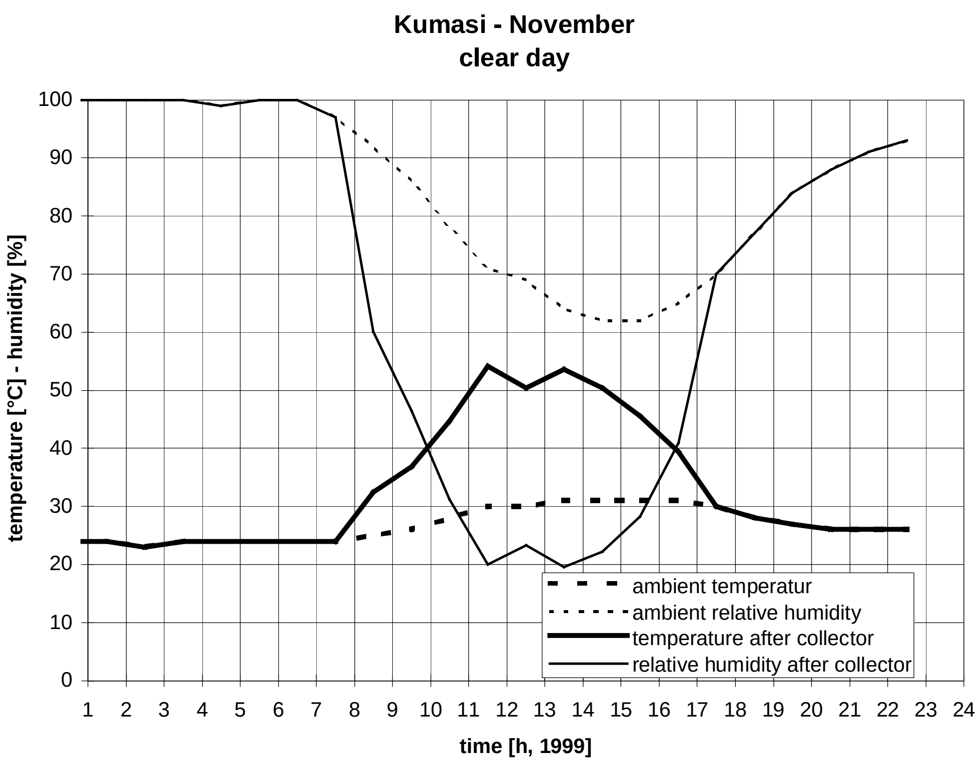
SOLAR ENERGY CENTER DENMARK

DANISH TECHNOLOGICAL INSTITUTE

Simulations to support the design of a solar crop dryer and a solar kiln



Solar Energy Centre Denmark
Danish Technological Institute

Simulations to support the design of a solar crop dryer and a solar kiln

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Solar Energy Centre Denmark
Danish Technological Institute

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Foreword

The survey is part of the project “Test and Research Project into the Drying of Food and Wood Products with Solar Heat” financed by Danida (Danish International Development Assistance) via the Danish Embassy in Ghana. The project was established based on an initiative by the Energy Commission of Ghana.

List of contents

1. Introduction

The report contains the results from runs with two special purpose simulation programs developed in order to be able to simulate the thermal behaviour of a solar air collector in combination with at solar crop dryer and a solar kiln.

The aim of the simulation results is to support the design of a solar crop dryer and a solar kiln by giving information on the expected temperature and humidity level of the air from a solar air collector under Ghanaian weather conditions in combination with the power transferred to the air in the collector and - for the solar crop dryer - the obtainable air flow rate in the dryer.

2. Simulation of a solar air collector for a solar crop dryer for Ghana

The purpose of the chapter is to investigate the temperature and humidity level of the air leaving a solar air collector under Ghanaian weather conditions. The purpose of the solar air collector is to be used in connection with at solar crop dryer for drying of maize for seed. The fan will be driven directly by pv-panels, which will lead to a variable air flow rate through the collector dependent on the solar radiation..

The weather data is from Kumasi. Weather data for three days in November 1999 and January 2000 has been applied (Jensen, 2000). They represent a clear day, an average day and an overcast day for both months. The weather data are shown in appendix A.

As efficiency for the solar air collector and air flow rate through the collector is used the measured values for the solar air collector from the Summer House Package from Aidt Miljø. This collector utilize the same type of cloth absorber as will be used in the collector of the solar crop dryer. The efficiency of the two collectors is, therefore, assumed to be rather similar. The efficiency is from (Fechner, 1999) while the characteristic of the fan/flow rate is from (Jensen, 1994). The measured efficiency for the collector when heating ambient air and the characteristic of the fan/flow rate are shown in figures 2.1 and 2.2.

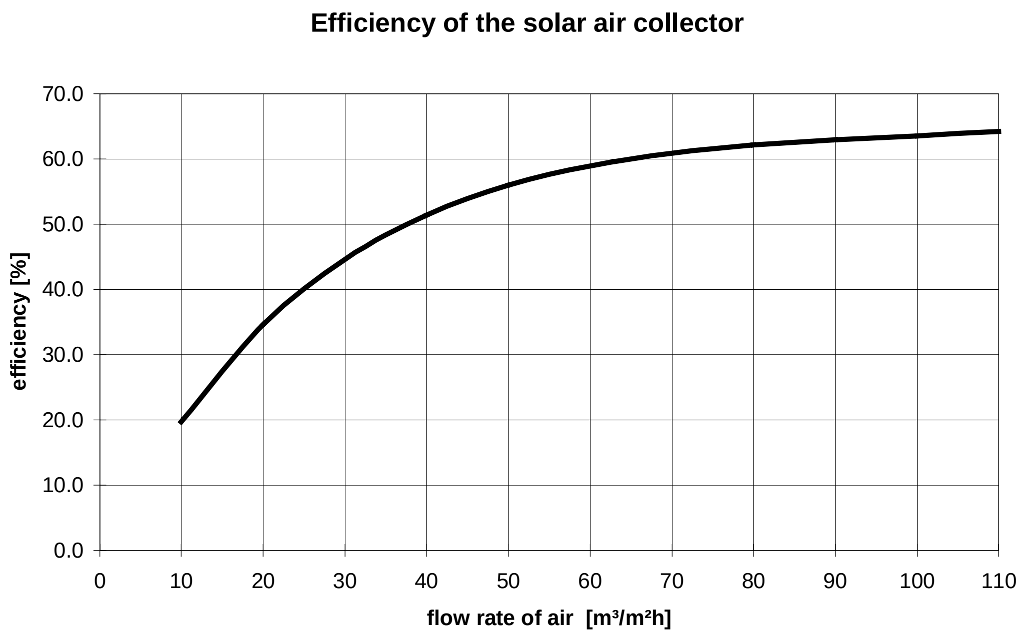


Figure 2.1. The applied efficiency curve for the solar air collector.

A small simulation program has been developed which is able to calculated the temperature and relative humidity of the air from the solar collector. The program is using the weather data in appendix A and calculates hour by hour the direct solar radiation and the incidence angle of the direct solar radiation on the collector. Together with the diffuse radiation the useful radiation is calculated by correcting for the reflection in the cover of the solar air collector at higher incidence angles than zero degree.

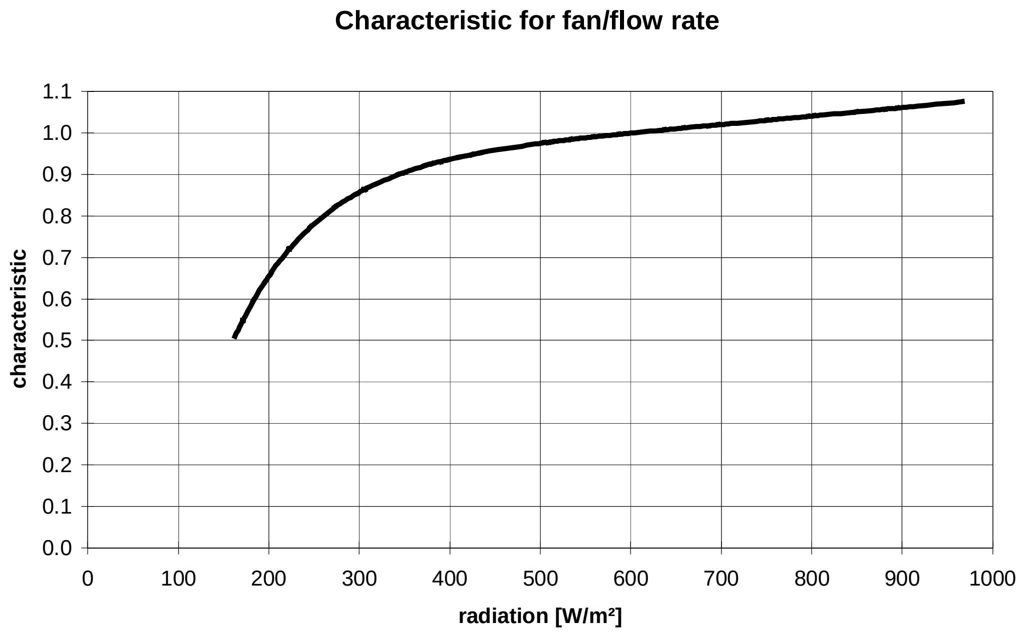


Figure 2.2. The applied characteristic of the fan/flow rate as function of the useful solar radiation - ie corrected for the incidence angle.

The input parameters is: the incidence angle modifier of the cover of the collector and the tilt and orientation of the collector. Information on the flow rate and the efficiency:

> For the flow rate two parameters has to be given: the nominal flow rate at a certain radiation level and the flow rate at this radiation level. In figure 2.2 the radiation level is chosen to be 600 W/m² where the characteristic is unity. In this way it is possible to change the characteristic of the flow rate dependent on the radiation level and thereby investigate the influence of different characteristics.
>
> For the efficiency a reduction factor has to be given, which is multiplied with the efficiency shown in figure 2.1. A reduction factor of 1 gives the curve in figure 2.1. The reduction factor may be used for parameter studies on the effect of the efficiency of the collector on the performance of the system.

The last parameter to be given is the allowed maximum temperature of the air to the drying chamber. The max allowed temperature when drying maize for seed is 45°C.

Results from using the simulation program are shown in appendix B and C. For both appendixes the following input parameters to the simulation program has been used:

incidence angle modifier:	3
tilt:	15°
orientation:	south
nominal flow rate:	60 m³/m²h at 600 W/m²
reduction of efficiency:	0.9 as the collector is expected to be a little less efficient than the collector in the Summer House Package

The only difference between the results in appendix B and C is that there is no restrictions on the temperature to the drying chamber in appendix B while the max temperature in appendix C is 45°C.

Two graphs are shown in appendix B and C for each day. The first graph shows the ambient temperature and ambient relative humidity together with the temperature and relative humidity of the air from the collector. The second graph shows the flow rate of air and the power input from the sun to the air.

References

Fechner, H., 1999. IEA Task 19 Solar Air Systems. Investigation on Series Produced Solar Air Collectors. Arsenal Research. Department of Renewable Energy. Austria.

Jensen, S.Ø., 1994. Test of the Summer House Package from Aidt Miljø. Thermal Insulation Laboratory. Technical University of Denmark. Report no. 94-1,

Jensen, S.Ø., 2000. Ghanaian weather data for simulation purposes. Solar Energy Centre Denmark, Danish Technological Institute. ISBN 87-7756-582-7.

3. Simulation of a solar air collector for a solar kiln for Ghana

The purpose of the chapter is to investigate the temperature level and power output of a solar air collector under Ghanaian weather conditions. The purpose of the solar air collector is to be used in connection with a solar kiln for drying of wood.

The weather data is from Kumasi. Weather data for three days in November 1999 and January 2000 has been applied (Jensen, 2000). They represent a clear day, an average day and an overcast day for both months. The weather data are shown in appendix A.

As efficiency for the solar air collector is used the measured values for the solar air collector from the Summer House Package from Aidt Miljø. This collector utilize the same type of cloth absorber as is foreseen to be used in the collector of the solar kiln. The efficiency of the two collectors is, therefore, assumed to be rather similar. The efficiency is from (Fechner, 1999). The measured efficiency of the collector when re-circulating air is shown in figures 3.1. The air flow rate through the collector is assumed to be constant over the day.

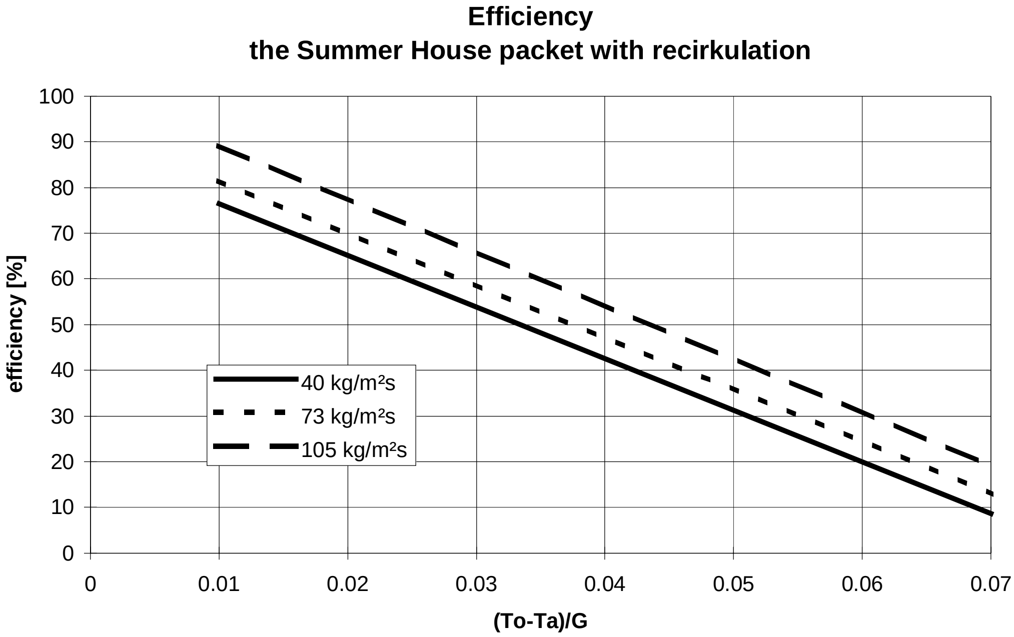


Figure 3.1. The applied efficiency curves for the solar air collector.
Where: T_o is the outlet temperature of the collector [°C],
T_a is the ambient temperature [°C],
G is the usable solar radiation on the collector (ie corrected for the incidence angle of the solar radiation) [W/m²].

Based on the measured efficiency curves from figure 3.1 the following equation for the efficiency dependent on the mass flow rate of the air has been established:

$$\eta = a \cdot (T_o - T_a)/G + b \quad (3.1)$$

where: $a = -1139.2 + 0.5653 \cdot m - 0.0084 \cdot m^2$
$b = 86.161 - 0.0204 \cdot m + 0.0015\ m^2$
m is the mass flow rate of the air [kg/m²s].

A small simulation program has been developed which is able to calculate the temperature, relative humidity of the air out of the solar collector and the power transferred to air in the collector. The program is using the weather data in appendix A and calculates hour by hour the direct solar radiation and the incidence angle of the direct solar radiation on the collector. Together with the diffuse radiation the useful radiation is calculated by correcting for the reflection of the radiation by the cover of the solar air collector at higher incidence angles than zero degree.

The input parameters is: the incidence angle modifier of the cover of the collector and the tilt and orientation of the collector. Information on the air flow rate and the efficiency of the solar air collector. For the efficiency a reduction factor has to be given, which is multiplied with the efficiency shown in figure 3.1 and equation 3.1. A reduction factor of 1 gives the curve in figure 3.1. The reduction factor may be used for parameter studies on the effect of the efficiency of the collector on the performance of the system.

The simulation program does not contain a drying chamber. Instead the program reads the inlet temperature and the relative humidity of the air to the collector in a file containing values for the two parameters for each hour of the day. In this way it will be possible to simulate the dynamic behaviour of the collector with regards not only to the climate but also to the conditions in a drying chamber.

Results from using the simulation program are shown in appendix C-E. The following input parameters to the simulation program has been used:

incidence angle modifier:	3
tilt:	15°
orientation:	south
air flow rate:	60 m^3/m^2h
reduction of efficiency:	0.9 as the collector is expected to be a little less efficient than the collector in the Summer House Package
Inlet temperature:	50 °C (appendix C), 35°C (appendix D) and ambient temperature + 5 K (appendix E)
Relative humidity of the air:	95%

Three different inlet temperatures (kiln temperatures) have been applied in order to investigate the influence of this parameter on the performance of the collector.

Two graphs are shown in appendix C-E for each day. The first graph shows the temperature and relative humidity of the air to and from the collector together with the ambient temperature. The second graph shows the power input from the sun to the air and the efficiency of the collector.

The daily energy input to the drying chamber from the solar air collector lay for the abovementioned conditions between 0.11 and 2.56 kWh/m^2. Together with knowledge on the necessary drying conditions for wood these values will make it possible to make a first guess on the size of the solar kiln - ie the capacity and solar collector area.

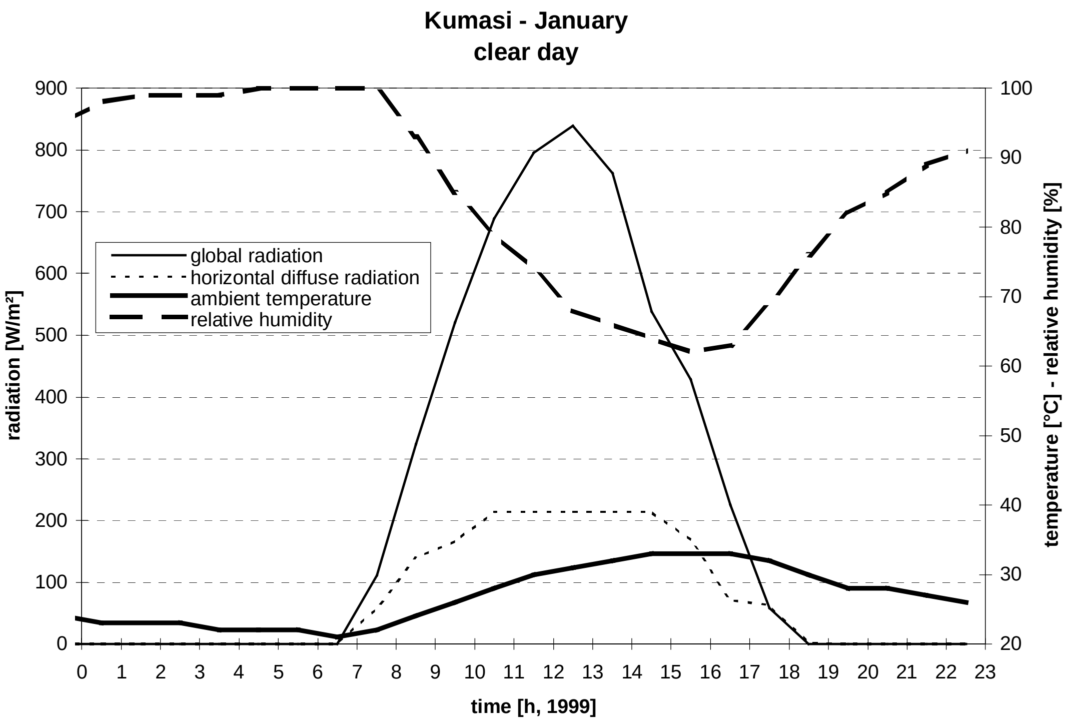
References

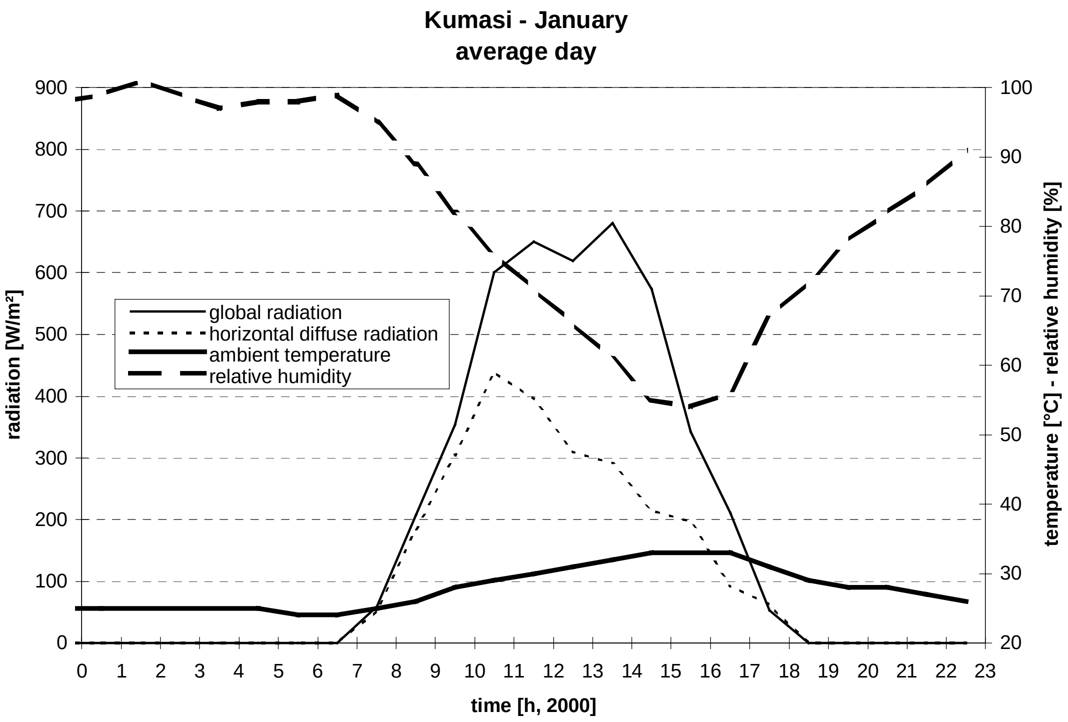
Fechner, H., 1999. IEA Task 19 Solar Air Systems. Investigation on Series Produced Solar Air Collectors. Arsenal Research. Department of Renewable Energy. Austria.

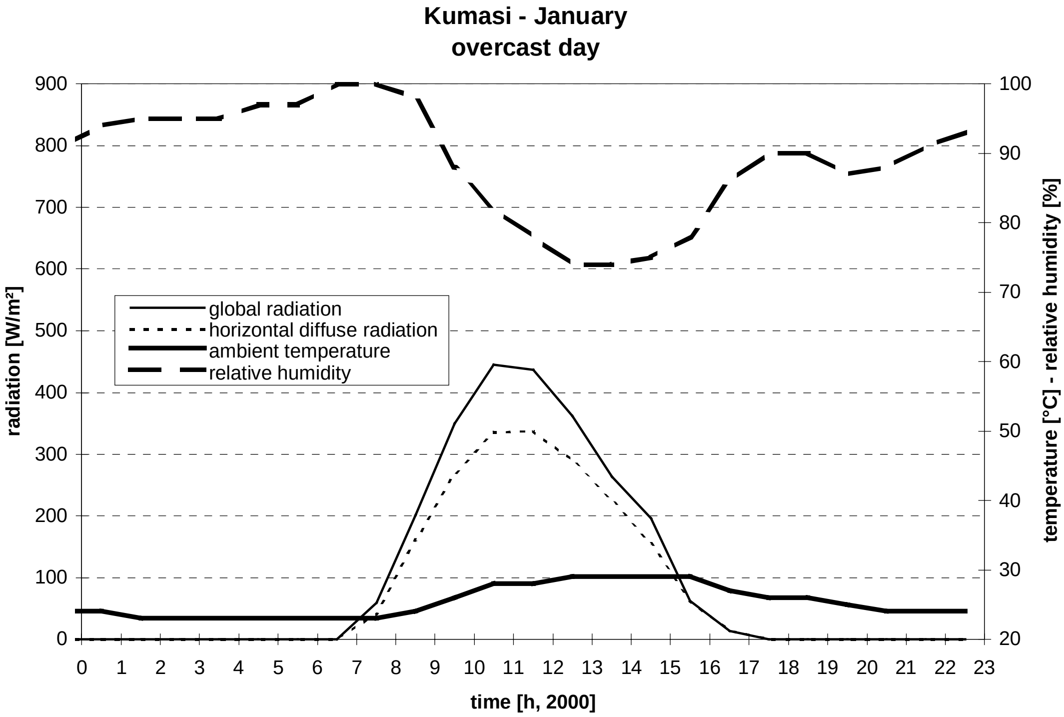
Jensen, S.Ø., 2000. Ghanaian weather data for simulation purposes. Solar Energy Centre Denmark, Danish Technological Institute. ISBN 87-7756-582-7.

Appendix A

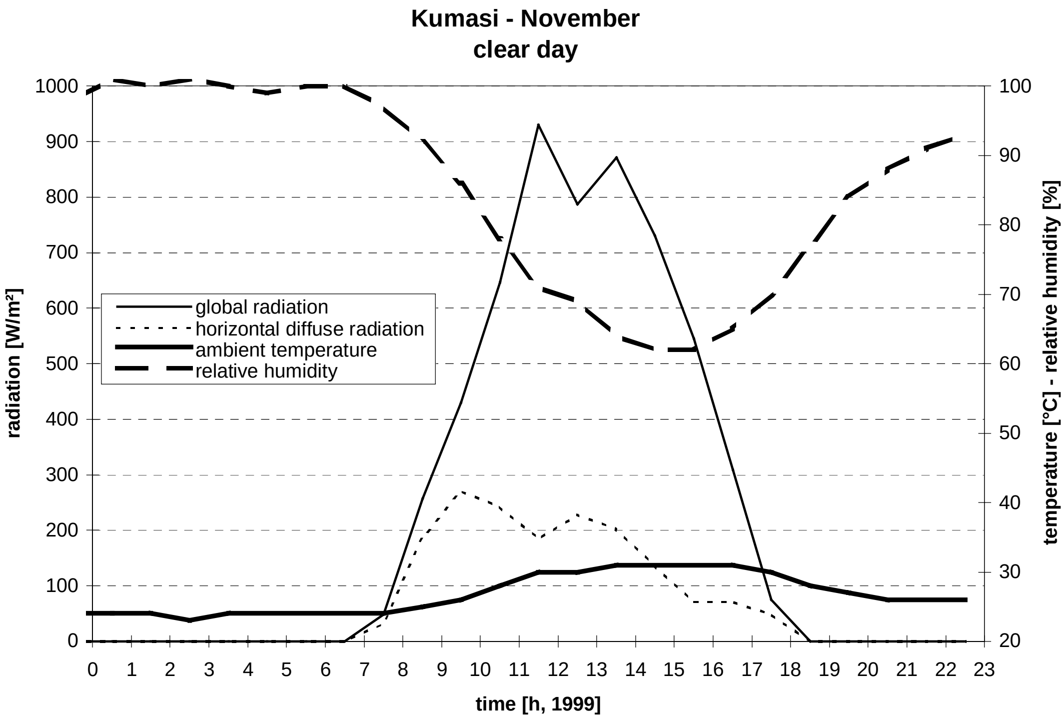
January 2000

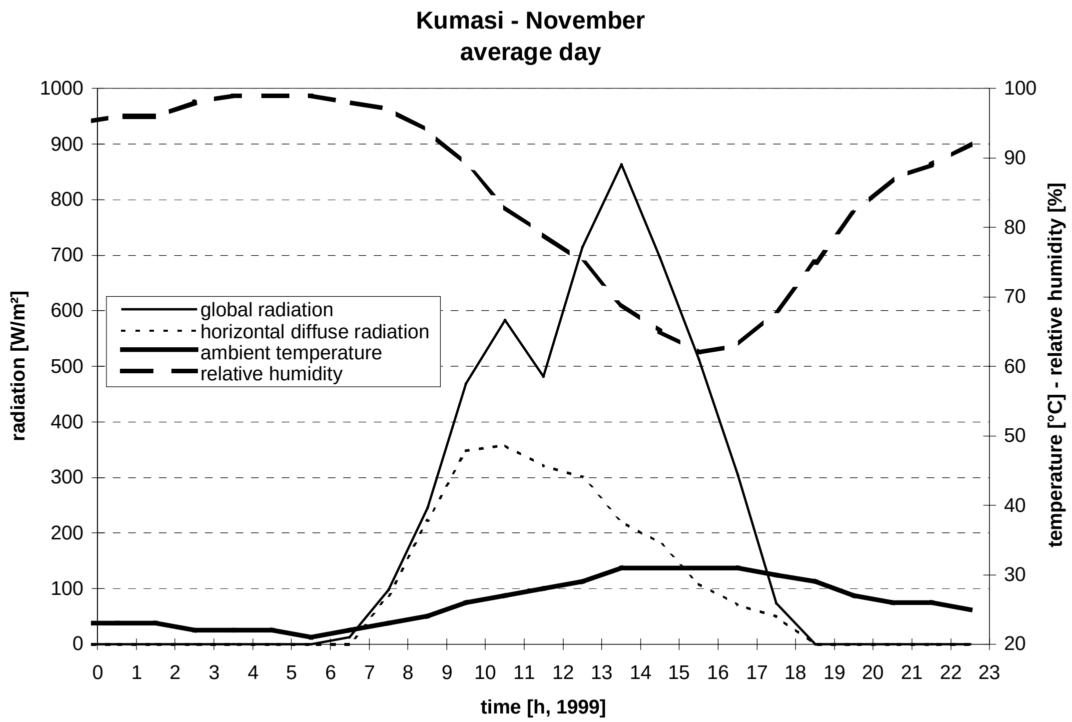






November 1999




Kumasi - November
average day
radiation [W/m²]
temperature [°C] - relative humidity [%]
time [h, 1999]
global radiation
horizontal diffuse radiation
ambient temperature
relative humidity
0
100
200
300
400
500
600
700
800
900
1000
20
30
40
50
60
70
80
90
100
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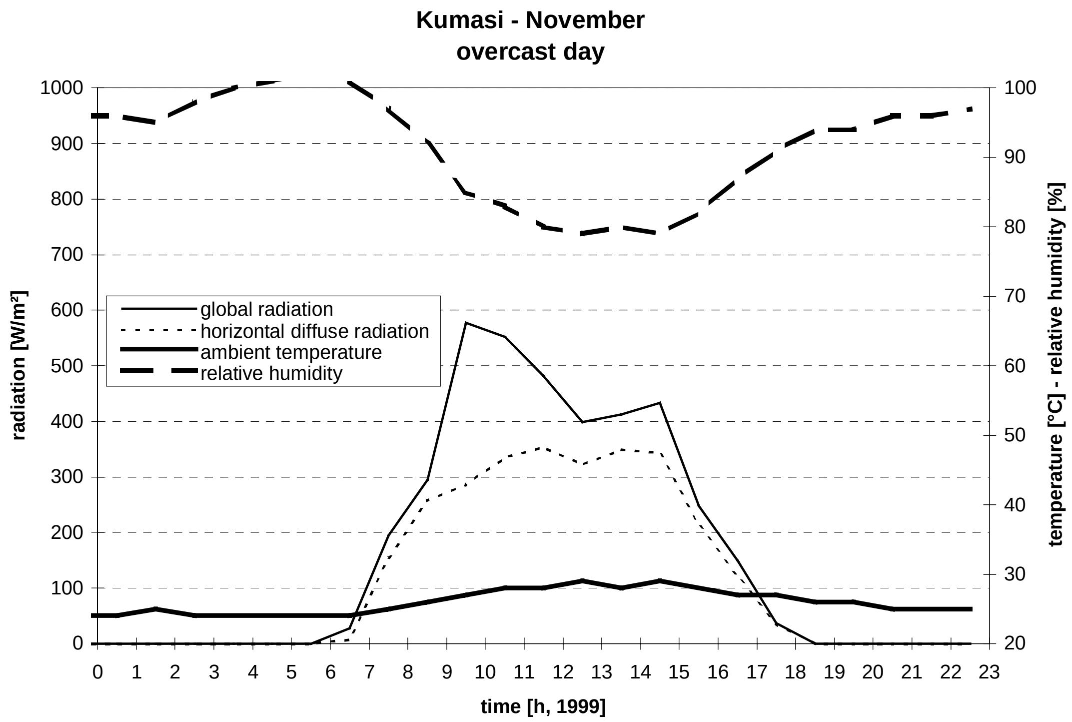
Kumasi - November
overcast day
radiation [W/m²]
temperature [°C] - relative humidity [%]
time [h, 1999]
global radiation
horizontal diffuse radiation
ambient temperature
relative humidity
0
100
200
300
400
500
600
700
800
900
1000
20
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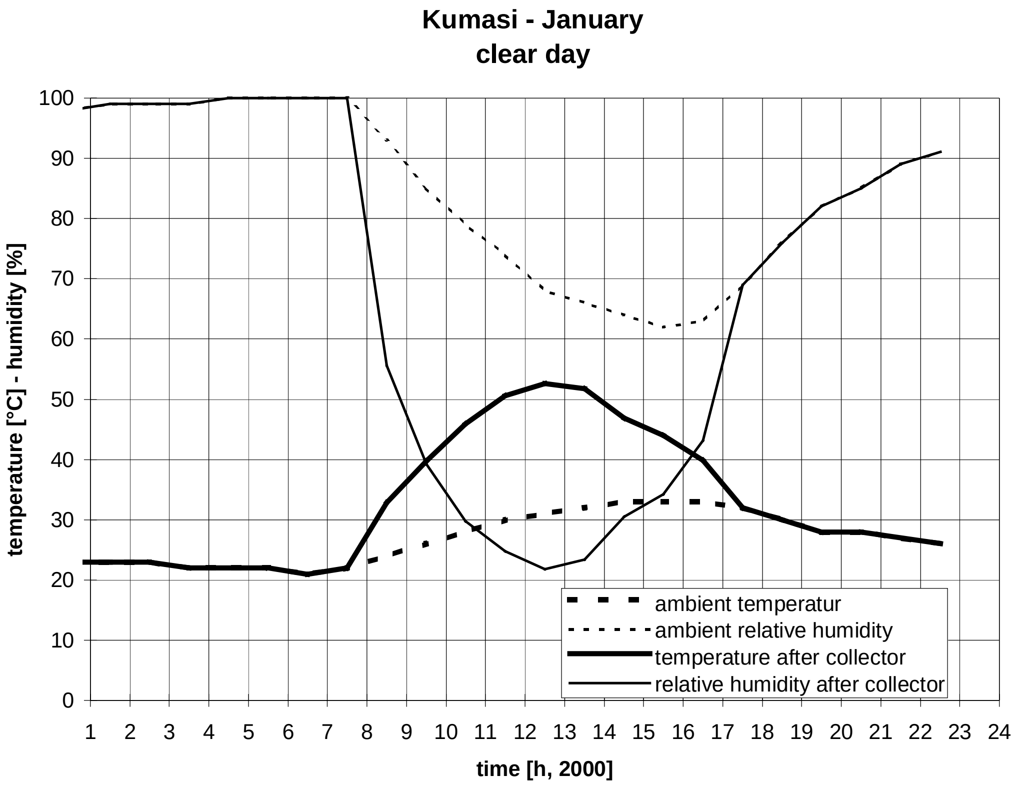
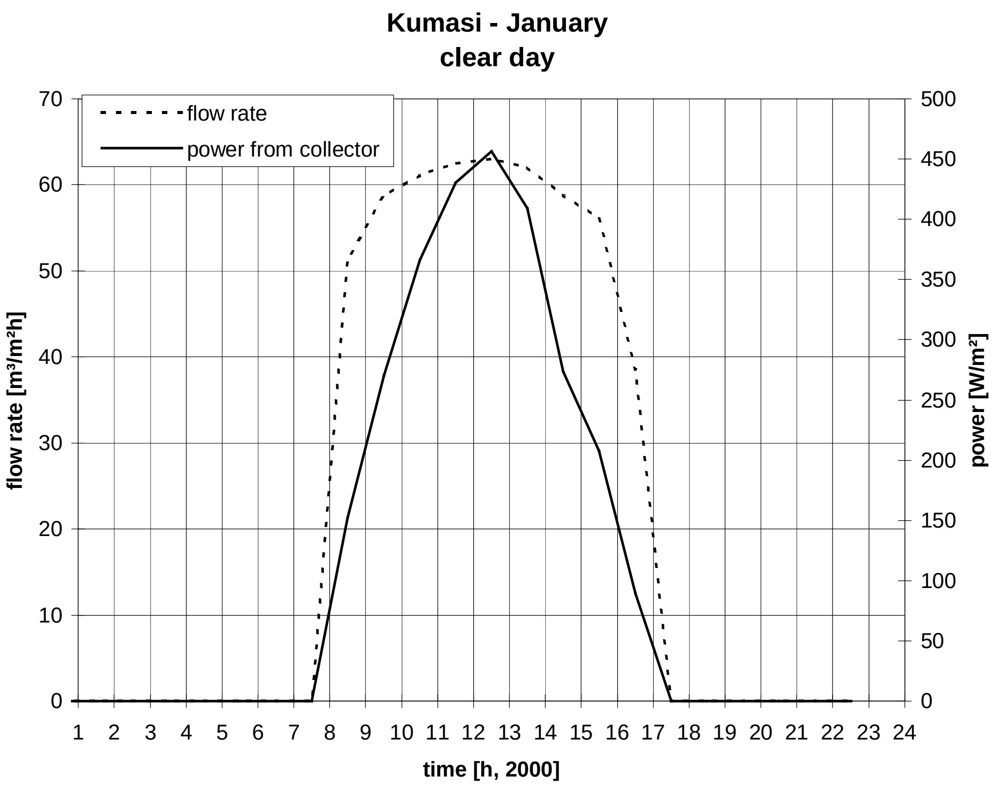
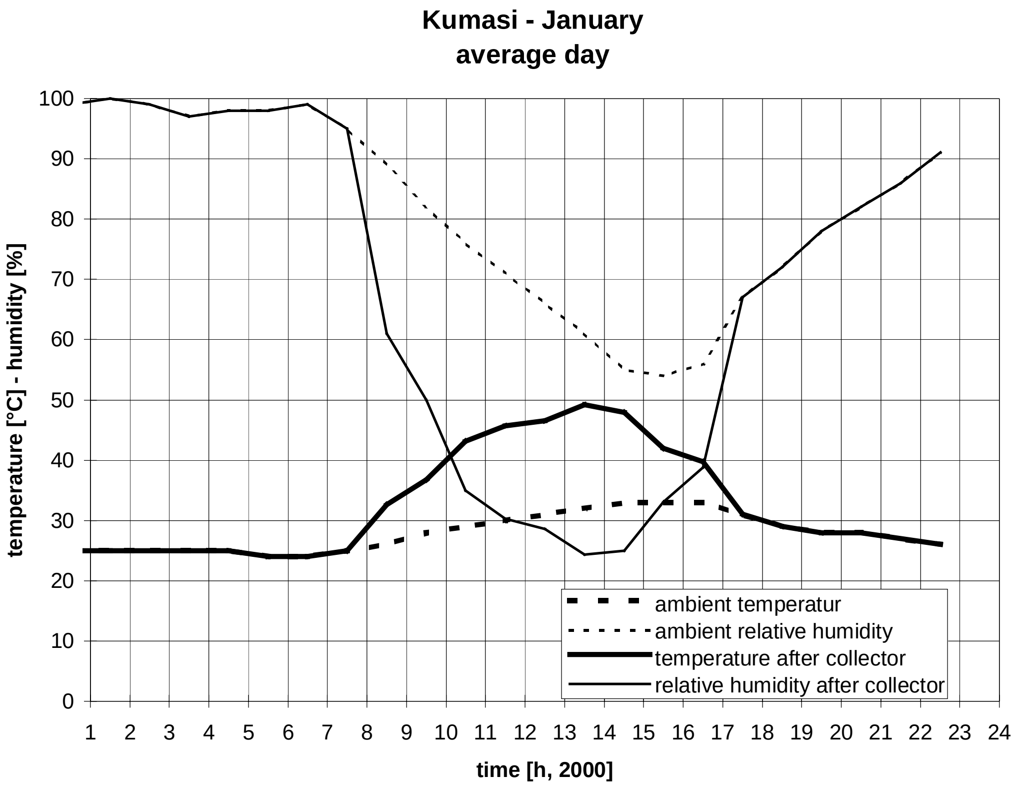
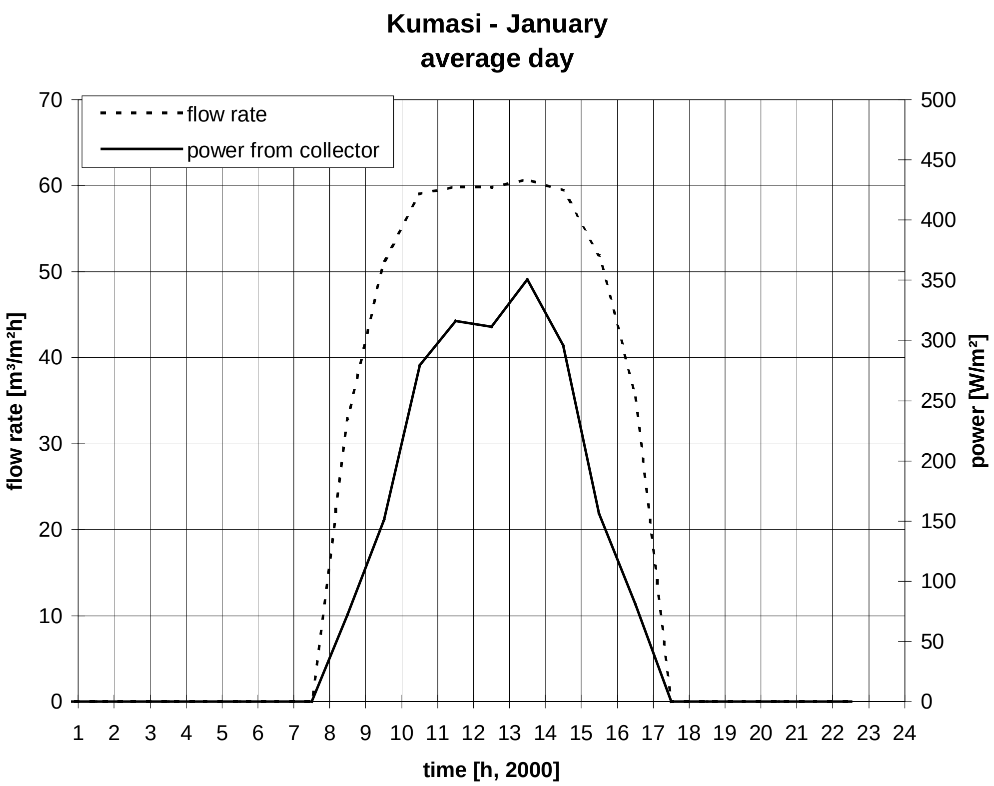
Appendix B

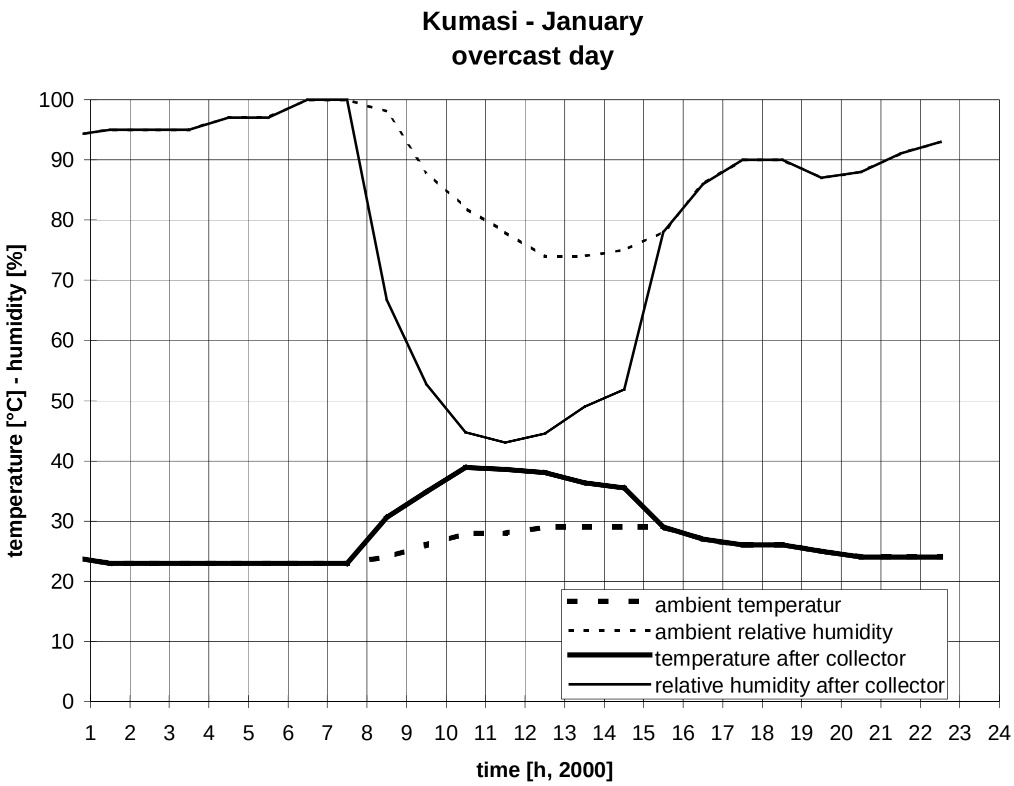
January 2000

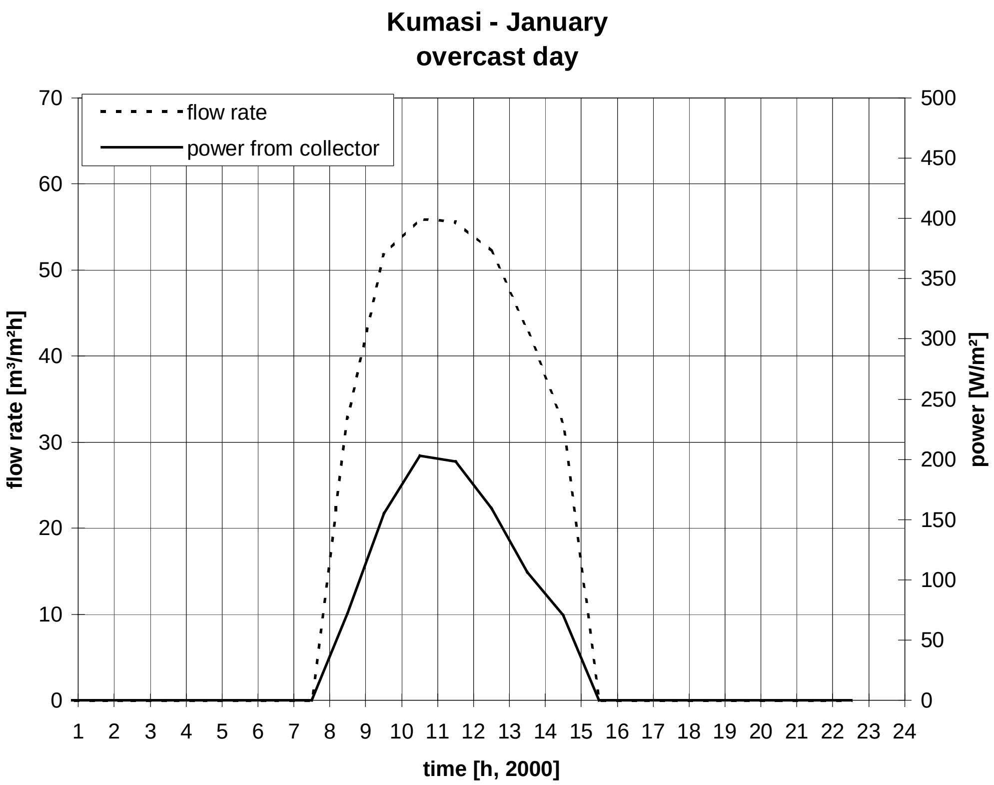





Kumasi - January
average day
temperature [°C] - humidity [%]
time [h, 2000]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector


Kumasi - January
average day
flow rate [m³/m²h]
power [W/m²]
time [h, 2000]
flow rate
power from collector


Kumasi - January
overcast day
temperature [°C] - humidity [%]
time [h, 2000]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector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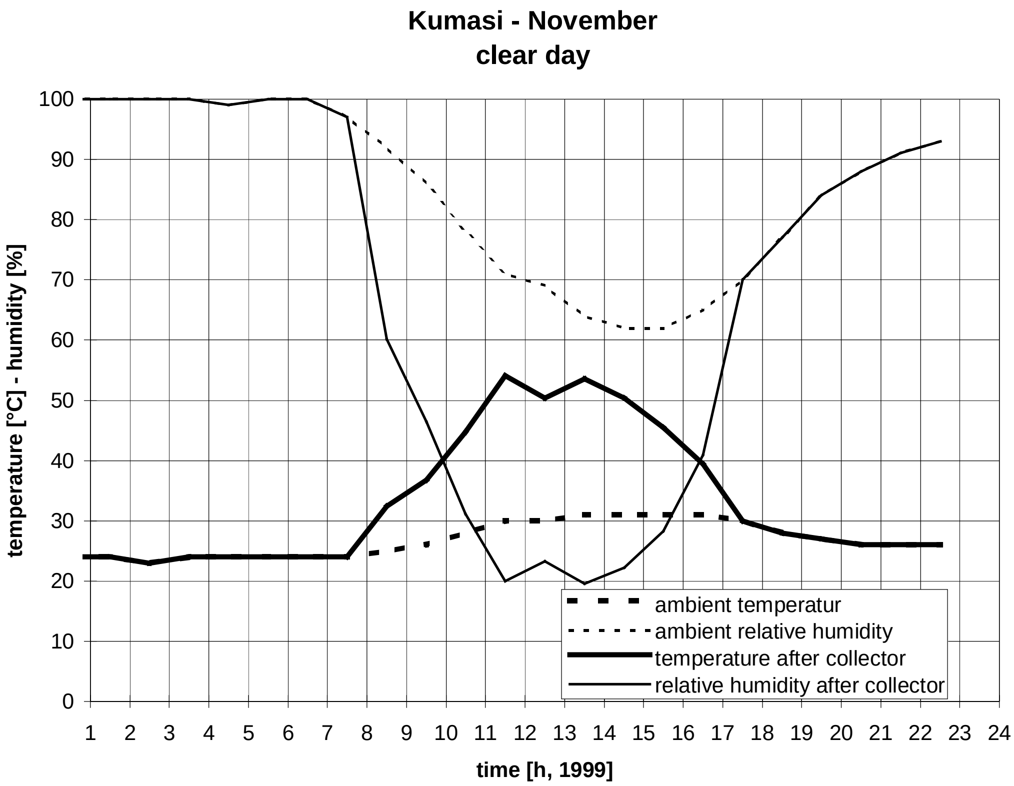
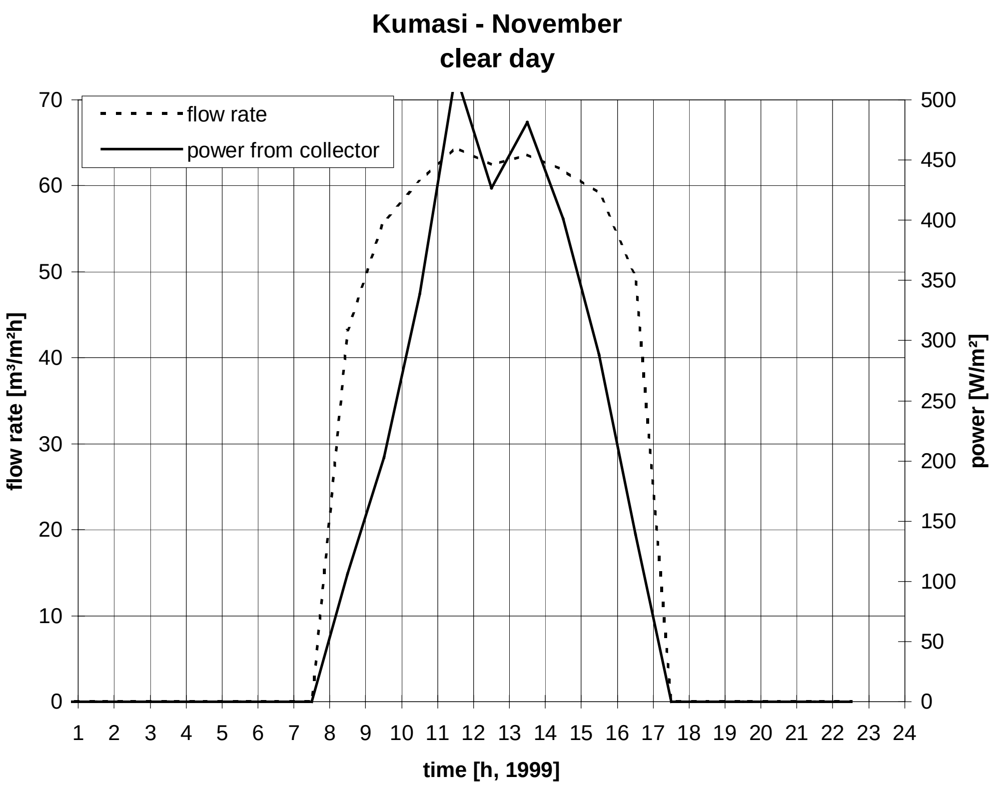
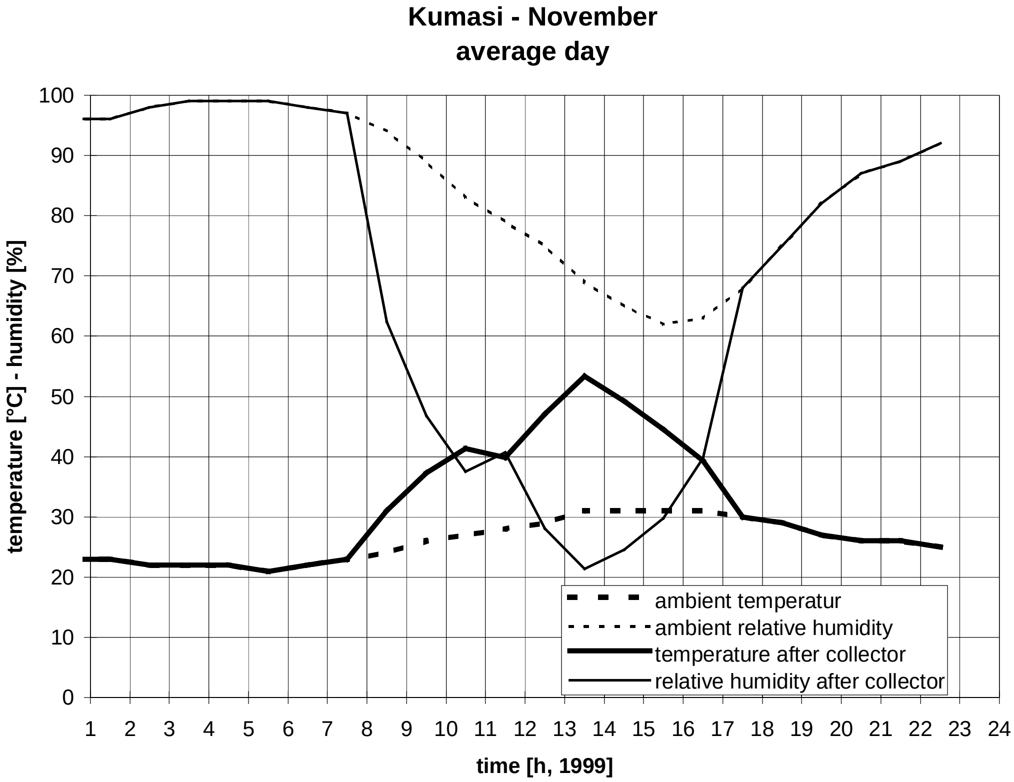
overcast day
flow rate [m³/m²h]
power [W/m²]
time [h, 2000]
flow rate
power from collector

February 1999






Kumasi - November
average day
temperature [°C] - humidity [%]
time [h, 1999]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector
100
90
80
70
60
50
40
30
20
10
0
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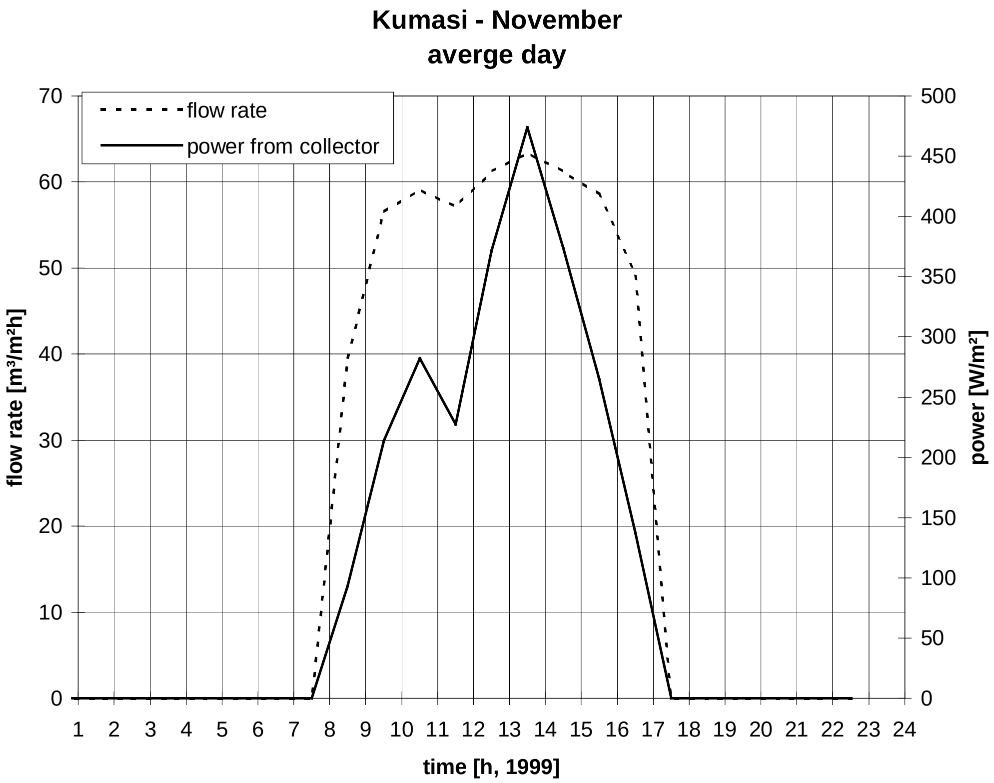
Kumasi - November
averge day
flow rate [m³/m²h]
power [W/m²]
time [h, 1999]
flow rate
power from collector
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50
40
30
20
10
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300
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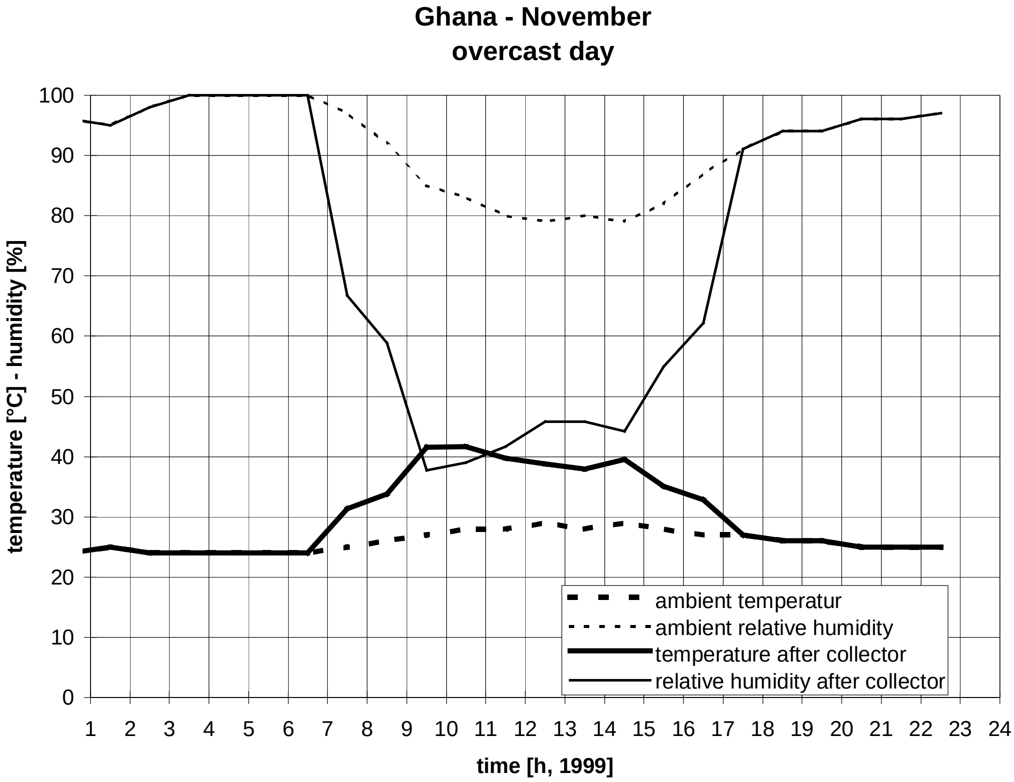
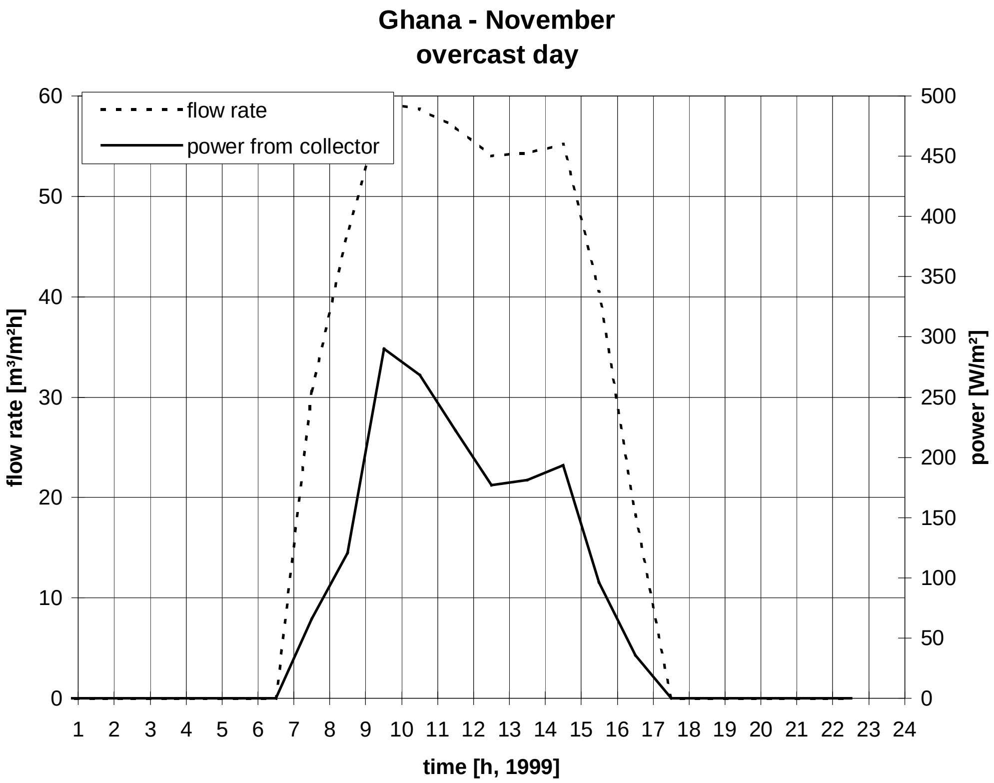
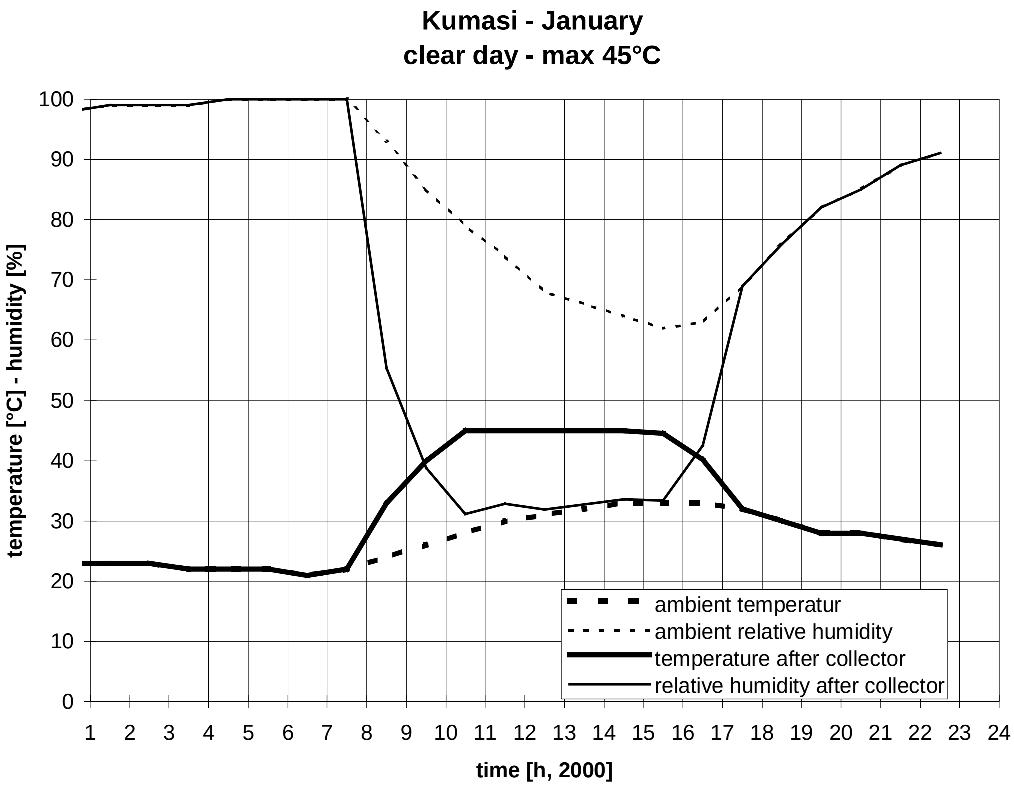
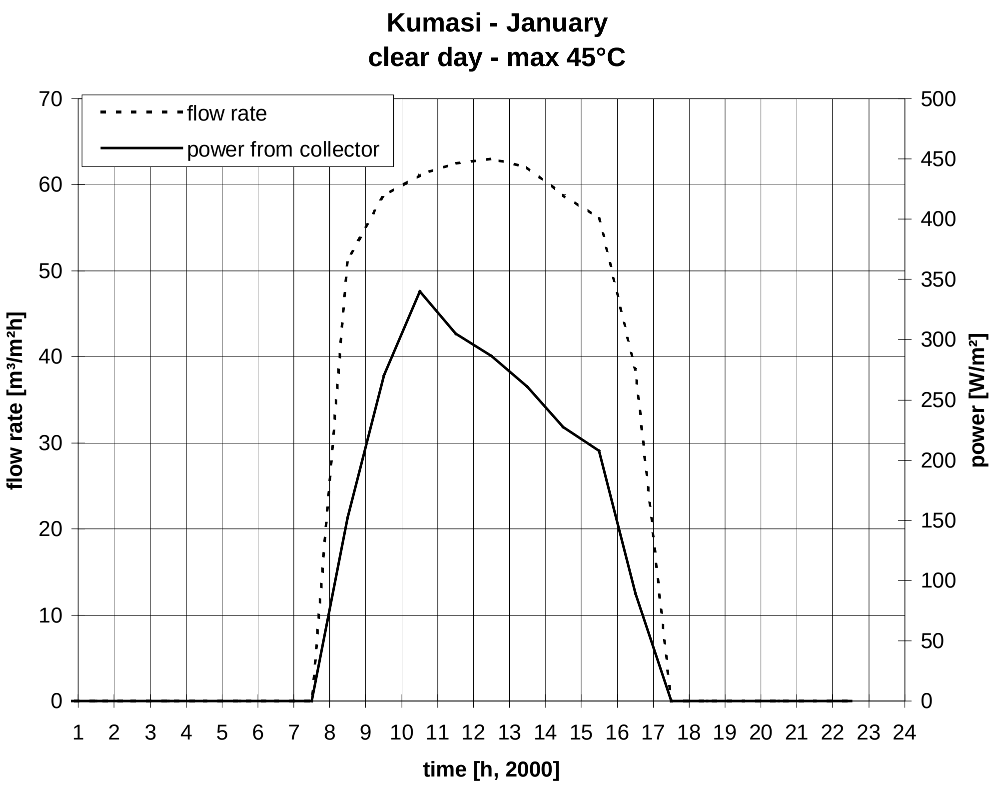

Ghana - November
overcast day
temperature [°C] - humidity [%]
time [h, 1999]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector

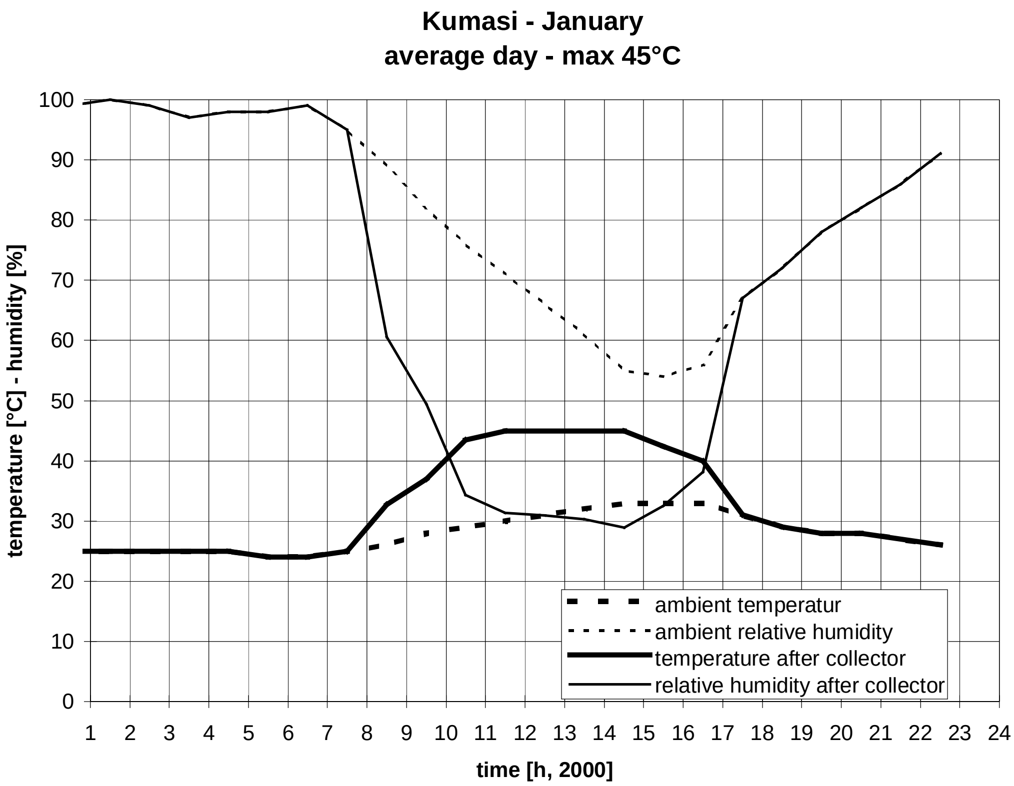

Ghana - November
overcast day
flow rate [m³/m²h]
power [W/m²]
time [h, 1999]
flow rate
power from collector

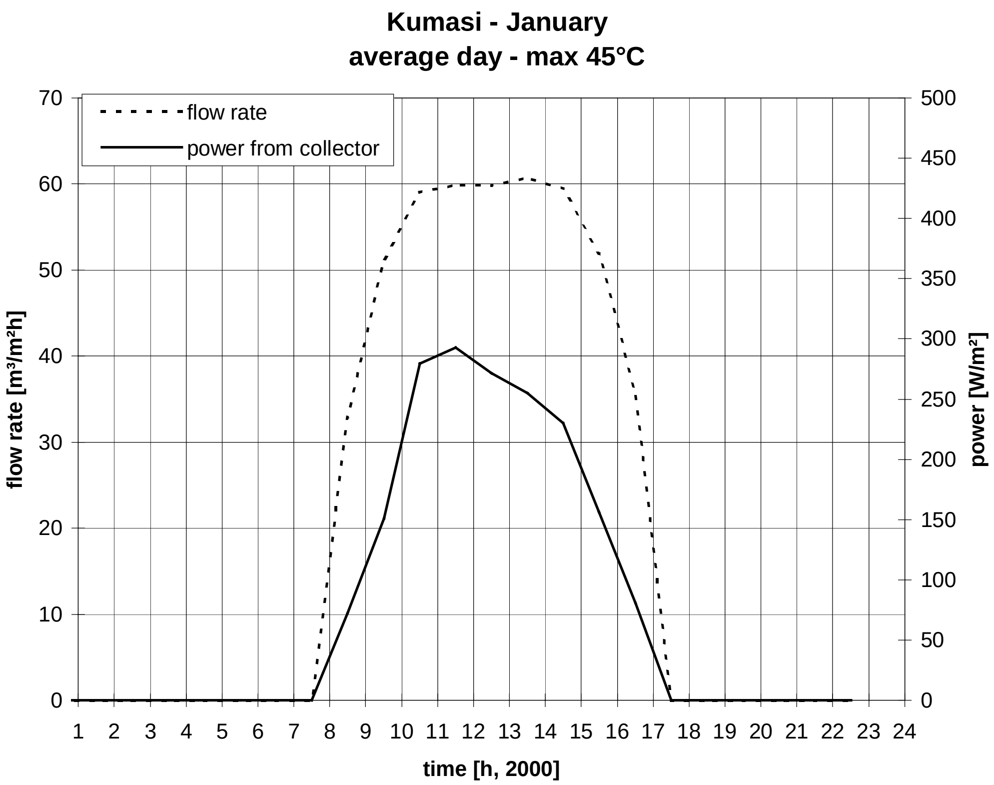
Appendix C

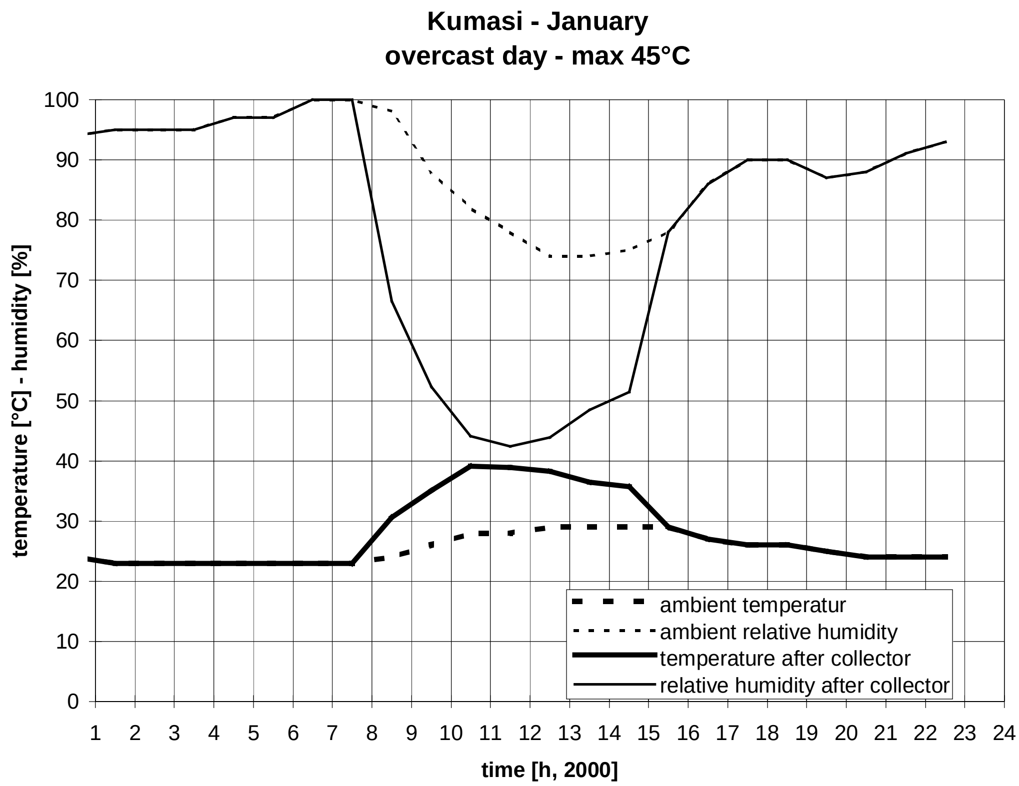
January 2000 - max 45°C

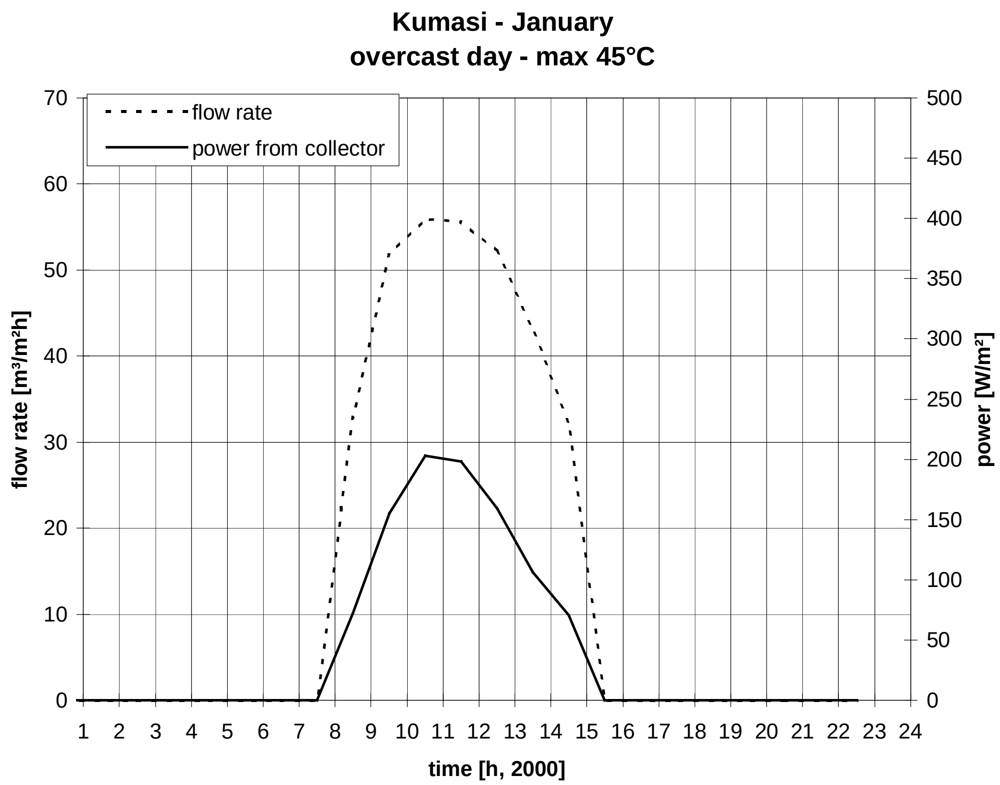





Kumasi - January
average day - max 45°C
temperature [°C] - humidity [%]
time [h, 2000]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector


Kumasi - January
average day - max 45°C
flow rate [m³/m²h]
power [W/m²]
time [h, 2000]
flow rate
power from collector


Kumasi - January
overcast day - max 45°C
temperature [°C] - humidity [%]
time [h, 2000]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector
100
90
80
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24


Kumasi - January
overcast day - max 45°C
flow rate
power from collector
flow rate [m³/m²h]
power [W/m²]
time [h, 2000]
70
60
50
40
30
20
10
0
500
450
400
350
300
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200
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100
50
0
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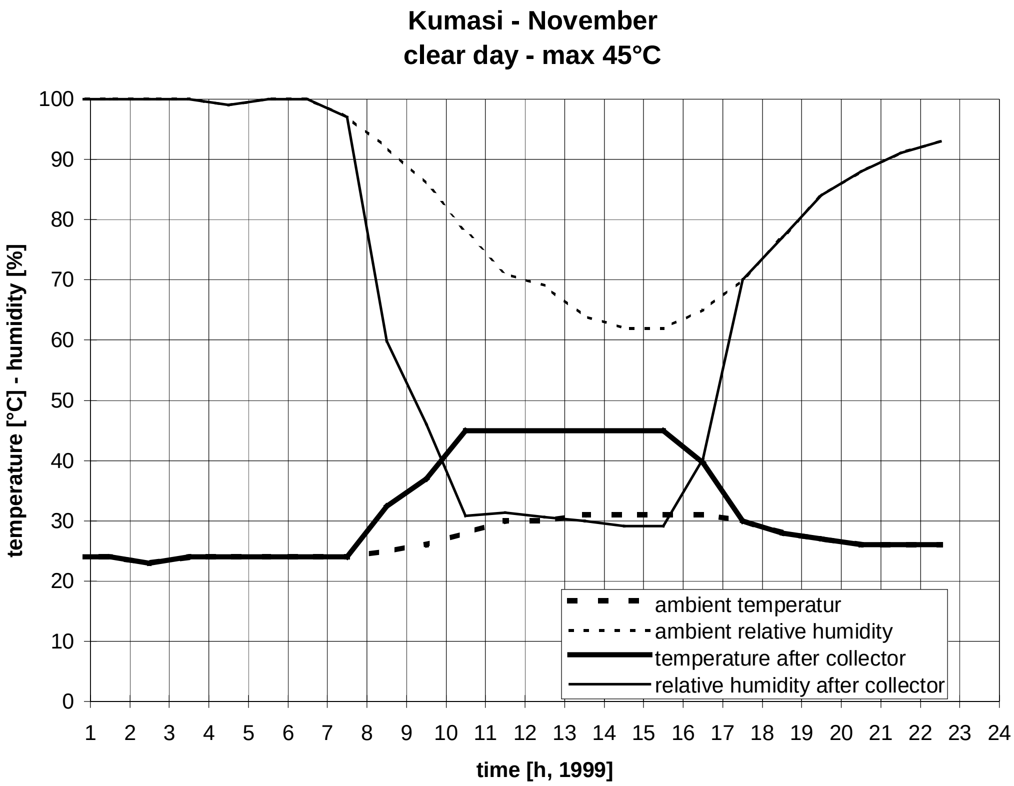
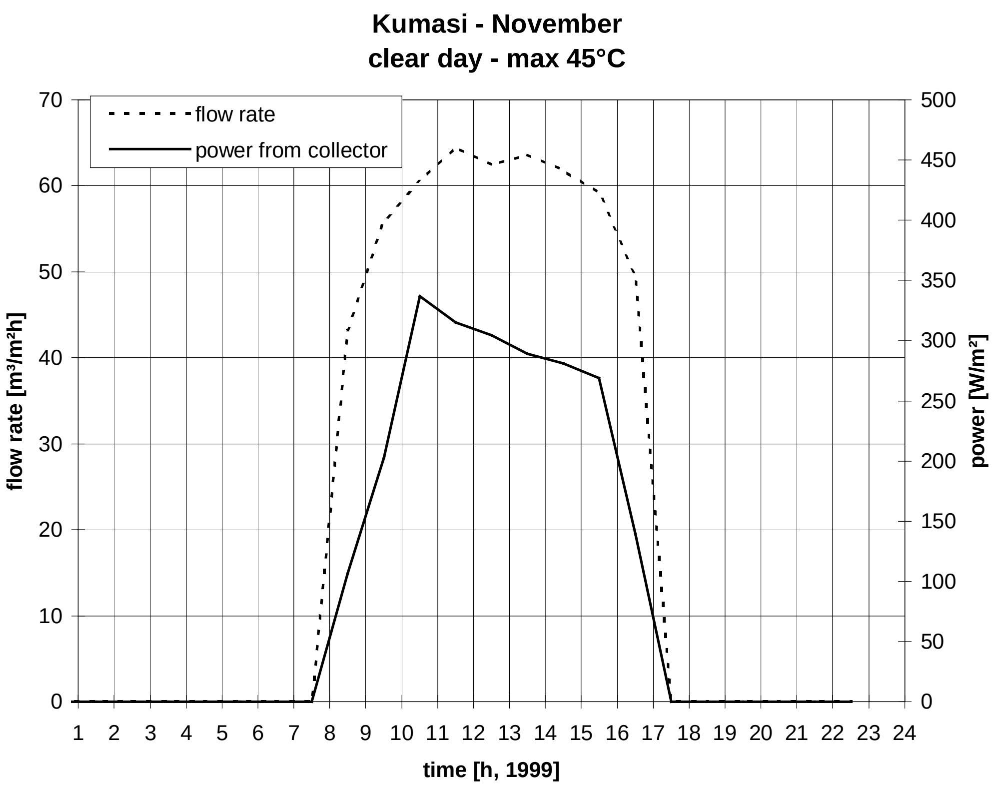
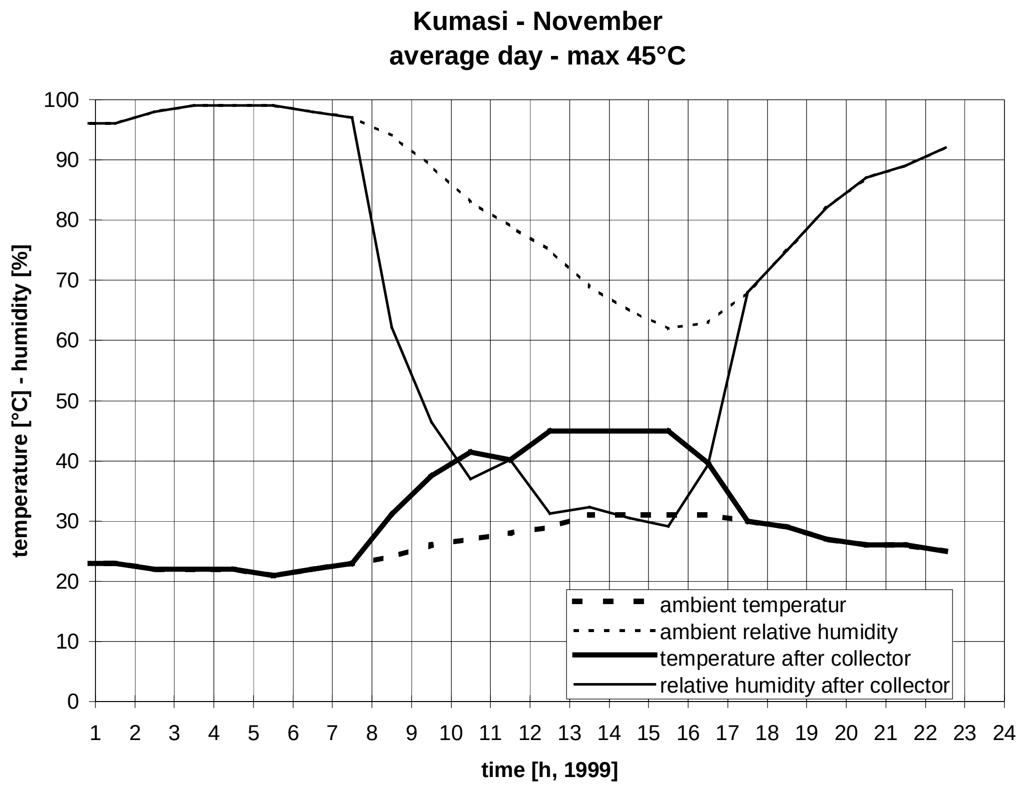
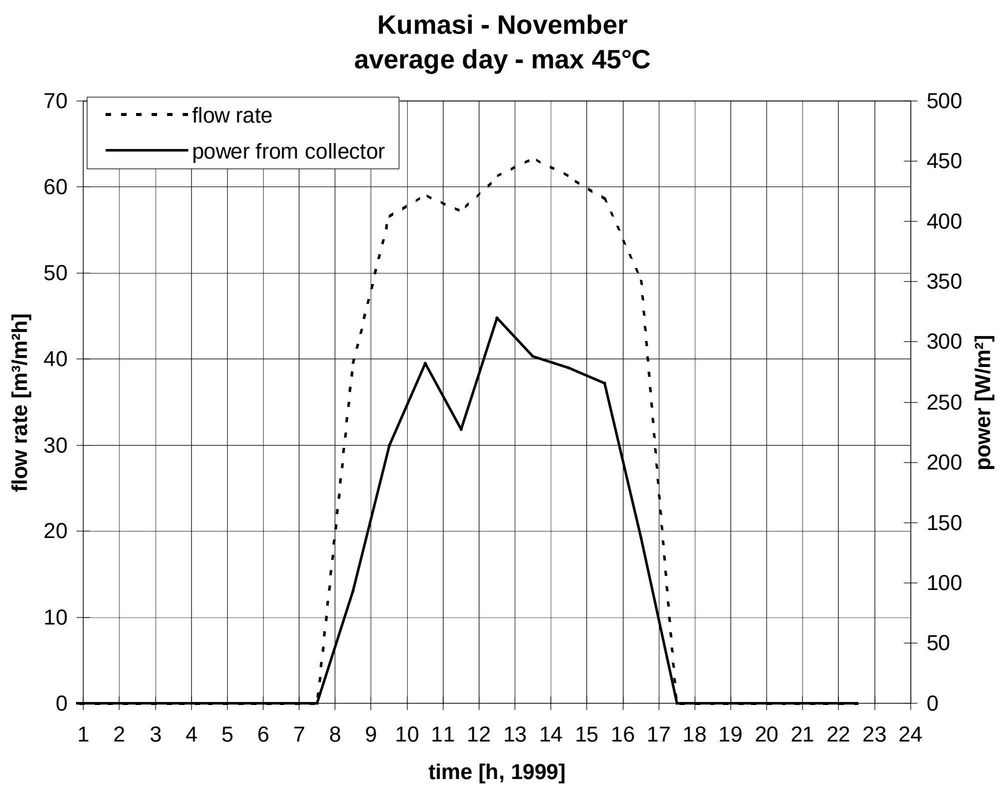
February 1999 - max 45°C



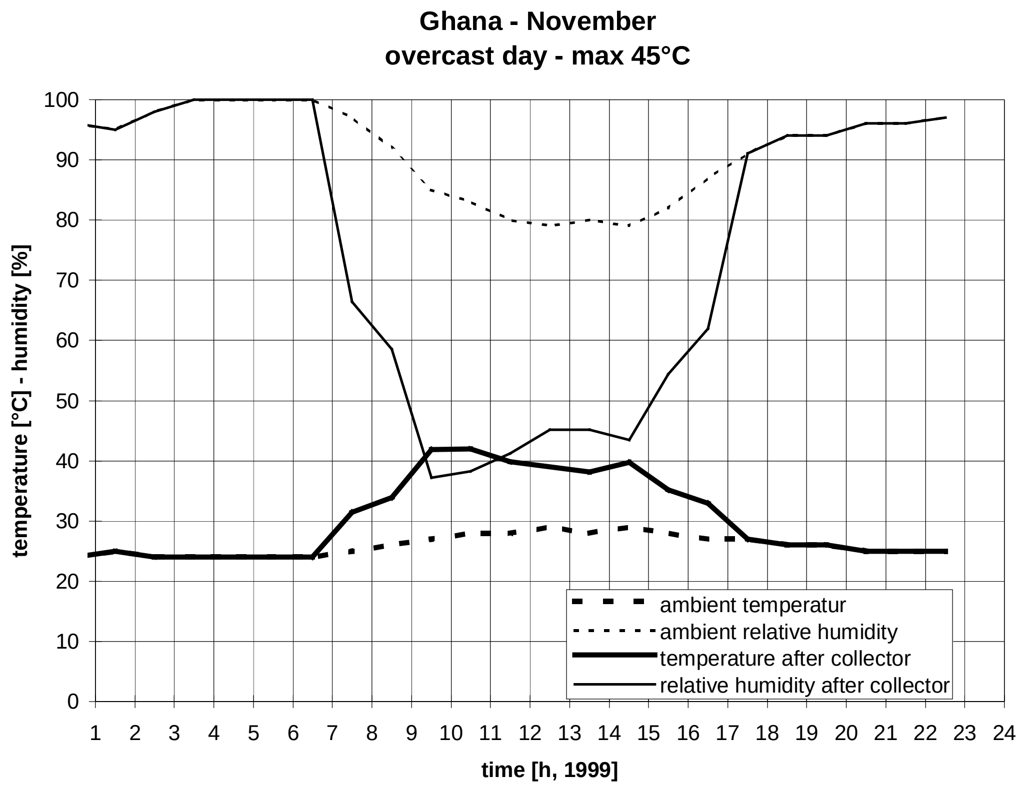




Kumasi - November
average day - max 45°C
temperature [°C] - humidity [%]
time [h, 1999]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector



Kumasi - November
average day - max 45°C
flow rate [m³/m²h]
power [W/m²]
time [h, 1999]
flow rate
power from collector


Ghana - November
overcast day - max 45°C
temperature [°C] - humidity [%]
time [h, 1999]
ambient temperatur
ambient relative humidity
temperature after collector
relative humidity after collector
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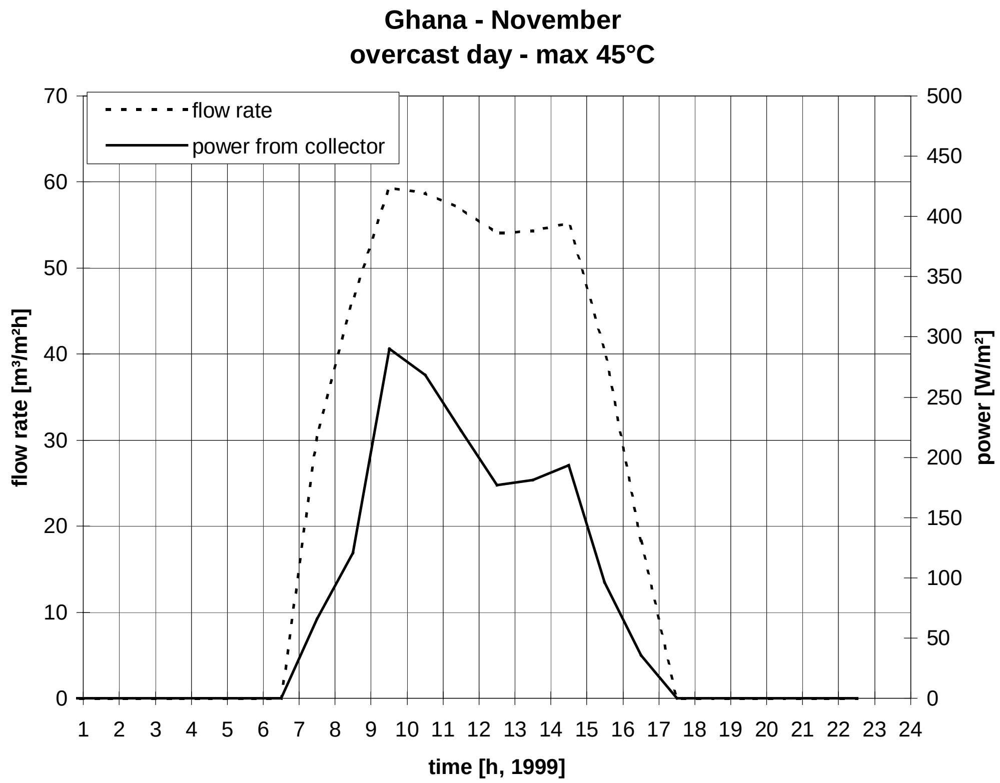
Ghana - November
overcast day - max 45°C
flow rate [m³/m²h]
power [W/m²]
time [h, 1999]
flow rate
power from collector
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60
70
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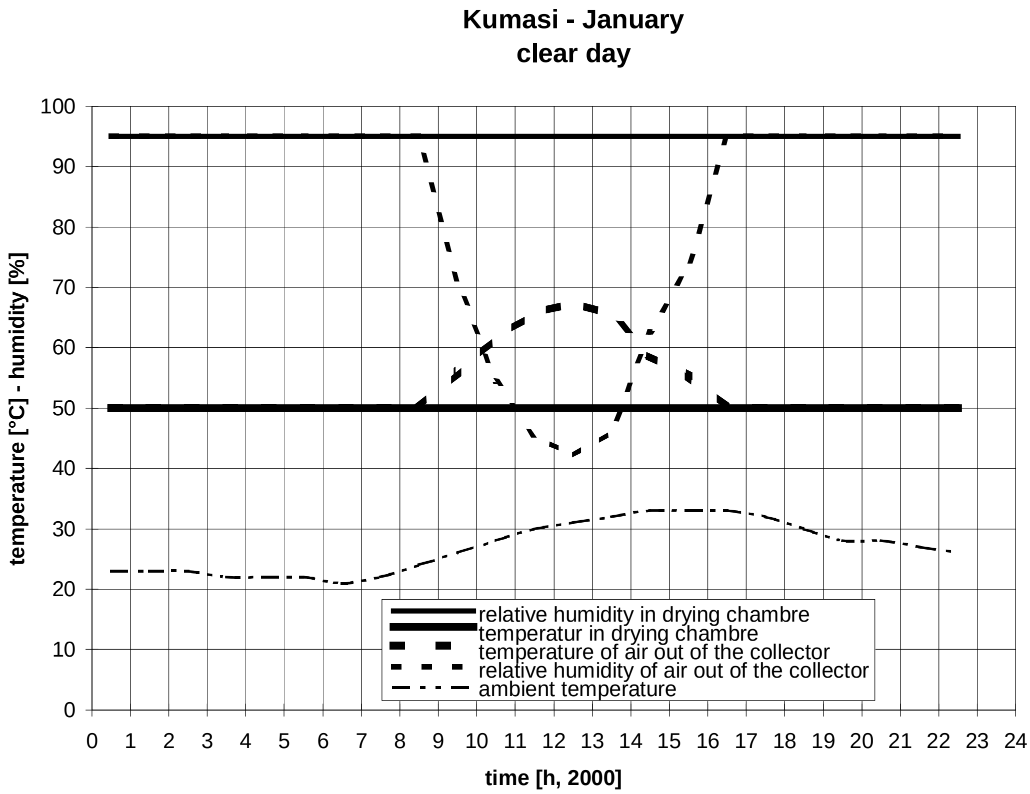
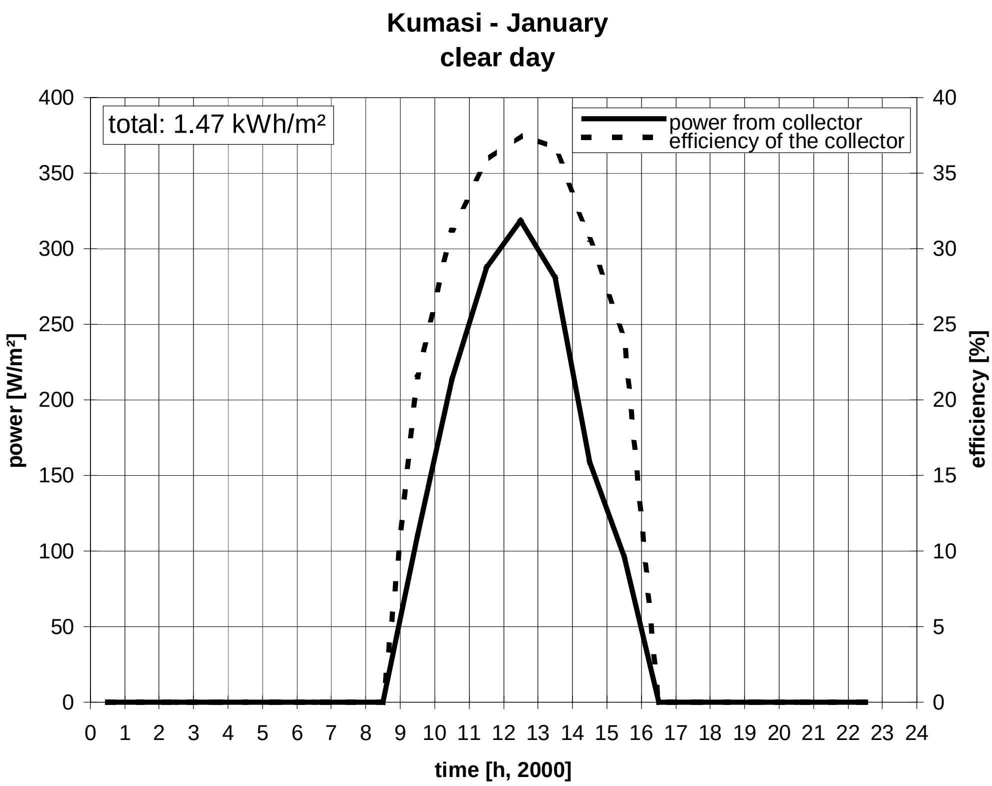
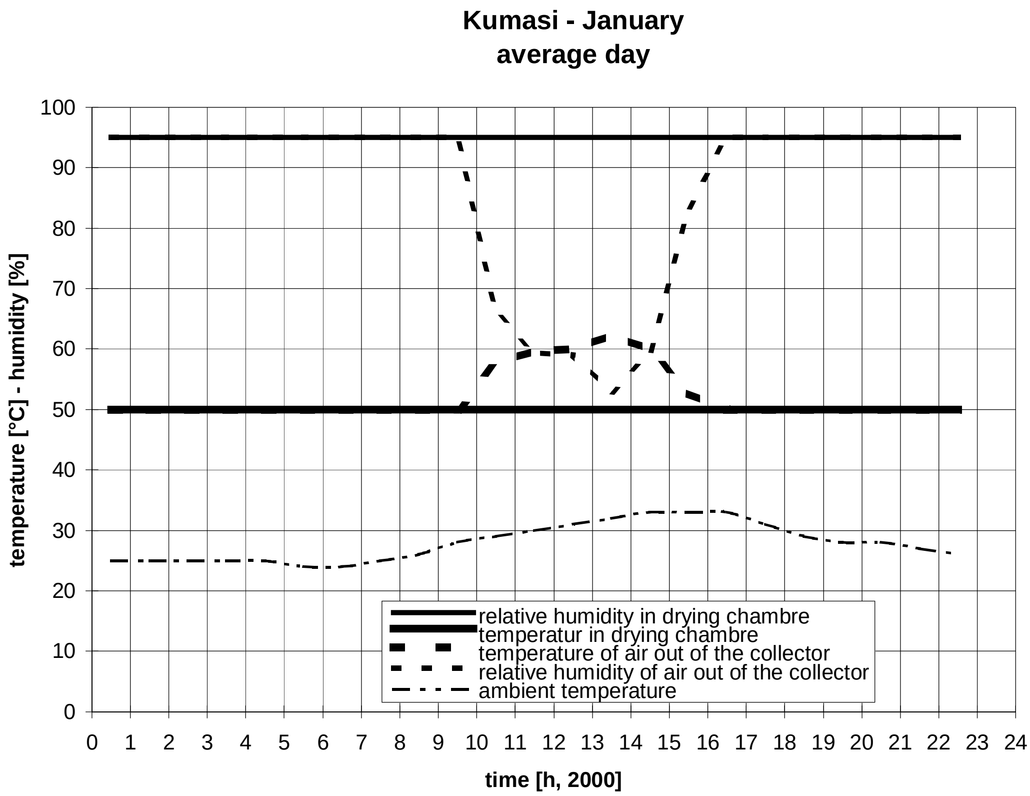
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

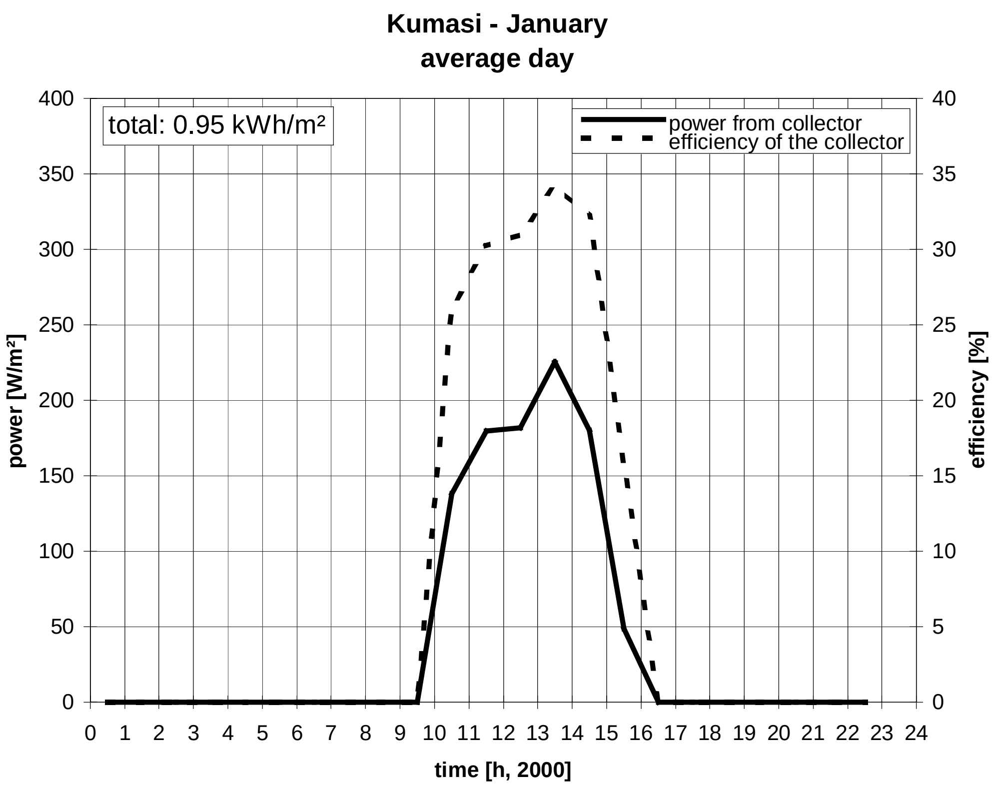
Appendix C

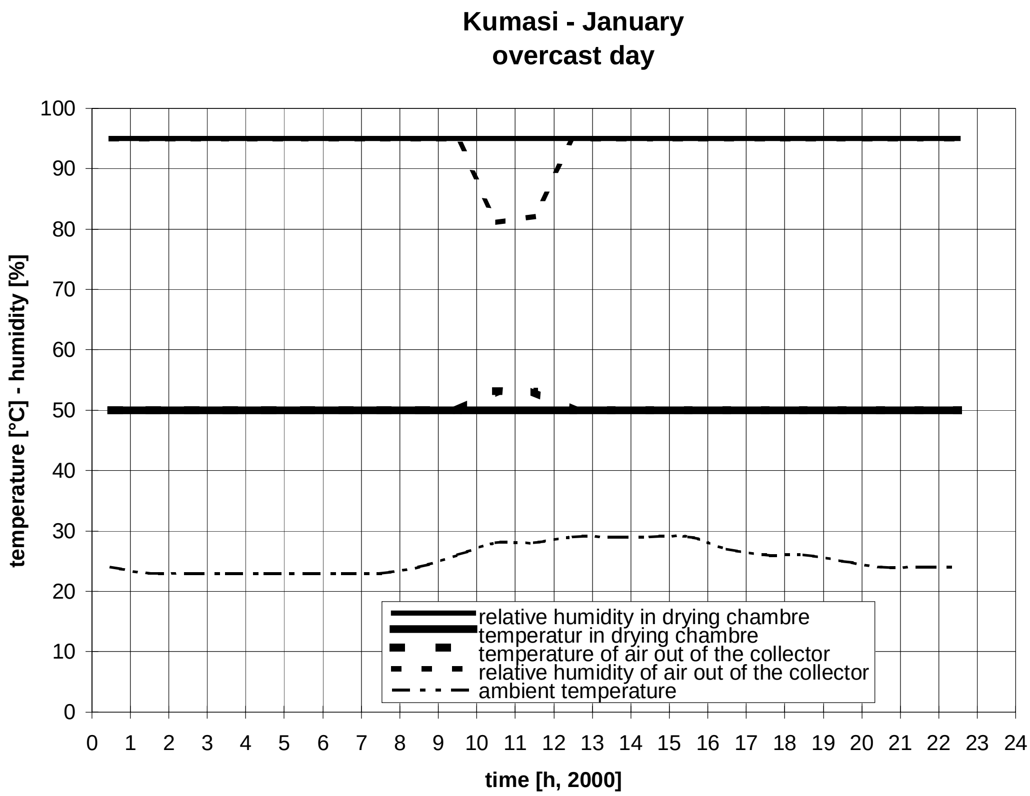
January 2000 - kiln temperature: 50°C

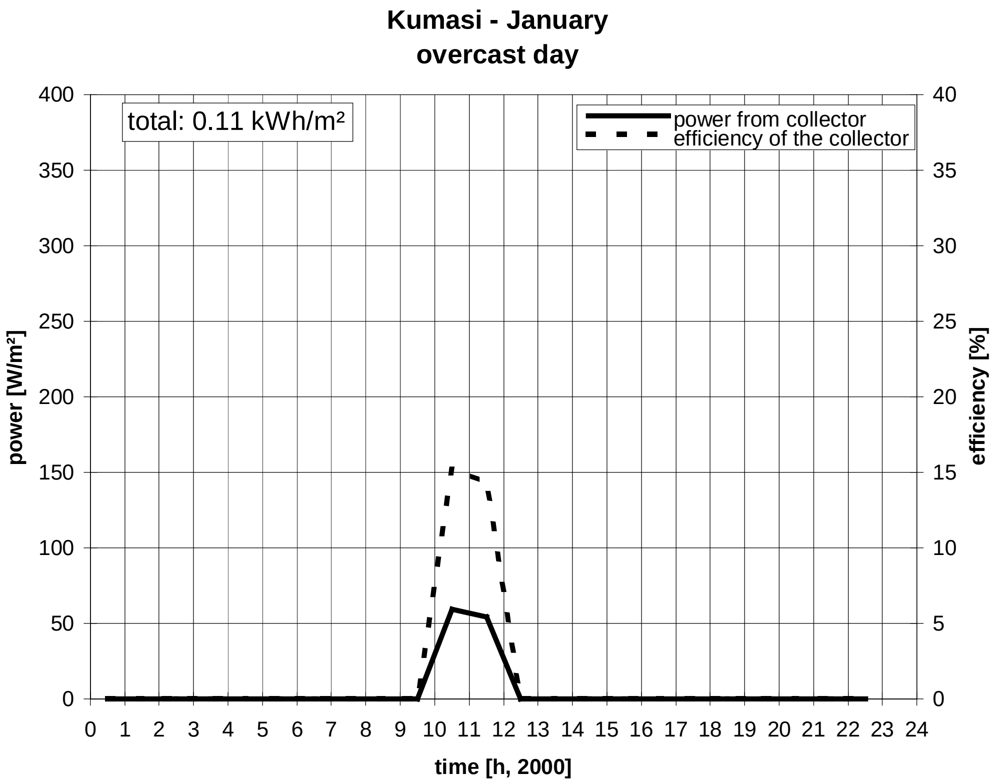




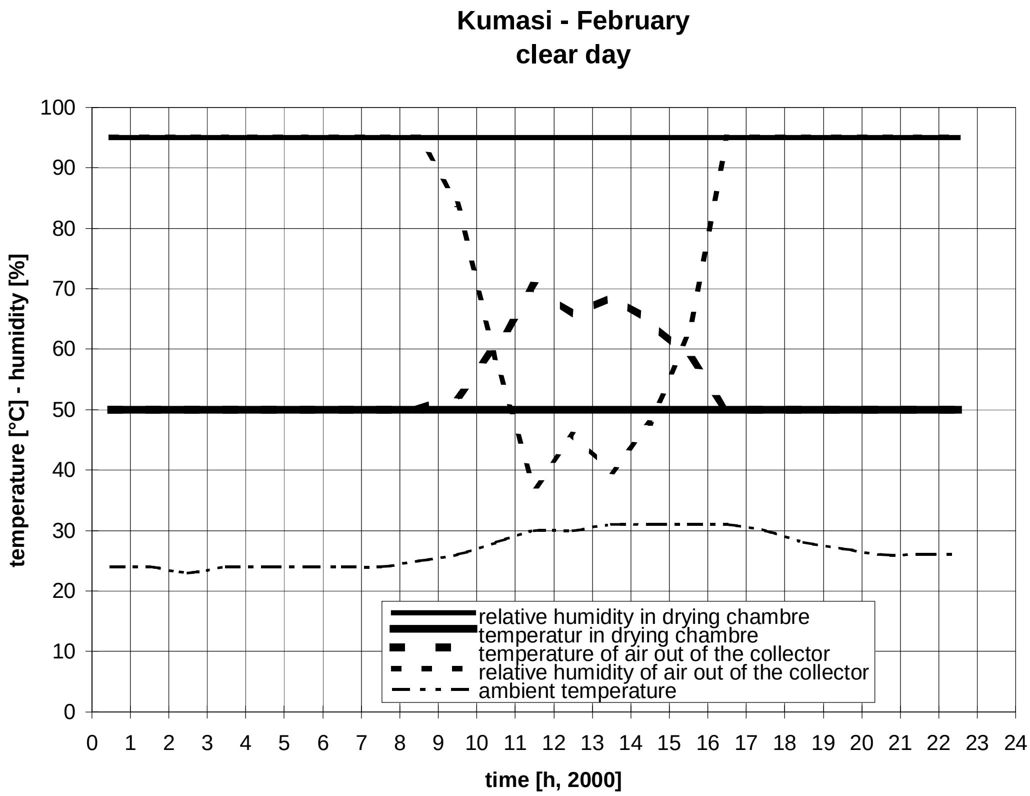

Kumasi - January
average day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature

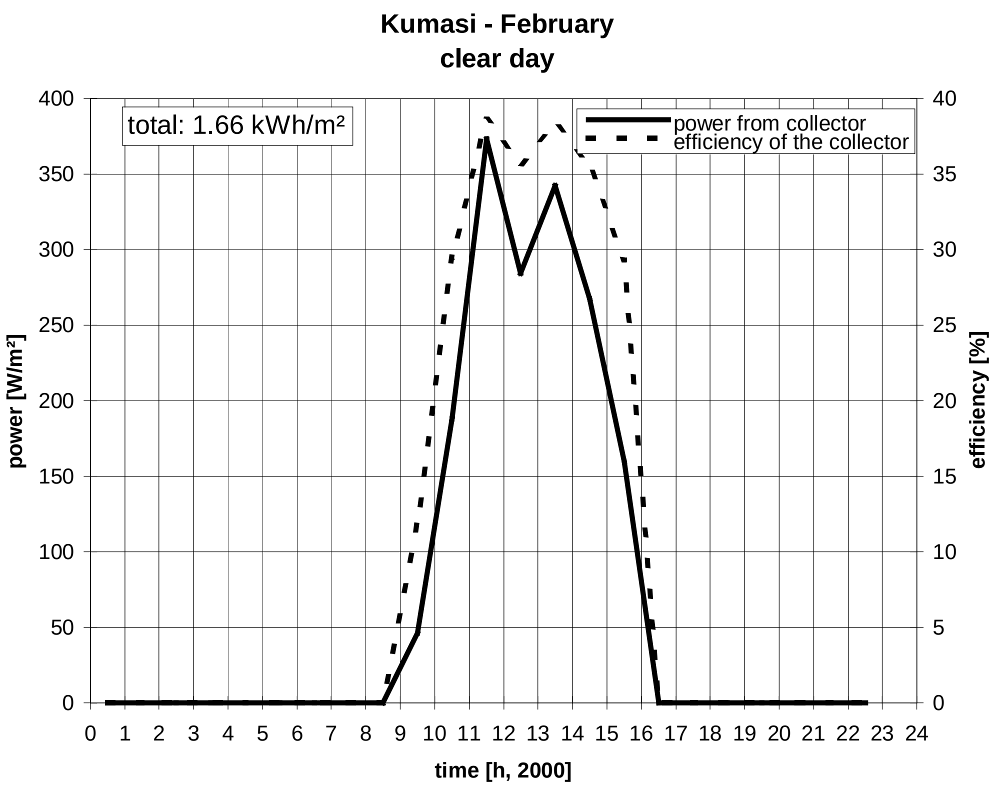

Kumasi - January
average day
total: 0.95 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]

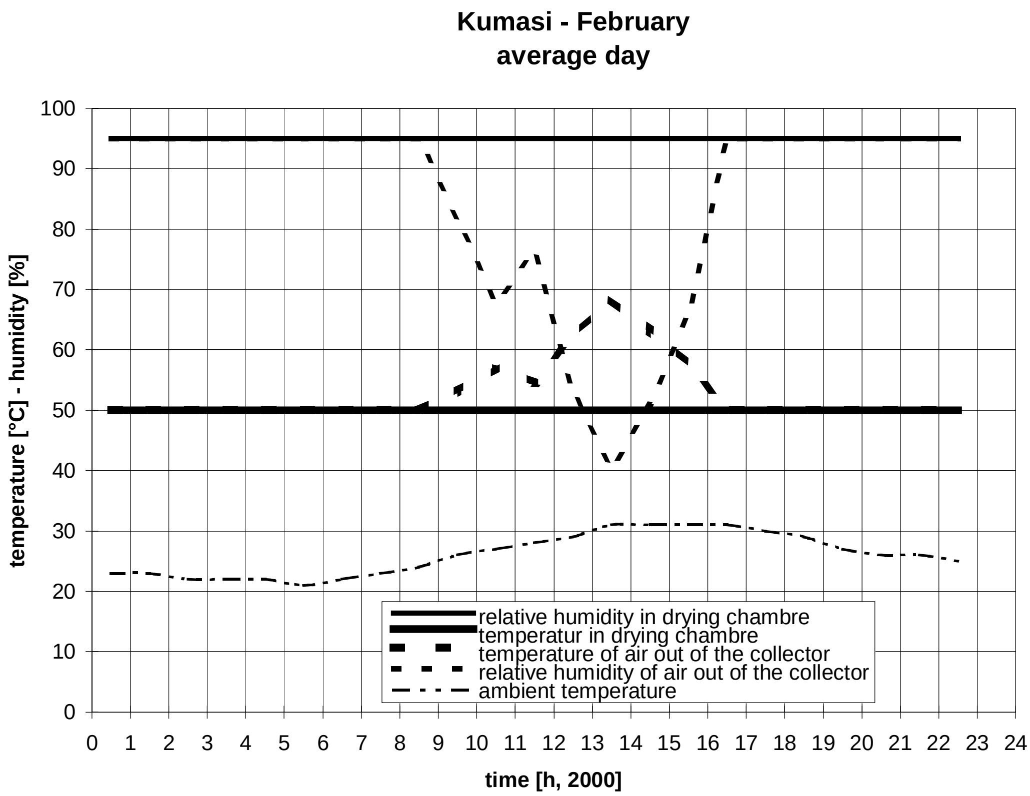

Kumasi - January
overcast day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature


Kumasi - January
overcast day
total: 0.11 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]

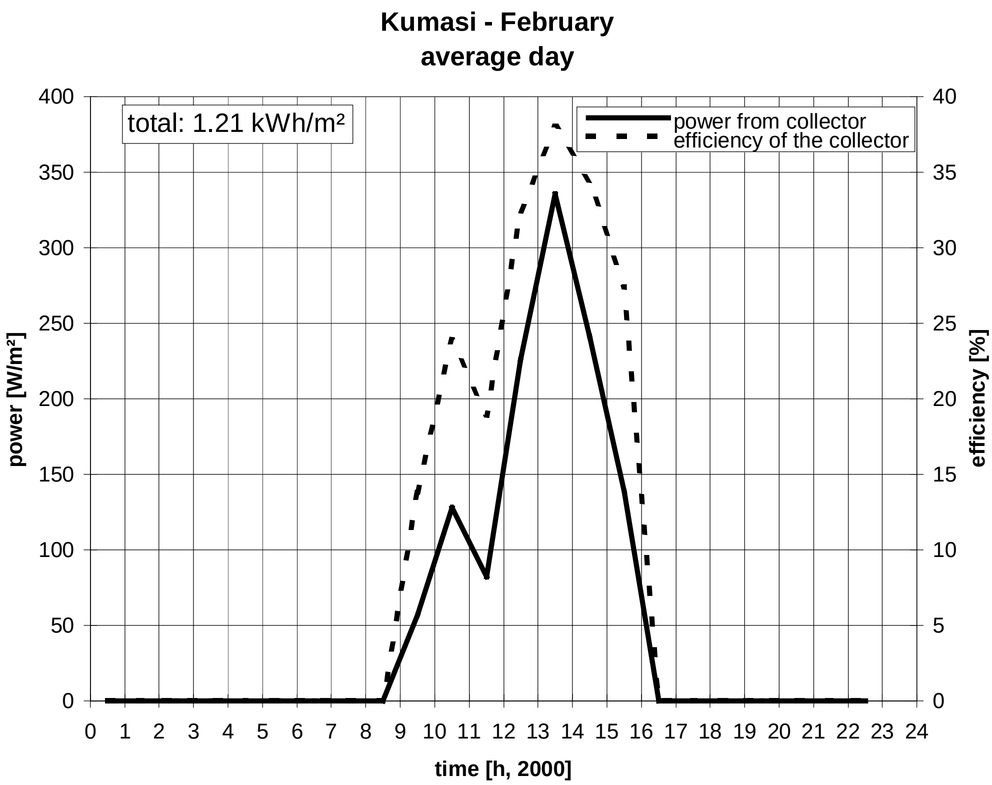
February 1999 - kiln temperature: 50°C



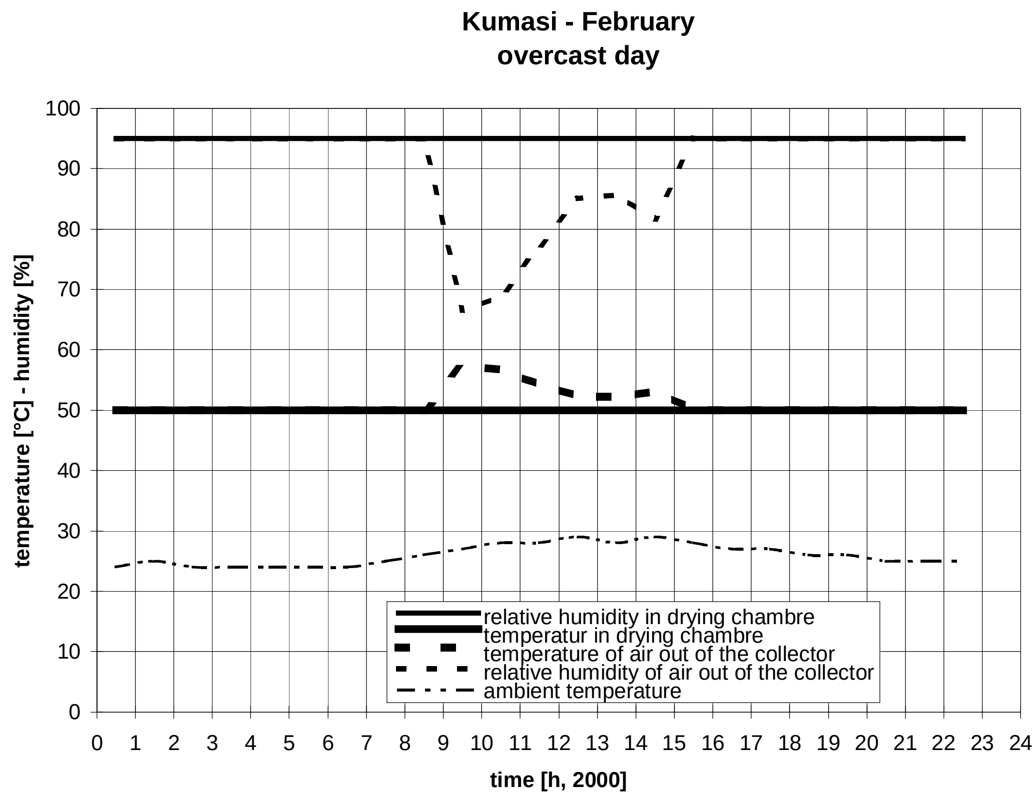


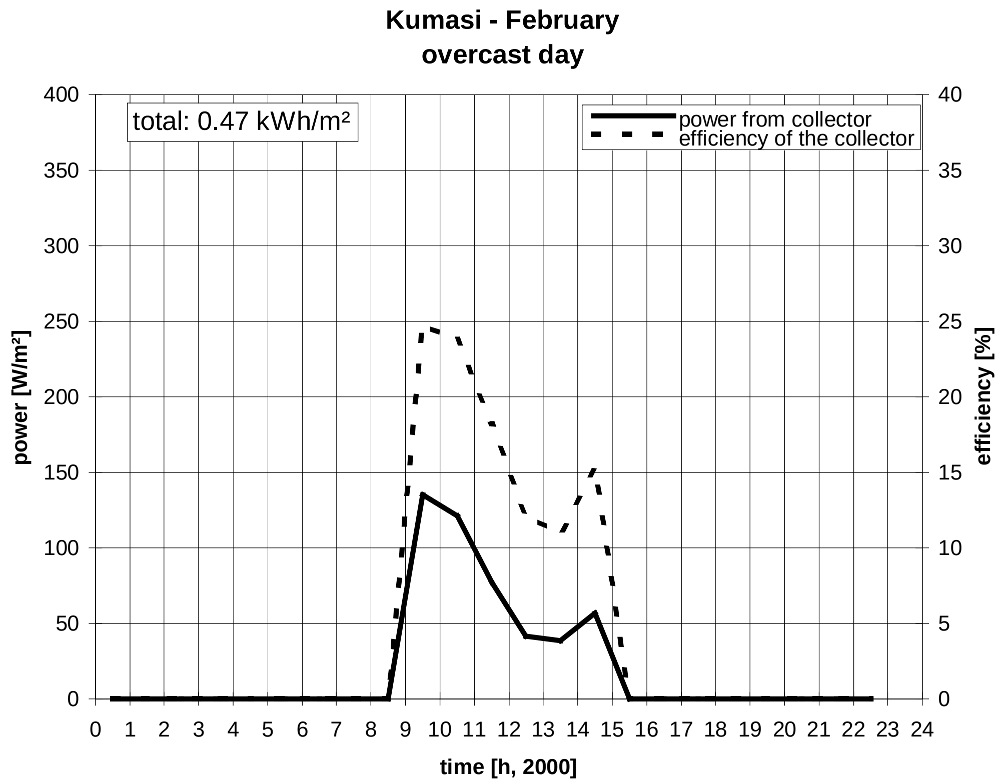


Kumasi - February
average day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature



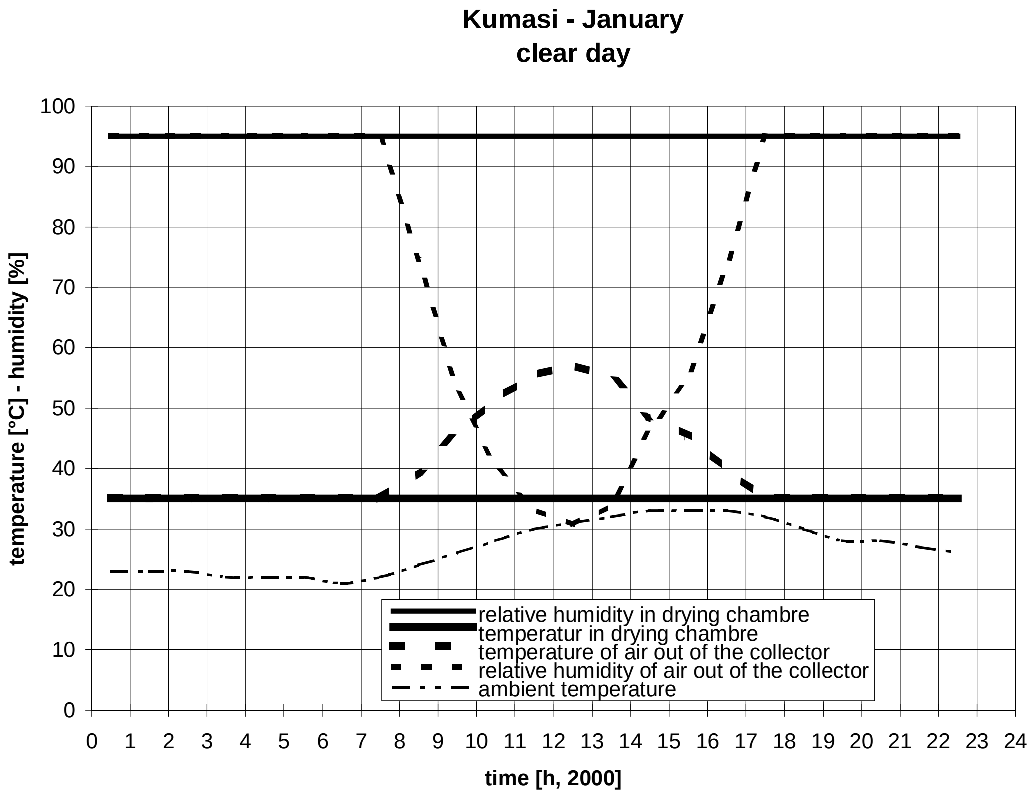
Kumasi - February
average day
total: 1.21 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]

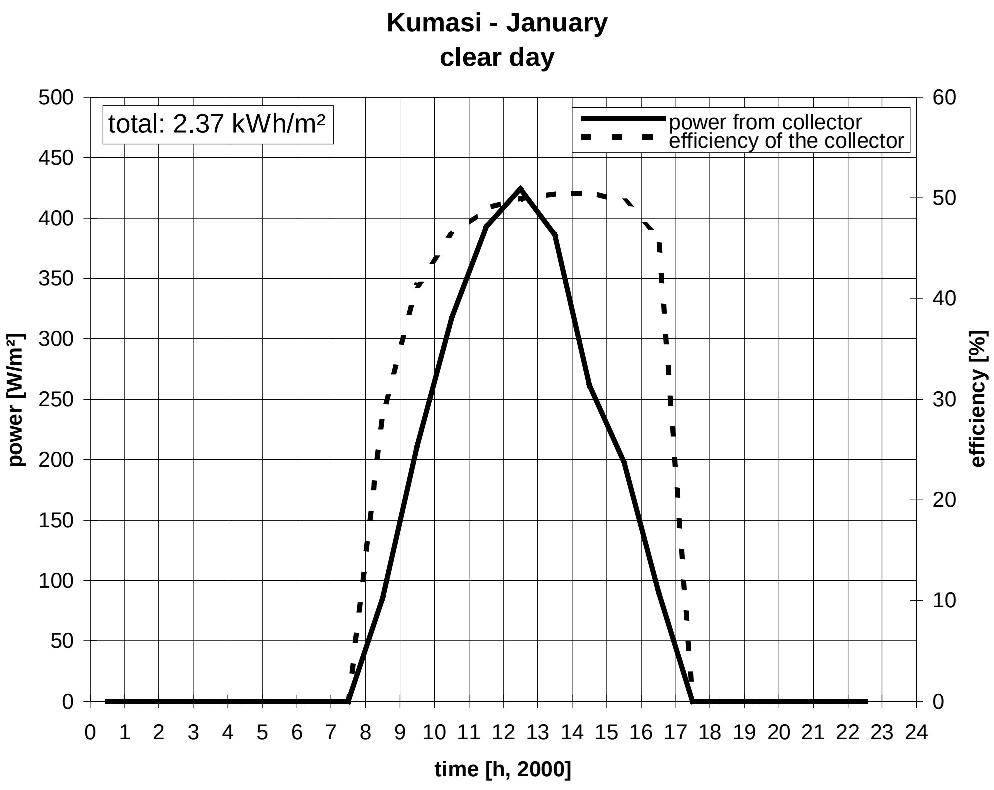

Kumasi - February
overcast day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature
0
10
20
30
40
50
60
70
80
90
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

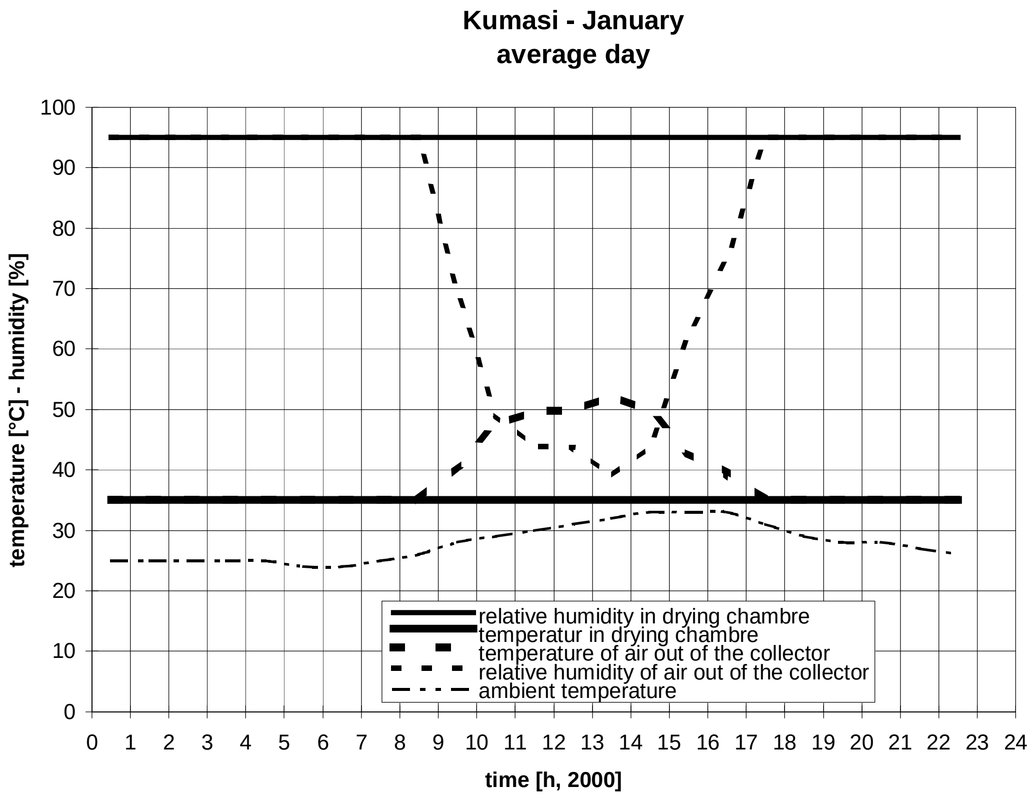

Kumasi - February
overcast day
total: 0.47 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]
0
50
100
150
200
250
300
350
400
0
5
10
15
20
25
30
35
40
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

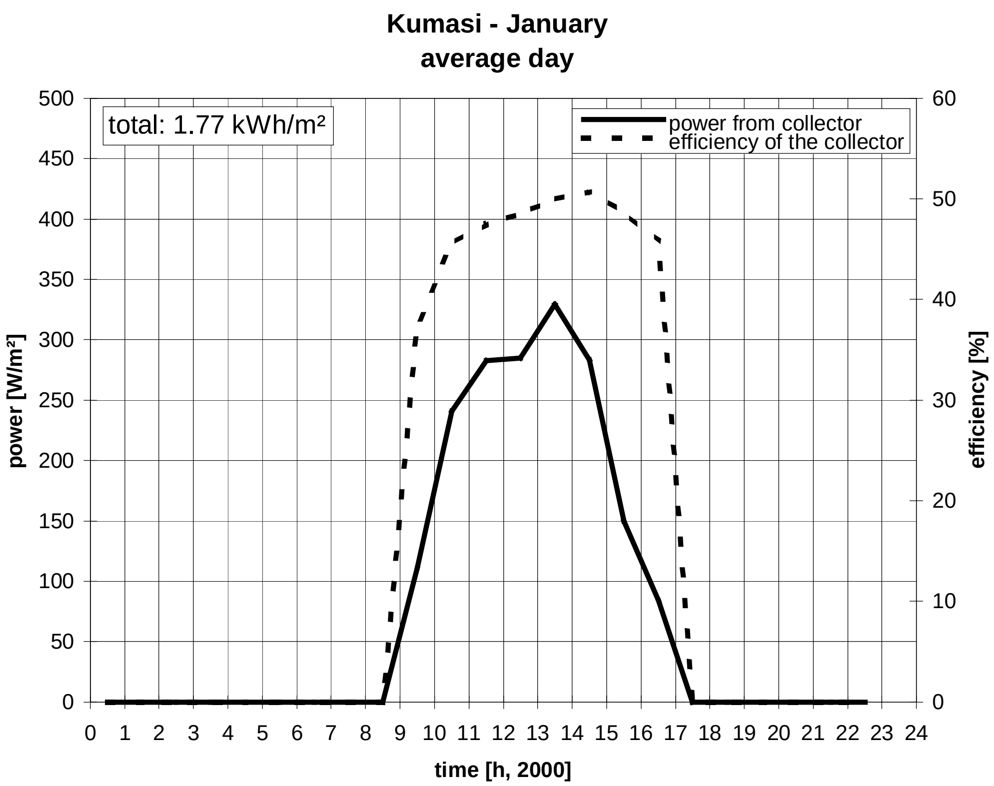
Appendix D

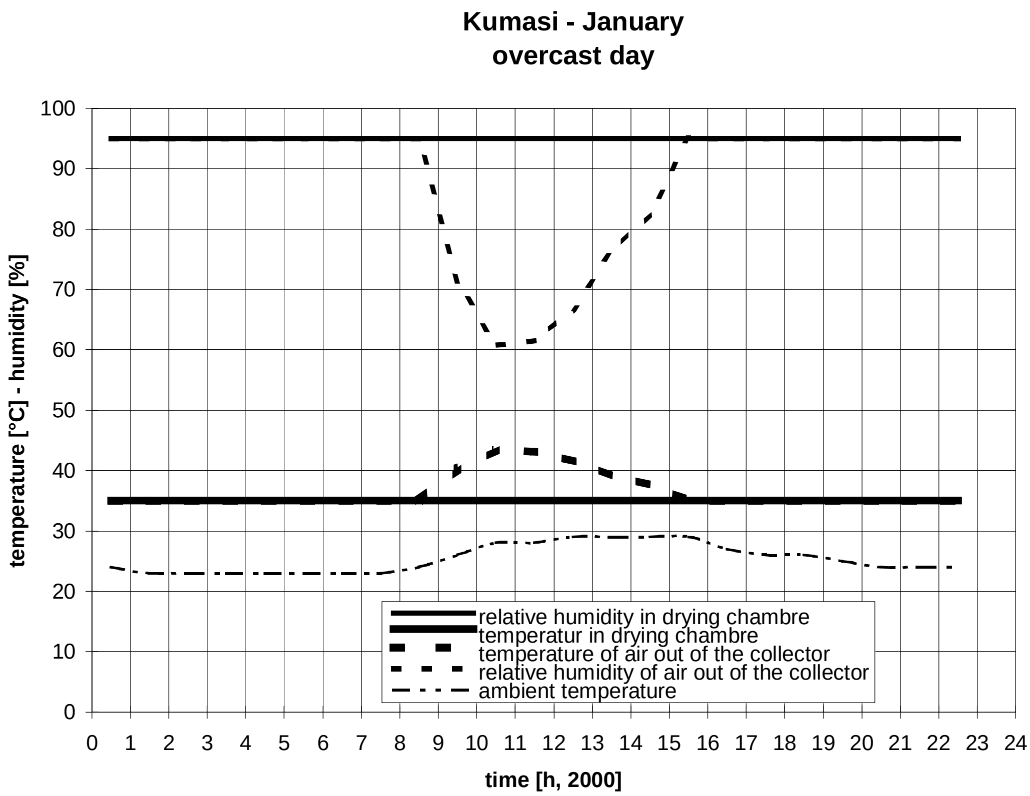
January 2000 - kiln temperature: 35°C

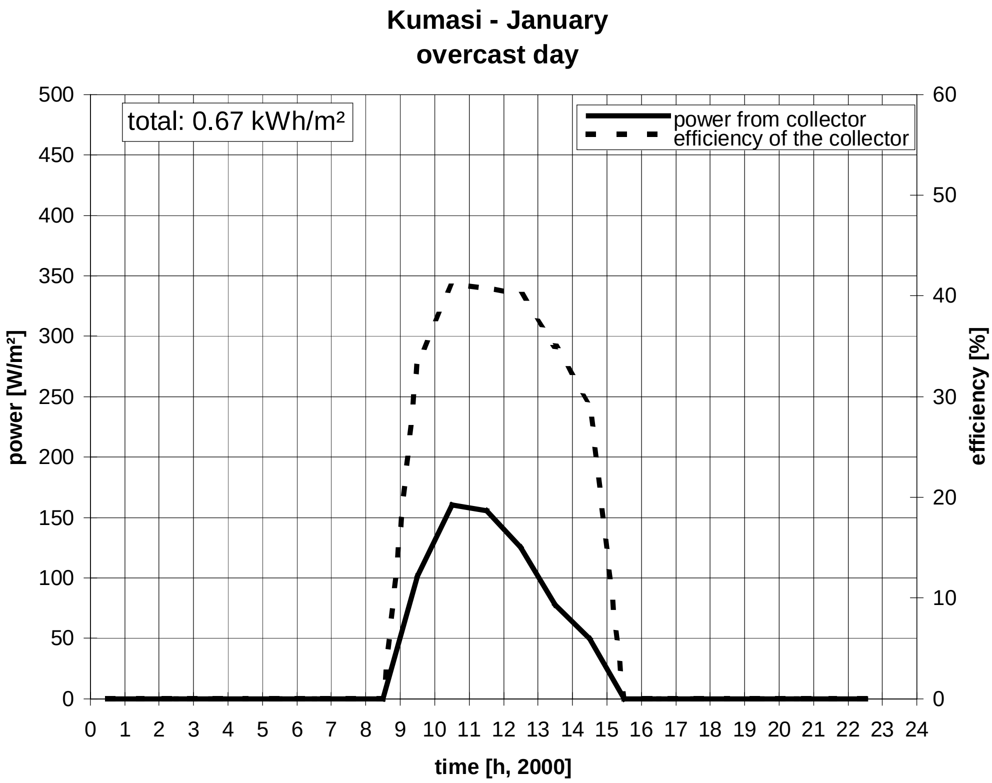




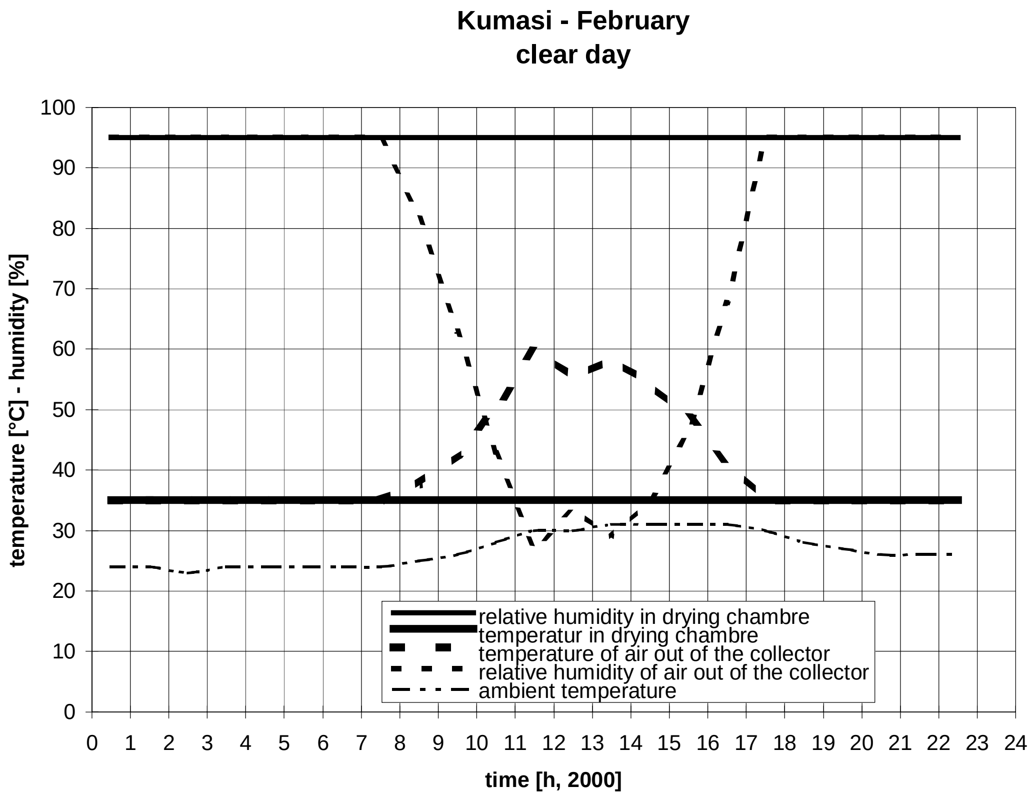

Kumasi - January
average day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature

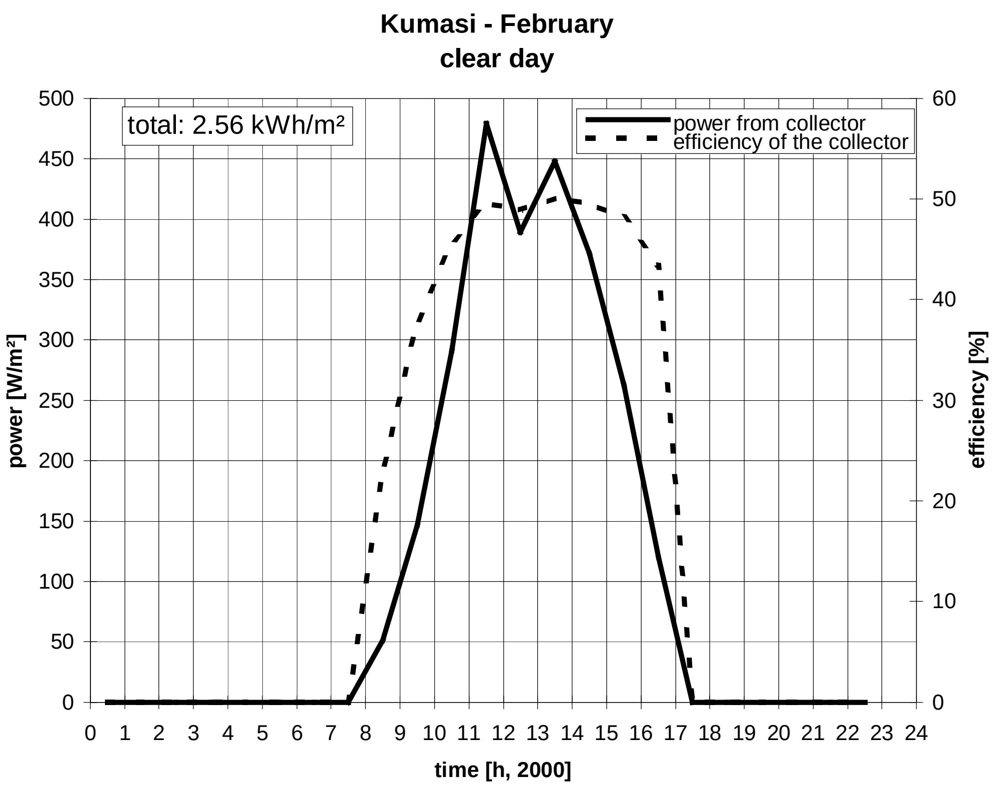

Kumasi - January
average day
total: 1.77 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]

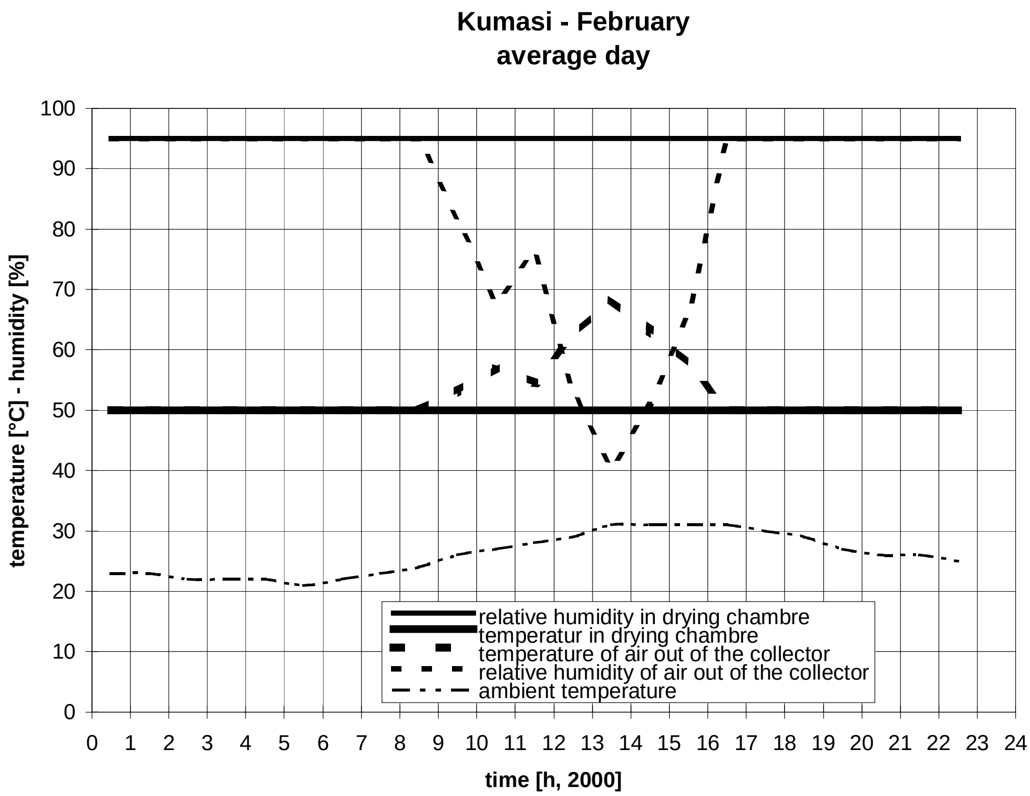

Kumasi - January
overcast day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature

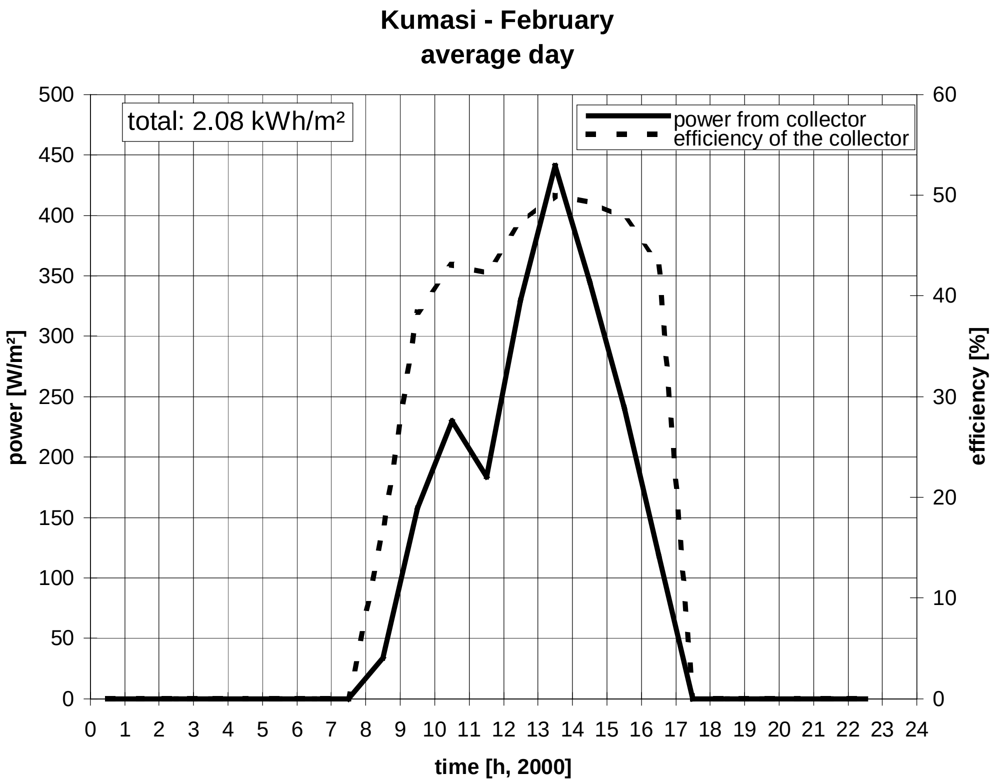

Kumasi - January
overcast day
total: 0.67 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]

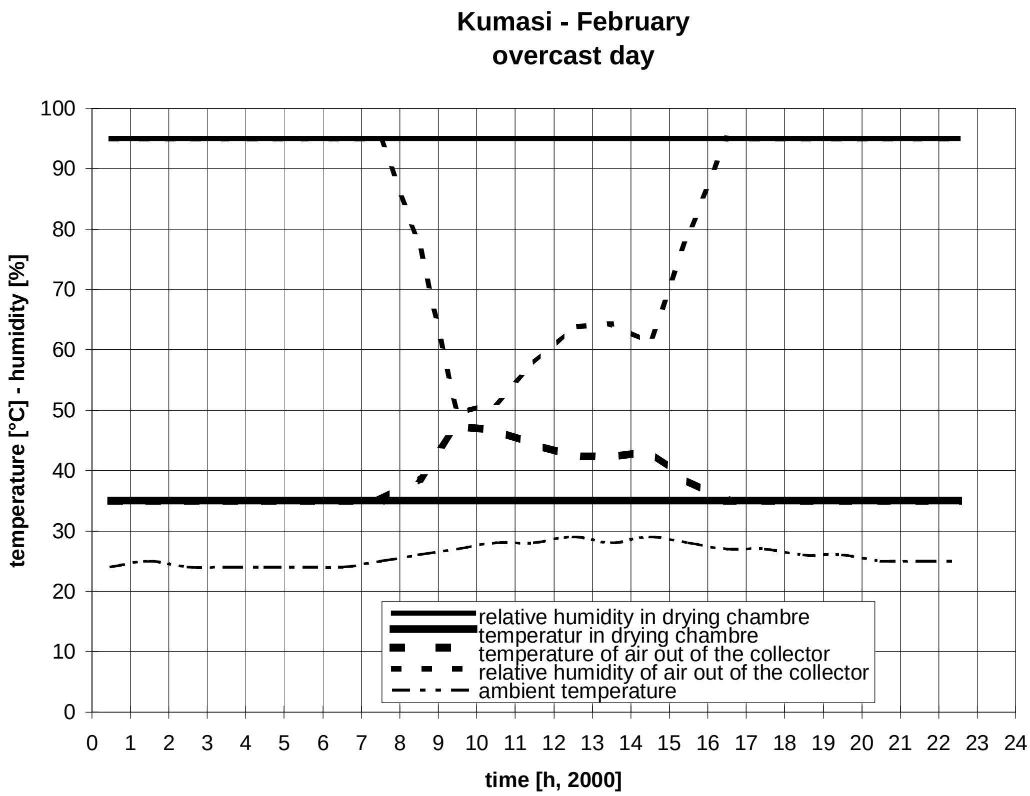
February 1999 - kiln temperature: 35°C

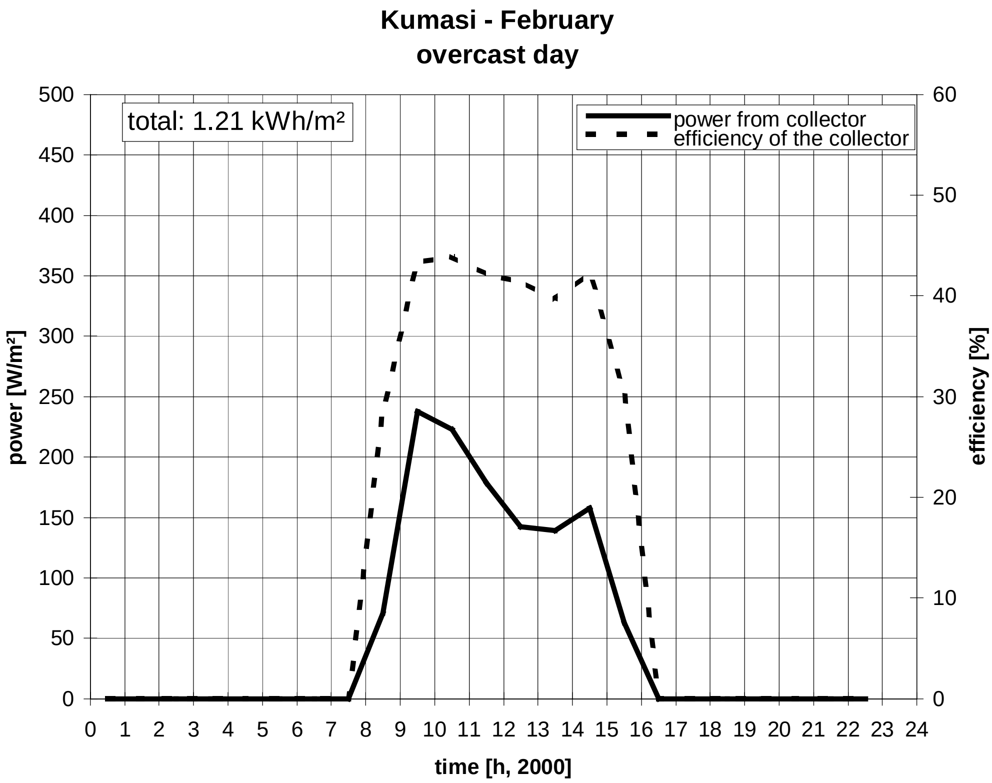





Kumasi - February
average day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature

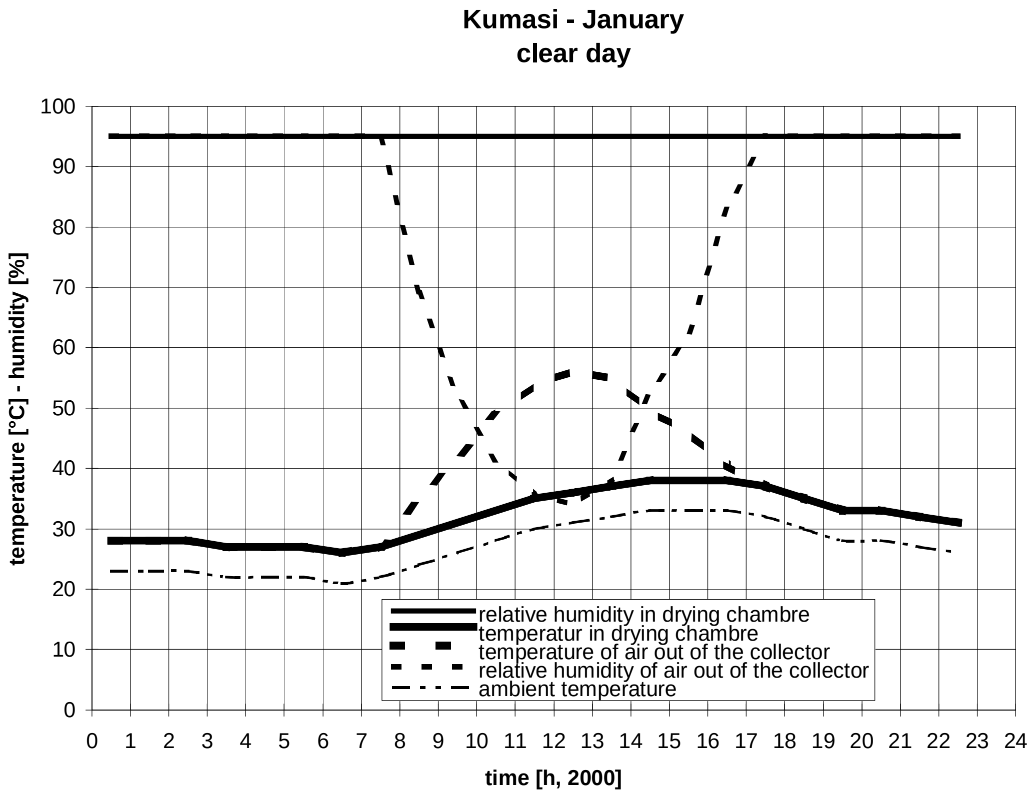

Kumasi - February
average day
total: 2.08 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]

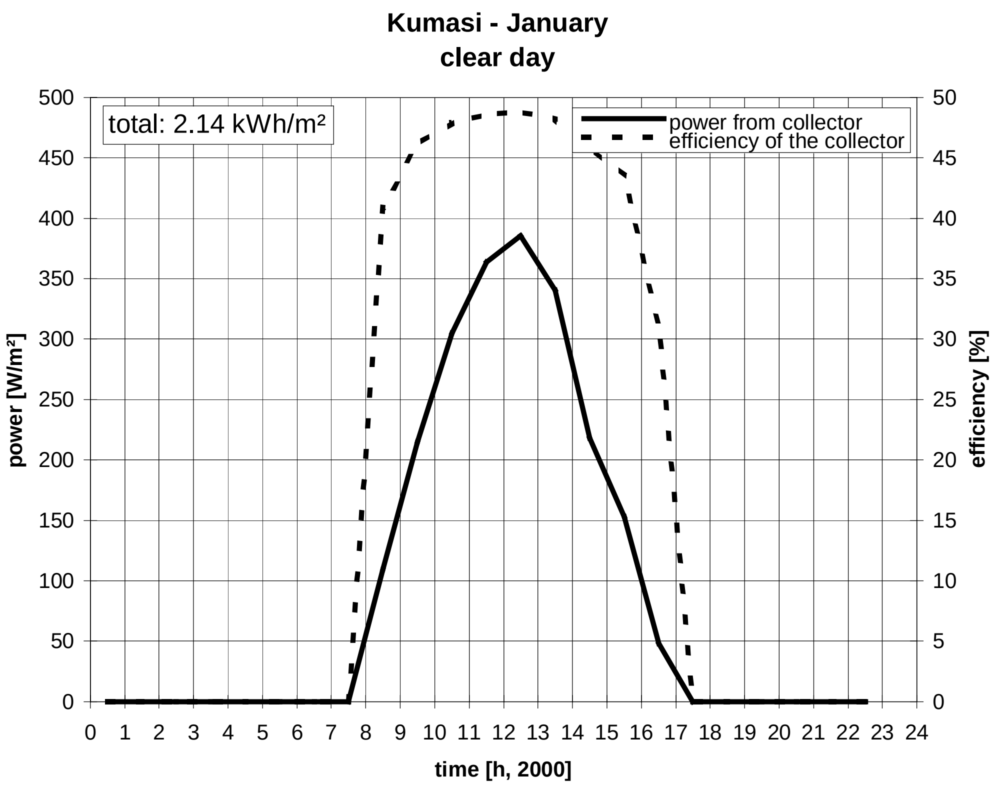

Kumasi - February
overcast day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature
0
10
20
30
40
50
60
70
80
90
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

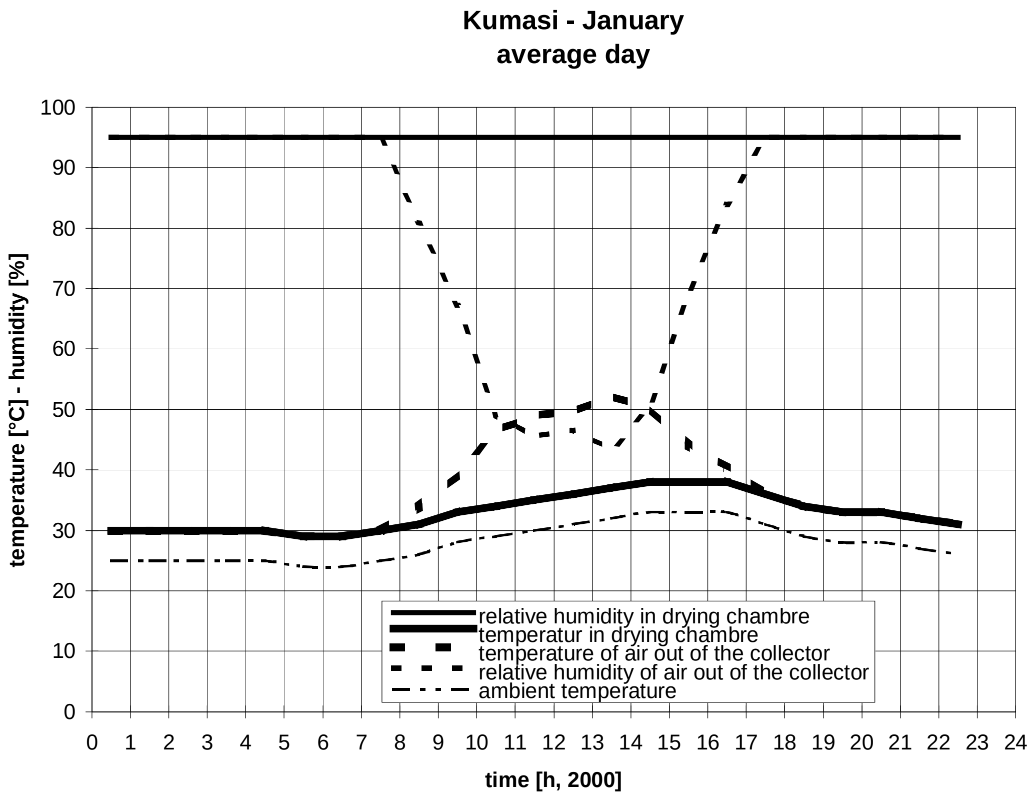

Kumasi - February
overcast day
total: 1.21 kWh/m²
power from collector
efficiency of the collector
power [W/m²]
efficiency [%]
time [h, 2000]
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

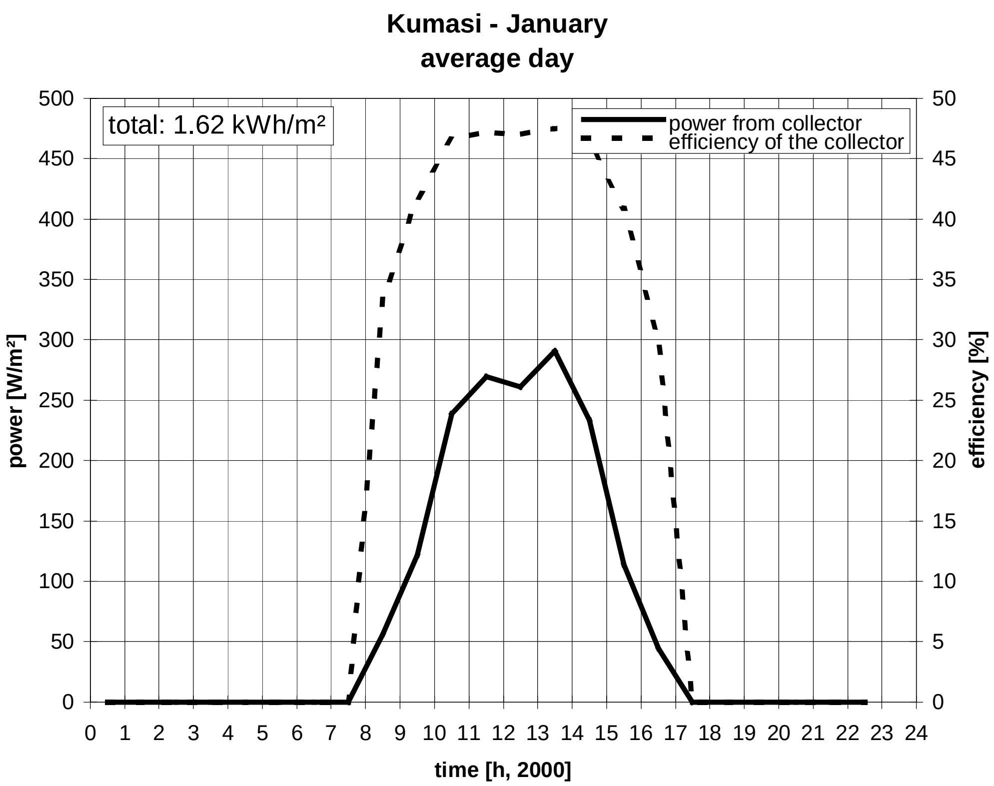
Appendix E

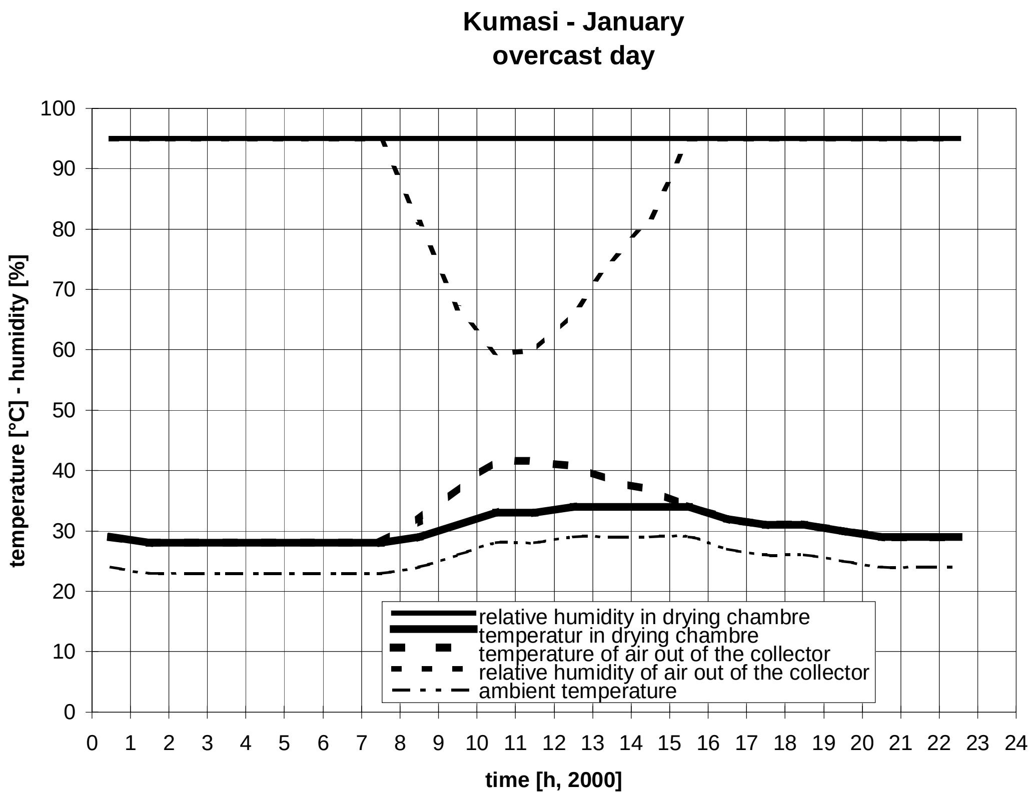
January 2000 - kiln temperature: T_{amb} + 5 K

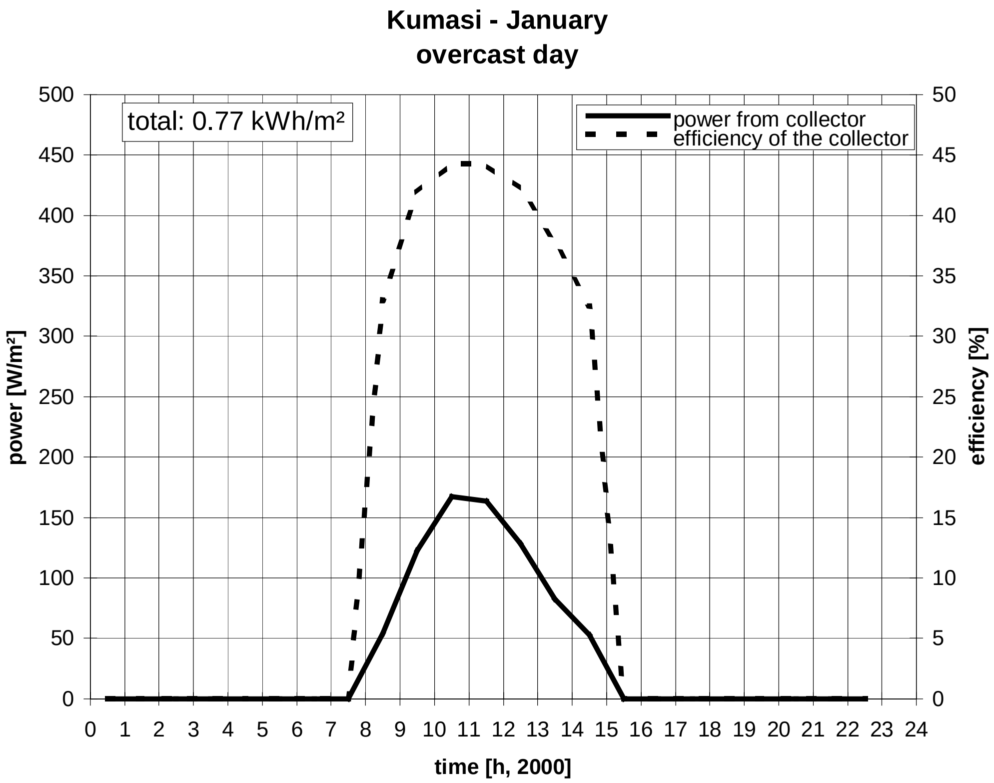




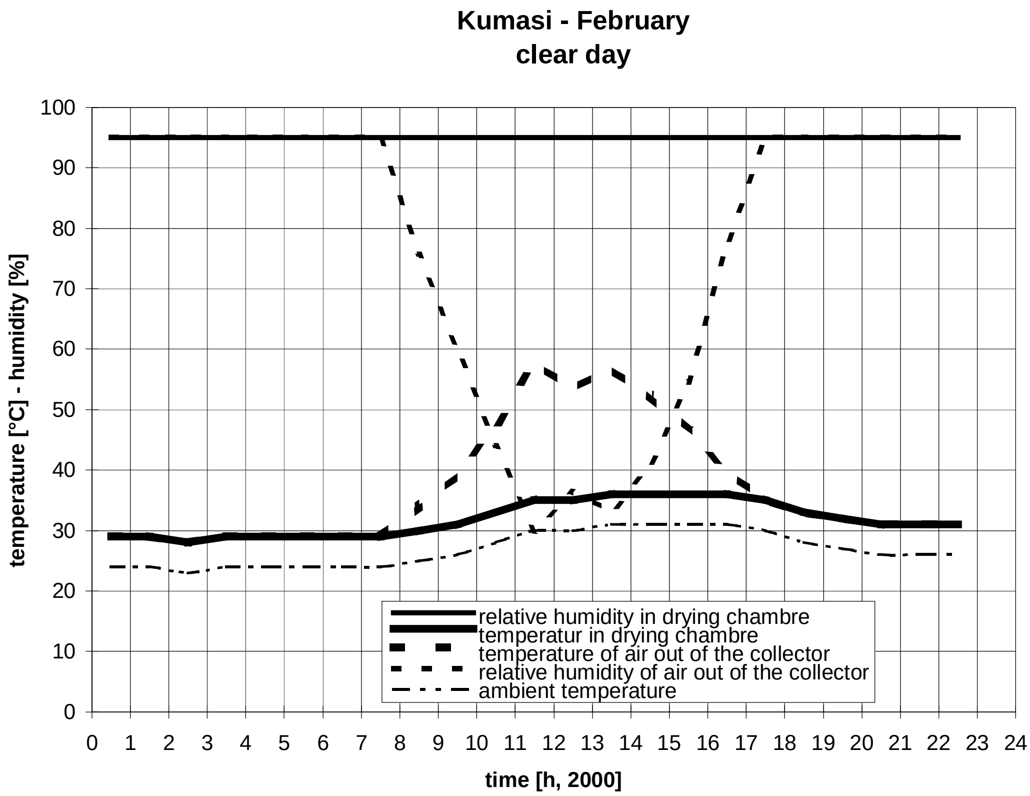

Kumasi - January
average day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature

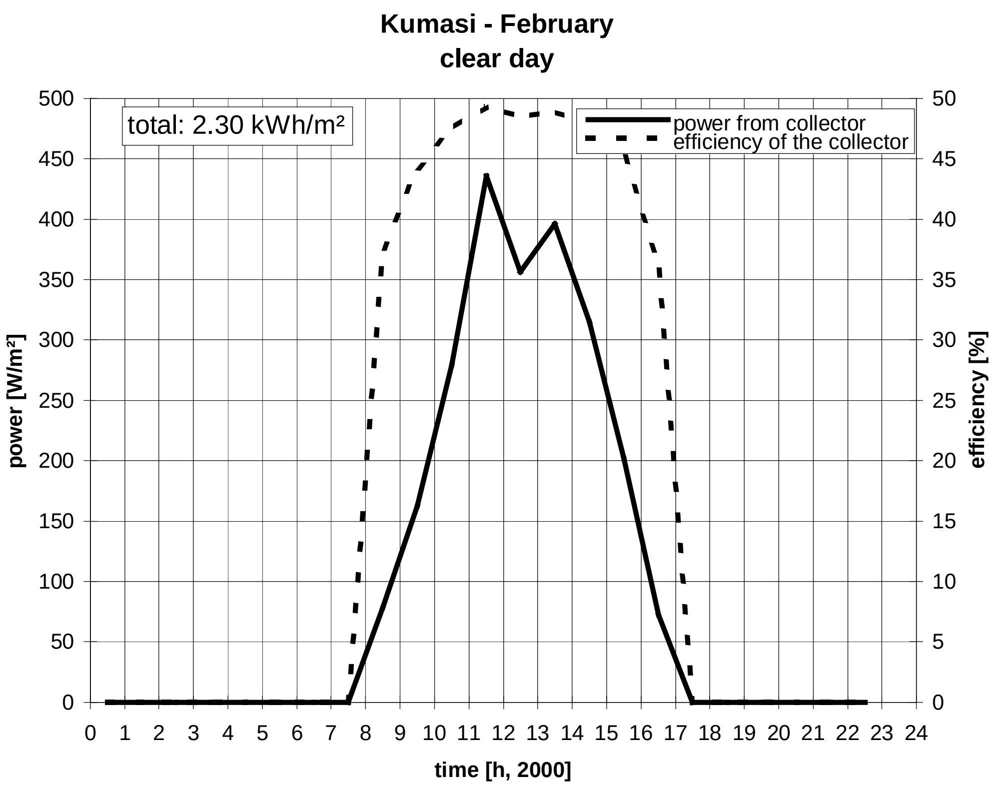

Kumasi - January
average day
total: 1.62 kWh/m²
power [W/m²]
efficiency [%]
time [h, 2000]
power from collector
efficiency of the collector

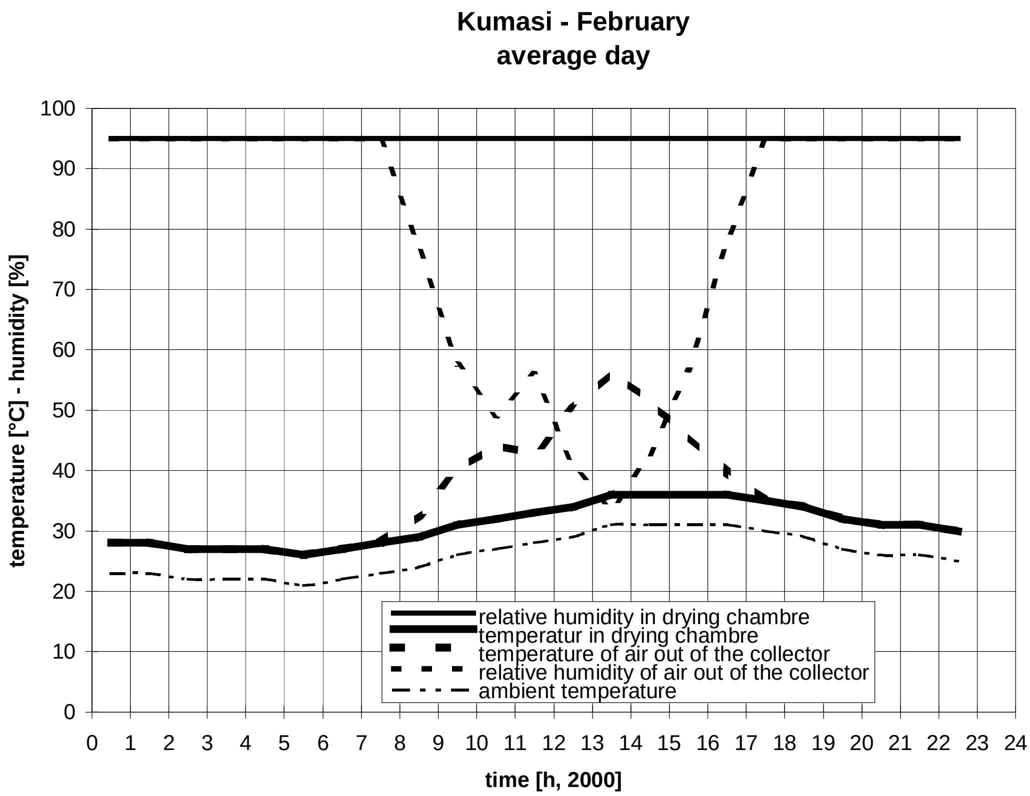

Kumasi - January
overcast day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature

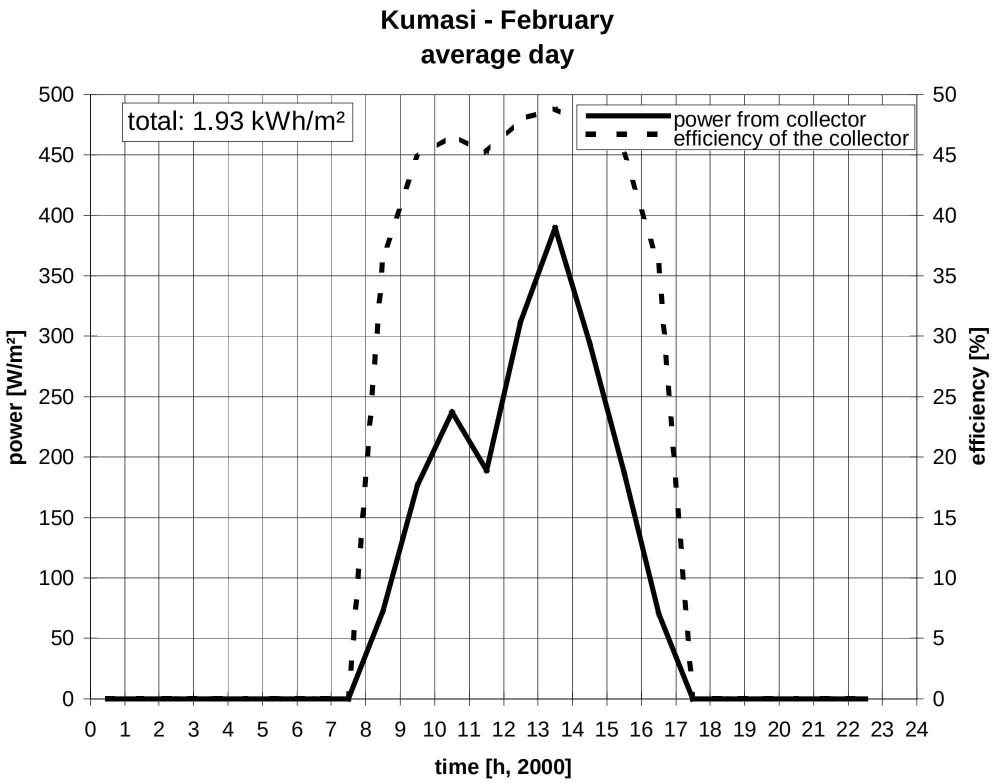

Kumasi - January
overcast day
total: 0.77 kWh/m²
power [W/m²]
efficiency [%]
time [h, 2000]
power from collector
efficiency of the collector

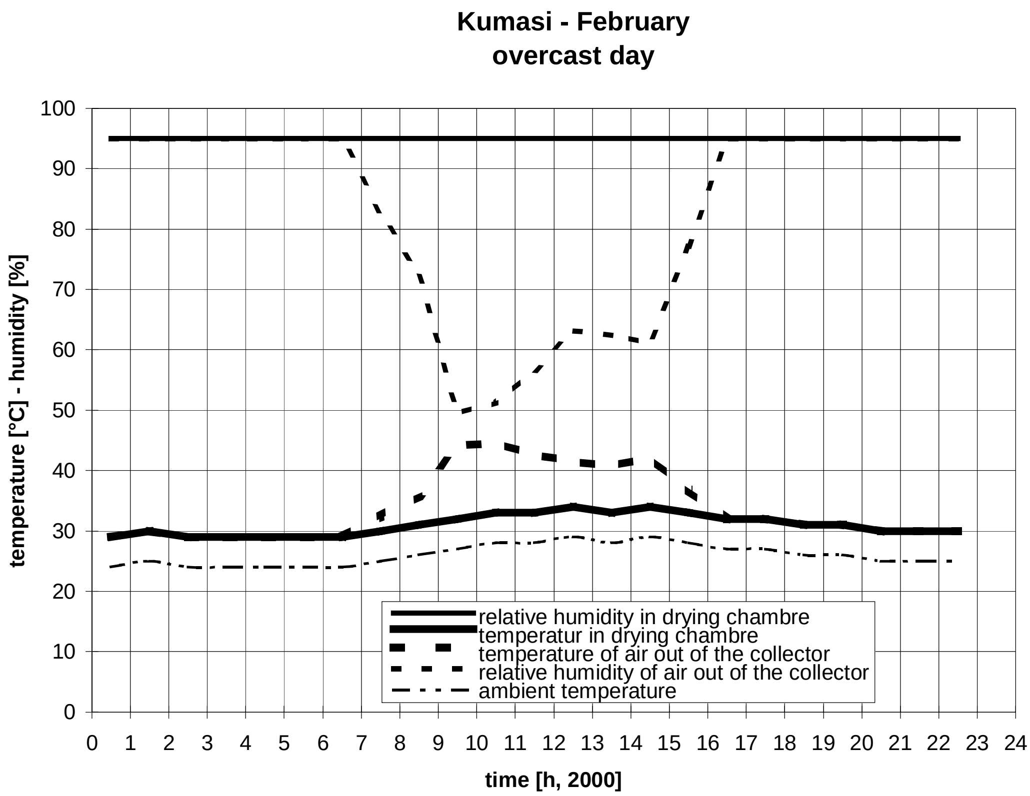
February 1999 - kiln temperature: T_{amb} + 5 K



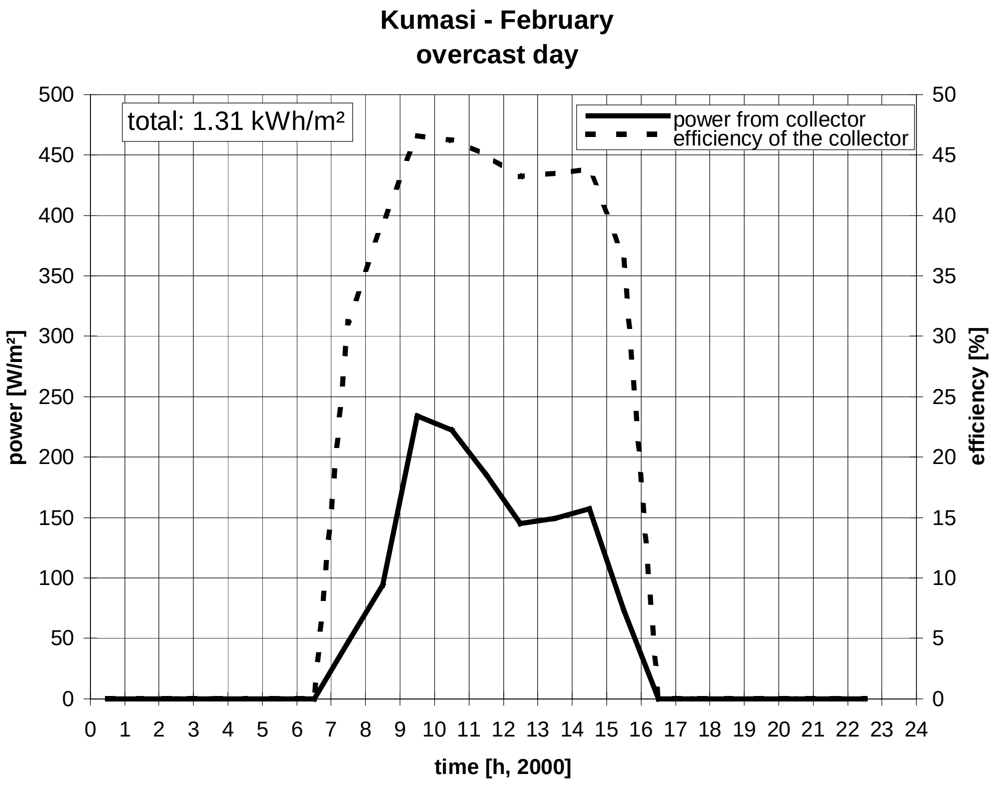



Kumasi - February
average day
temperature [°C] - humidity [%]
time [h, 2000]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature


Kumasi - February
average day
total: 1.93 kWh/m²
power [W/m²]
efficiency [%]
time [h, 2000]
power from collector
efficiency of the collector



Kumasi - February
overcast day
100
90
80
70
60
50
40
30
20
10
0
temperature [°C] - humidity [%]
relative humidity in drying chambre
temperatur in drying chambre
temperature of air out of the collector
relative humidity of air out of the collector
ambient temperature
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time [h, 2000]



Kumasi - February
overcast day
total: 1.31 kWh/m²
power from collector
efficiency of the collector
500
450
400
350
300
250
200
150
100
50
0
power [W/m²]
50
45
40
35
30
25
20
15
10
5
0
efficiency [%]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time [h, 2000]