | 3,668         | 5,557         |
| amount of water used [l]             | 740           | 910           | 600           |
| amount of water used [kg]            | 717,87        | 882,79        | 582,06        |
| water enthalpy [kJ/kg]               | 607,210       | 589,225       | 654,967       |
| steam enthalpy [kJ/kg]               | 2737,846      | 2732,679      | 2742,951      |
| work energy [kJ/kg]                  | 2130,636      | 2143,454      | 2087,985      |
| work energy [kWh/kg]                 | 0,592         | 0,596         | 0,580         |
| <b>total daily work energy [kWh]</b> | <b>425,21</b> | <b>526,04</b> | <b>337,86</b> |

## II.III Efficiency of the solar steam system

To calculate the efficiency we take the calculated values for the solar energy and the steam energy.

### II.III.I Theoretically calculations

$$\eta = \frac{Q_t}{Q_s} \quad (28)$$

$\eta$  efficiency of solar steam system

$Q_t$  total daily steam energy [kWh]

$Q_s$  total daily caught direct solar radiation by system [kWh]

The daily collected direct solar radiation by the whole system has to be calculated as follows:

$$Q_s = S_{D,d} \cdot A_s \quad (29)$$

$Q_s$  total daily caught direct solar radiation by system [kWh]

$S_{D,d}$  daily direct solar radiation  $\left[ \frac{kWh}{m^2} \right]$

$A_s$  mirror area of whole system  $[m^2]$

To calculate formula 29 first the area of one Scheffler mirror (formula 30), aperture of one Scheffler mirror (formula 31.1/31.2) and then the whole mirror area of the system (formula 32).

$$A_M = \frac{\pi}{4} \cdot D \cdot d \quad (30)$$

$A_M$  area of Schefflermirror  $[m^2]$

$D$  diameter one of ellipse  $[m]$

$d$  diameter two of ellipse  $[m]$

$$A_{M.A} = A_M \cdot \cos \left( 43,23 - \frac{\rho}{2} \right) \quad (31.1)$$

Because a normal solar steam system has a lower and a higher dish, the term  $(-\rho/2)$  could be neglected.

$$A_{M.A} = A_M \cdot \cos(43,23) \quad (31.2)$$

|           |   |            |
|-----------|---|------------|
| $A_{M.A}$ | <i>apperure of Schefflermirror</i>      | $[m^2]$    |
| $A_M$     | <i>area of Schefflermirror</i>          | $[m^2]$    |
| $\rho$    | <i>elevation angle of suns position</i> | $[^\circ]$ |

$$A_S = N \cdot A_{M.A} \quad (32)$$

|           |   |         |
|-----------|---|---------|
| $A_S$     | <i>area of all dishes in the system</i> | $[m^2]$ |
| $N$       | <i>number of dishes in the system</i>   |         |
| $A_{M.A}$ | <i>apperure of Schefflermirror</i>      | $[m^2]$ |

$S_{D,d}$ , the daily solar radiation is shown in the graphs in Appendix .

### II.III.II Example 25.03.04

First the formula 30 is calculated, the diameters for the Scheffler mirror are  $D=4,7m$  and  $d=3,425m$ :

$$A_M = \frac{\pi}{4} \cdot D \cdot d = \frac{\pi}{4} \cdot 4,7 m \cdot 3,425 m = 12,643 m^2$$

Formula 31.2:

$$A_{M.A} = A_M \cdot \cos(43,23) = 12,643 m^2 \cdot \cos(43,23) = 9,231 m^2$$

Formula 32, in this system is the number of dishes 20:

$$A_S = N \cdot A_{M.A} = 20 \cdot 9,231 m^2 = 184,62 m^2$$

With formula 32 and the daily solar radiation  $S_{D,d} = 8,66 \text{ kWh}/m^2$ , formula 29 can be calculated:

$$Q_S = S_{D,d} \cdot A_S = 8,66 \frac{kWh}{m^2} \cdot 184,62 m^2 = 1598,81 kWh$$

At least the efficiency of the system (formula 28) is calculated:

$$\eta = \frac{Q_t}{Q_s} = \frac{526,04 \text{ kWh}}{1598,81 \text{ kWh}} = 0,329 = 32,9\%$$

### II.III.III Efficiency of the solar steam system

In table 3 the efficiency of the solar steam system at three days are shown. Also the average efficiency is calculated and the collected solar radiation of the complete system.

Table 3: Efficiency of the solar steam system at various days

| day                                      | 18.03.2004   | 25.03.2004   | 28.03.2004   |
|--|--------------|--------------|--------------|
| total daily steam energy [kWh]           | 425,21       | 526,04       | 337,86       |
| total daily direct solar radiation [kWh] | 1506,50      | 1598,81      | 1340,34      |
| <b>efficiency [%]</b>                    | <b>28,23</b> | <b>32,90</b> | <b>25,21</b> |
| <b>average efficiency [%]</b>            | <b>28,78</b> |              |              |

The average efficiency of the steam system is at the moment 28,78%. But it seems possible to increase up to 32% if there is a better load management, some trees are cut and the focus is adjusted better.

## II.IV Diesel saving and CO<sub>2</sub> reduction

How much diesel is saved and how much the production of CO<sub>2</sub> is reduced is calculated with the days used in the equations before. As in the points before first the theoretically calculation is shown.

A normal diesel burner produces per litre diesel 10kg of steam. So formula 33 shows, how to get from kg produced steam to litre saved diesel.

$$V_D = \frac{m_s}{10 \frac{\text{kg}}{\text{l}}} \quad (33)$$

$$\begin{array}{ll} V_D & \text{amount of diesel} \quad [\text{kg}] \\ m_s & \text{produced steam} \quad [\text{kg}] \end{array}$$

One litre of diesel generates with a standard diesel burner 2,2kg of CO<sub>2</sub>. With the value from the calculation (33) the reduction of CO<sub>2</sub> can be calculated (formula 34).

$$m_{CO_2} = V_D \cdot 2,2 \frac{kg}{l} \quad (34)$$

$m_{CO_2}$       amount of CO<sub>2</sub> reduced      [kg]  
 $V_D$           volume of Diesel saved          [l]

#### II.IV.I Example 25.03.04

Like the calculations before the calculations are explained with the help of the data from 25.03.04.

Formula 33, the amount of produced steam is 882,79 kg (table 4):

$$V_D = \frac{m_s}{10 \frac{kg}{l}} = \frac{882,79 \text{ kg}}{10 \frac{kg}{l}} = 88,279 \text{ l}$$

Formula 34:

$$m_{CO_2} = V_D \cdot 2,2 \frac{kg}{l} = 88,279 \text{ l} \cdot 2,2 \frac{kg}{l} = 194,21 \text{ kg}$$

#### I.IV.II Diesel saving and CO<sub>2</sub> reduction on various days

The diesel saving and the CO<sub>2</sub> reduction on the various days is calculated, like shown above. The calculated values are presented in table 4.

Table 4: Diesel saving on various days

| day                                     | 18.03.2004    | 25.03.2004    | 28.03.2004    |
|---|---------------|---------------|---------------|
| total daily produced steam [kg]         | 717,87        | 882,79        | 582,06        |
| steam produced per liter diesel [kg/l]  | 10,00         | 10,00         | 10,00         |
| <b>saved amount of diesel [l]</b>       | <b>71,79</b>  | <b>88,28</b>  | <b>58,21</b>  |
| <b>reduction of CO<sub>2</sub> [kg]</b> | <b>157,93</b> | <b>194,21</b> | <b>128,05</b> |

### **III. Drawings**

## **IV. Photos**