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Temperature and moisture distribution during solar drying of fruits and vegetables

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SOLAR DRYING OF BIOLOGICAL MATERIALS

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INTRODUCTION (1/3)

Post-harvest operations, especially the drying process for different materials of biological origin, plays an important role in influencing:

- **energy savings**
- **quality of end-products and**
- **environmental issues**

INTRODUCTION (2/3)

- There is a number of drying methods currently available, but it is worth taking into account the technical and economical benefits of solar drying, along with a substantial number of commercially available solar dryers in operation today.

- However, for some special cases individually designed solar dryers have also been developed.

INTRODUCTION (3/3)

- **In a typical agricultural farm, there is an impetus to maximise collection of all available energy resources, including solar, and distribute them optimally among the different consumers, including dryers, which require a fairly great portion of the total energy.**
- **This task requires an integrated energy/technology approach.**

SOLAR DRYING BACKGROUND (1/2)

- **The scope of solar drying is to produce a solid end-product of a certain percentage of moisture content for immediate use or for further long-term safe storage.**
- **This condition should be achieved at a moderate temperature level as some of the materials to be dried may be sensitive to higher temperature.**
- **The final goal is to improve the energy efficiency of the drying operation.**

SOLAR DRYING BACKGROUND (2/2)

- The applicable temperature range and energy requirement for moisture removal are the most important parameters in designing a safe and cost-effective drying system.
- In the following Table some essential data related to most frequently dried grains are listed.
- The values of water removed and energy required are valid for an amount of 1000 kg e.g. 1 tonne (1 t) of biological material to be dried.

Main drying parameters of some grains

Material	Moisture content		Maximum temperature for drying (°C)	Water to be removed (kg/t)	Energy required (kJ/t x 10^6)
	Initial (%)	Final (%)			
Corn	24	14	50	116,3	0,237
Maize	35	15	60	235,3	0,480
Rice	24	11	50	146,1	0,298
Wheat	20	16	45	47,6	0,097

Main drying parameters of some fruits

Material	Moisture content		Maximum temperature for drying (°C)	Water to be removed (kg/t)	Energy required (kJ/t x 10^6)
	Initial (%)	Final (%)			
Apple	80	24	70	736,8	1,502
Apricot	85	18	65	817,1	1,666
Banana	80	15	70	823,5	1,679
Grapes	80	15-20	70	750-823,5	1,529-1,679

MAIN FEATURES OF DESIGN AND OPERATION OF A SOLAR DRYING PROCESS:

- The material can be irradiated by the sun during drying.
- The drying space, the energy converting and transferring system are normally integrated in a single unit.
- The characteristics and time dependence of solar radiation should generally taken into account when designing the solar dryer and controlling its operation.
- Some peculiar factors influence the economy of drying.

R/D ACTIVITIES ON SOLAR DRYING (1/5)

Basic experimental research:

- **determination and checking the drying and material characteristics of various products**
- **experimental investigation for determining heat and mass transfer characteristics of various materials**
- **permitting maximum drying temperature of various materials**

R/D ACTIVITIES ON SOLAR DRYING (2/5)

Modelling and simulation:

- **development of modelling methods for solar drying processes**
- **elaboration of software packages for simulation**
- **elaboration of methods for determining the optimum collector area of solar dryers**
- **dimensioning methods for different type of solar dryers**

R/D ACTIVITIES ON SOLAR DRYING (3/5)

Long term performance measurements

Design, construction and testing:

- **use of desiccant materials**
- **design photovoltaic (PV) powered air flow**
- **constructing low cost solar dryers**

R/D ACTIVITIES ON SOLAR DRYING (4/5)

- There is no doubt that using solar energy is a promising solution in attaining technical, economical and environmental demands raised in the course of dying process.
- For this reason, several new approaches in application of dryers and biological materials have been developed in order to produce a high quality of product at competitive cost.

R/D ACTIVITIES ON SOLAR DRYING (5/5)

- **The feasibility of solar drying must include several additional factors, such as the local climate, the variety of biological materials, the amount of the material to be dried, etc.**

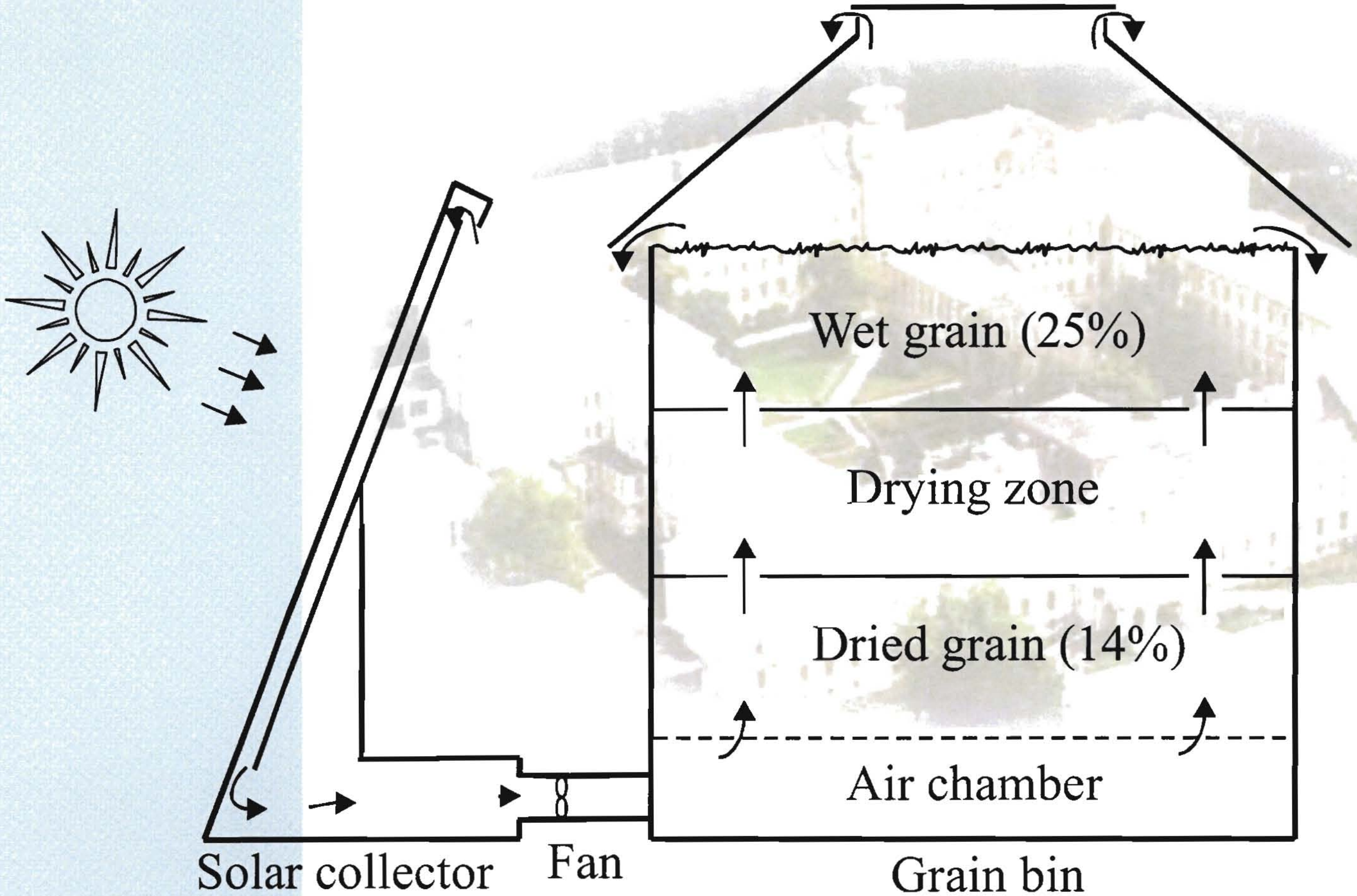
IN-BIN SOLAR GRAIN DRYING (1/2)

- The traditional use of solar energy for grain drying is a forced convection heated air in solar air collector.
- The most typical temperature rise is around 10 ^{0}C, depending on the solar radiation, air flow rate and solar collector surface area.
- A low-temperature system can accommodate several grain types in spite of the longer processing time.

IN-BIN SOLAR GRAIN DRYING (2/2)

- During the in-bin drying, the grain layers serve as storage for heat and moisture.
- Thus, the big fluctuations in drying air parameters along the drying zone could be avoided.
- The schematic draw of an in-bin drying is shown in the following Figure illustrating the moisture distribution in drying zone.

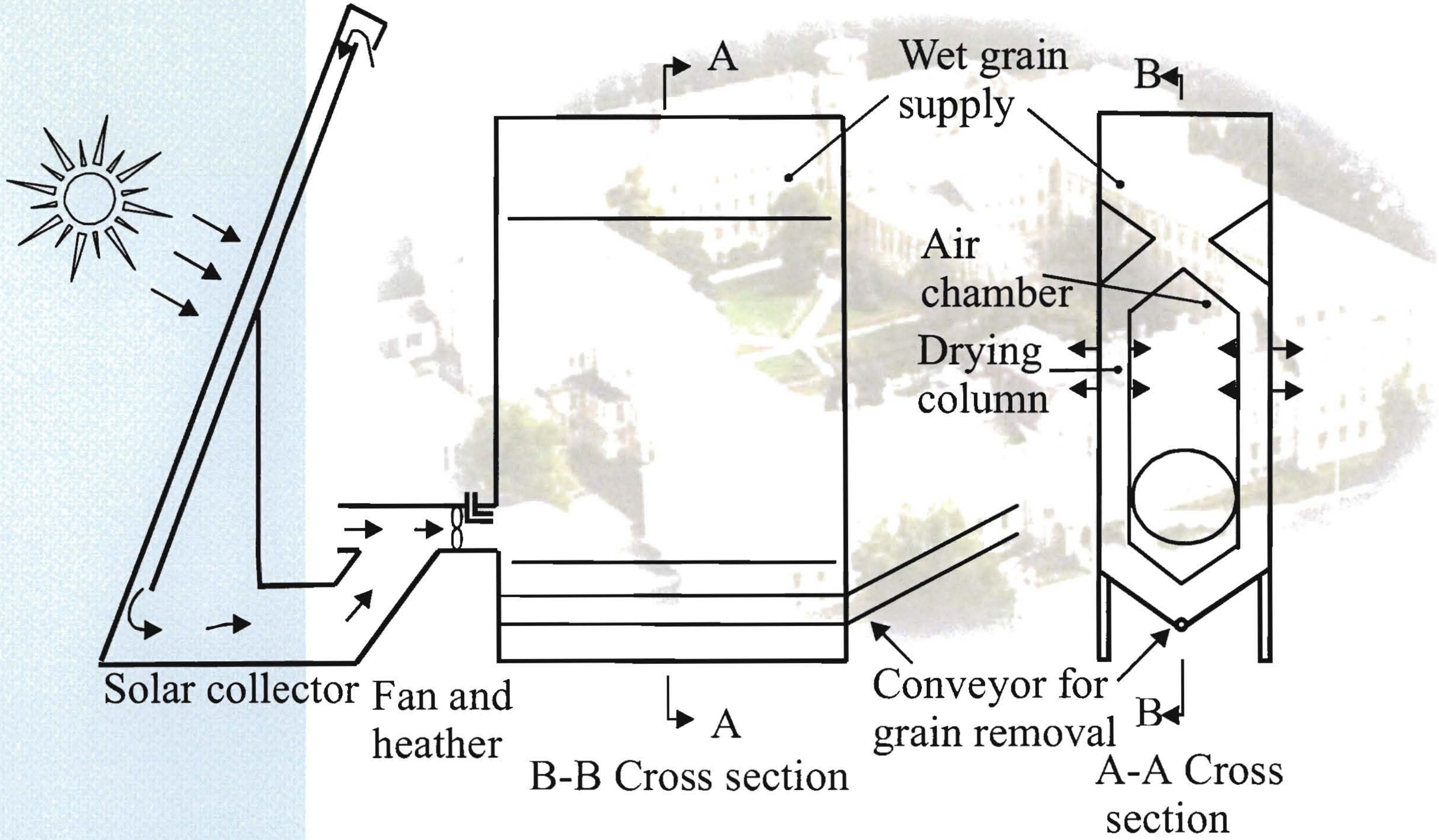
Scheme of in-bin solar grain drying (Parker, 1991)



HIGH TEMPERATURE SOLAR DRYING

- **In some of the cases an average 10 ^{0}C rise is not sufficient to stop the rapid fungi growth in the grain bed, therefore a high-temperature system is required.**
- **In this case the typical range of the temperature rise is 30-85 ^{0}C.**
- **In such drying system the solar energy is essentially used to preheat the ambient air before passing through the burner operated by gas or oil heating.**

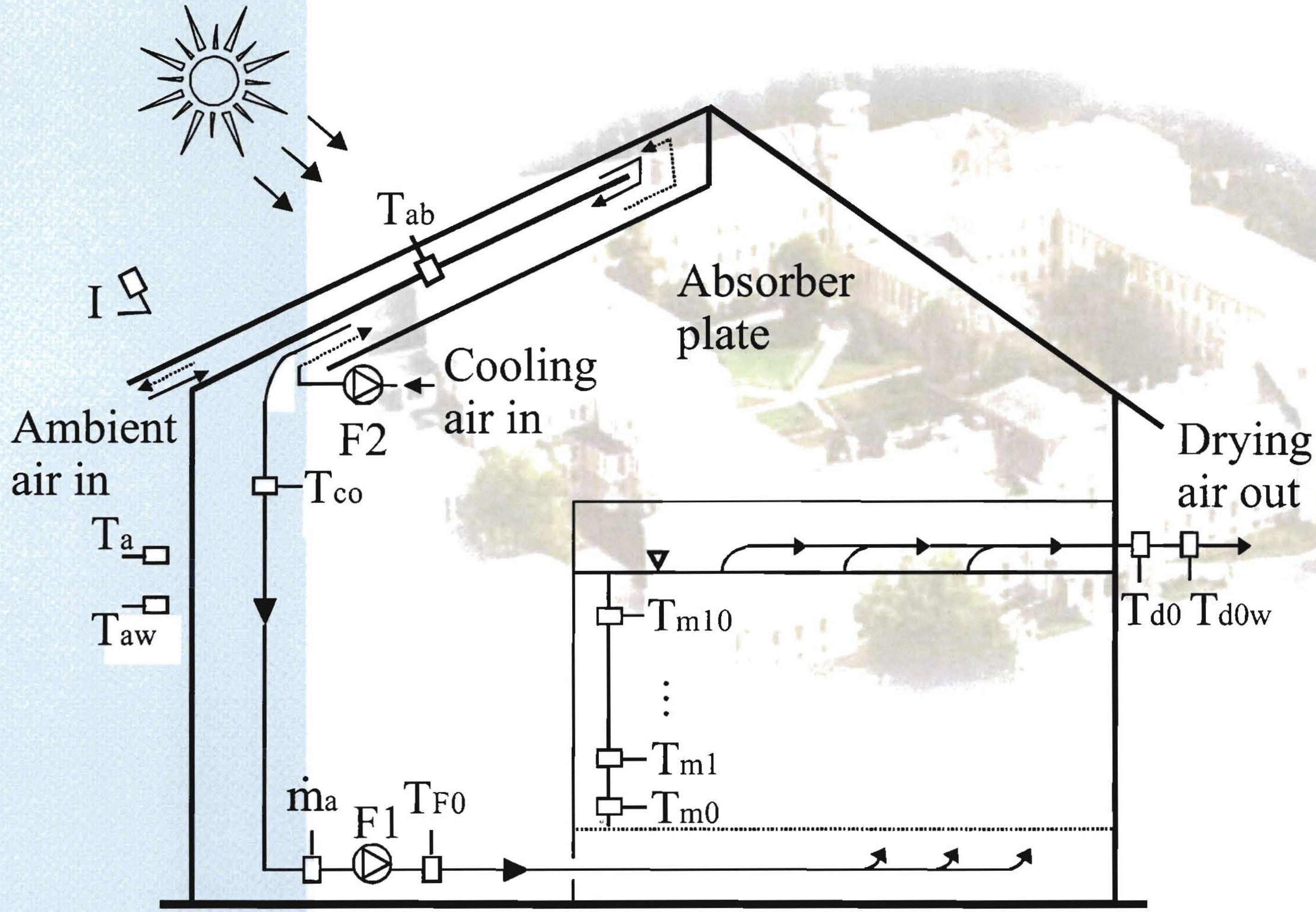
Scheme of high-temperature solar grain drying (Parker, 1991)



SOLAR BARLEY DRYING

- **Small-scale solar equipment can be used effectively world-wide for drying of various agricultural crops, such as the design developed at Colorado State University, Fort Collins, USA.**
- **The dryer is designed for producing of 2000 kg dried crops (most recently for barley) starting at 20-40% w.b. initial moisture content.**

Set-up of a solar crop dryer (Farkas and Smiths, 1988)



Collector

- **the structure is integrated into the roof**
- **the area is 36 m^2**
- **the absorber plates are 0.6 mm thick aluminium, coated with optically selective silicon paint**
- **the glass is 3 mm thick, tempered and with low iron content**
- **insulation is 25 mm thick fibreglass**

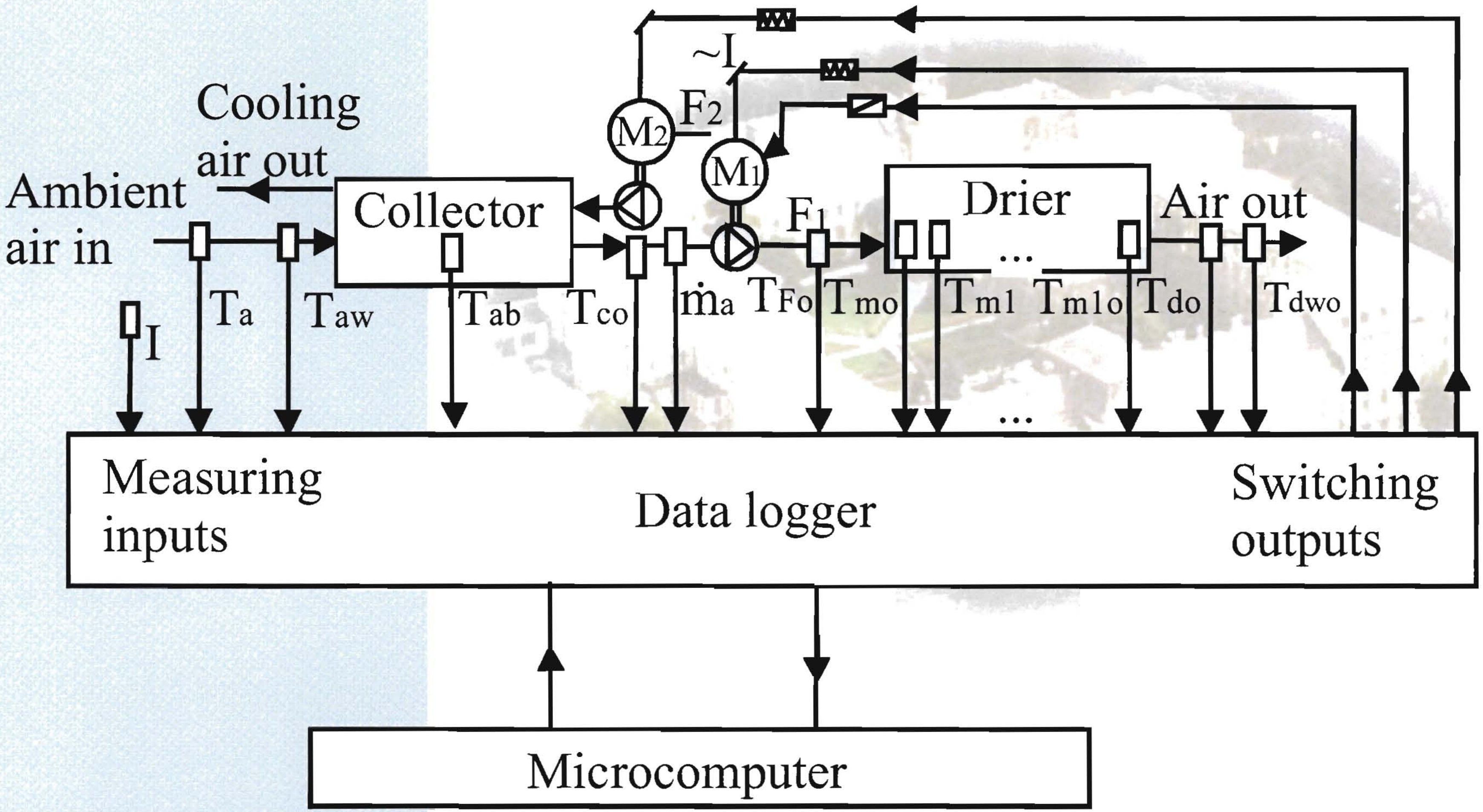
Dryer

- the size is 3 m long by 2.5 m wide by 1 m high
- the wall insulation is about 38 mm thick
- 3 mm x 3 mm wire mesh serves to keep the grain

Air system

- cross section of air channel is 0.15 m^2
- air flow rate is 500 l/s at a pressure of 10 kPa
- the required fan engine capacity is about 1 kW

Control scheme of solar barley dryer



CONTROL OF SOLAR BARLEY DRYING (1/6)

The control code running on the microcomputer checks the data logging and provides the following functions:

- **evaluation and printout of momentary values**
- **data saving for future processing**
- **set-up the necessary control signals**

CONTROL OF SOLAR BARLEY DRYING (2/6)

- **The location of the sensors is shown in Figure. The temperature and radiation sensors are directly connected, but the airflow rate sensor is indirectly connected to the computer, through a signal transformer.**

- **The scanning time is 300 *s* except the measurement of layer temperatures which takes place hourly. First, the control system switches off the fan *F1* to take the real temperatures and after that switches it on again.**

CONTROL OF SOLAR BARLEY DRYING (3/6)

- **The strategy of optimum control involves satisfying the drying requirements.**
- **The maximum thermal efficiency for the whole solar system must also be sought.**

CONTROL OF SOLAR BARLEY DRYING (4/6)

To keep the quality requirements:

- **For barley drying the material temperature cannot rise above a permissible value which was limited as 60 °C. This critical state may mainly occur during night intermissions by biological heat development. In such a situation the starting of an air blower is needed.**
- **The goal of drying is to achieve a desired final moisture content of 12% w.b.**

CONTROL OF SOLAR BARLEY DRYING (5/6)

The optimal use of total available energy:

- **The precondition for starting the drying process requires that the solar radiation must exceed a given value, which has been identified as 15 MJ/h.**
- **To stop the drying process the drying rate can be used. Its value was determined at 0,5 kg/h. This condition allows drying to continue by ambient energy, as well.**
- **The collector outlet air temperature below 60 °C.**

CONTROL OF SOLAR BARLEY DRYING (6/6)

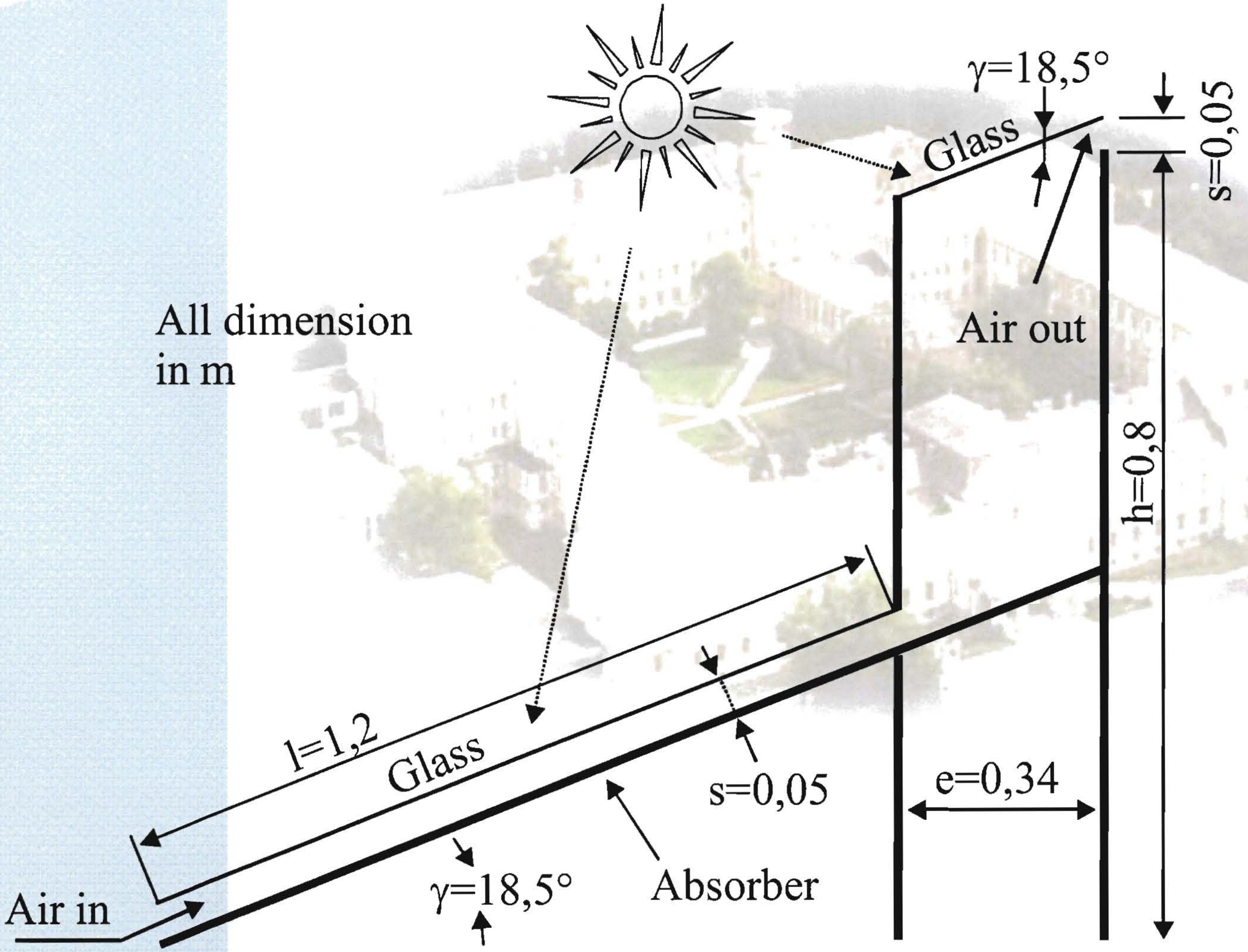
Additional conditions:

- **In the absence of drying the collector absorber temperature could rise to 150 °C, then the fan *F2* is applied for cooling.**
- **Support the temperature measurement procedure of material layer.**

SOLAR MAIZE DRYING (1/5)

- Either direct or indirect solar dryers are commonly used for grain dehydration.
- However, mixed-mode type of dryers can combine all the benefits of both approaches.
- In such a way, the grain can be dried directly by absorbed irradiation and indirectly through forced convection where the drying air is preheated in a solar collector.

Scheme of mixed-mode solar maize dryer (Simate, 2001)



SOLAR MAIZE DRYING (3/5)

For modelling a deep-bed model was used with conditions:

- **The heat falling on the top of the grain bed through transparent cover is transferred by downward conduction.**
- **The direction of the convective heat flow is just opposite, from the bottom to the top layer.**
- **The upward airflow through the drying bed is created by buoyancy pressure.**

SOLAR MAIZE DRYING (4/5)

- **Drying experiments were carried with a capacity of 10 kg maize at initial m.c. of 33% d.b. with 0,04 m grain depth.**
- **The average solar radiation of 635 W/m^2 provided 60-65 ^{0}C outlet collector temperature.**
- **The initial temperature of maize was 21,7 ^{0}C.**
- **Six hours was required to achieve the desired final m.c. of 16,2% d.b., which corresponded to 0,2 kg/h drying rate.**

SOLAR MAIZE DRYING (5/5)

- **Due to the double heat transfer mechanism, the efficiency of the mixed-mode dryer is higher than an ordinary system, whilst not causing serious overdrying of the grain, and removing the need for mixing.**

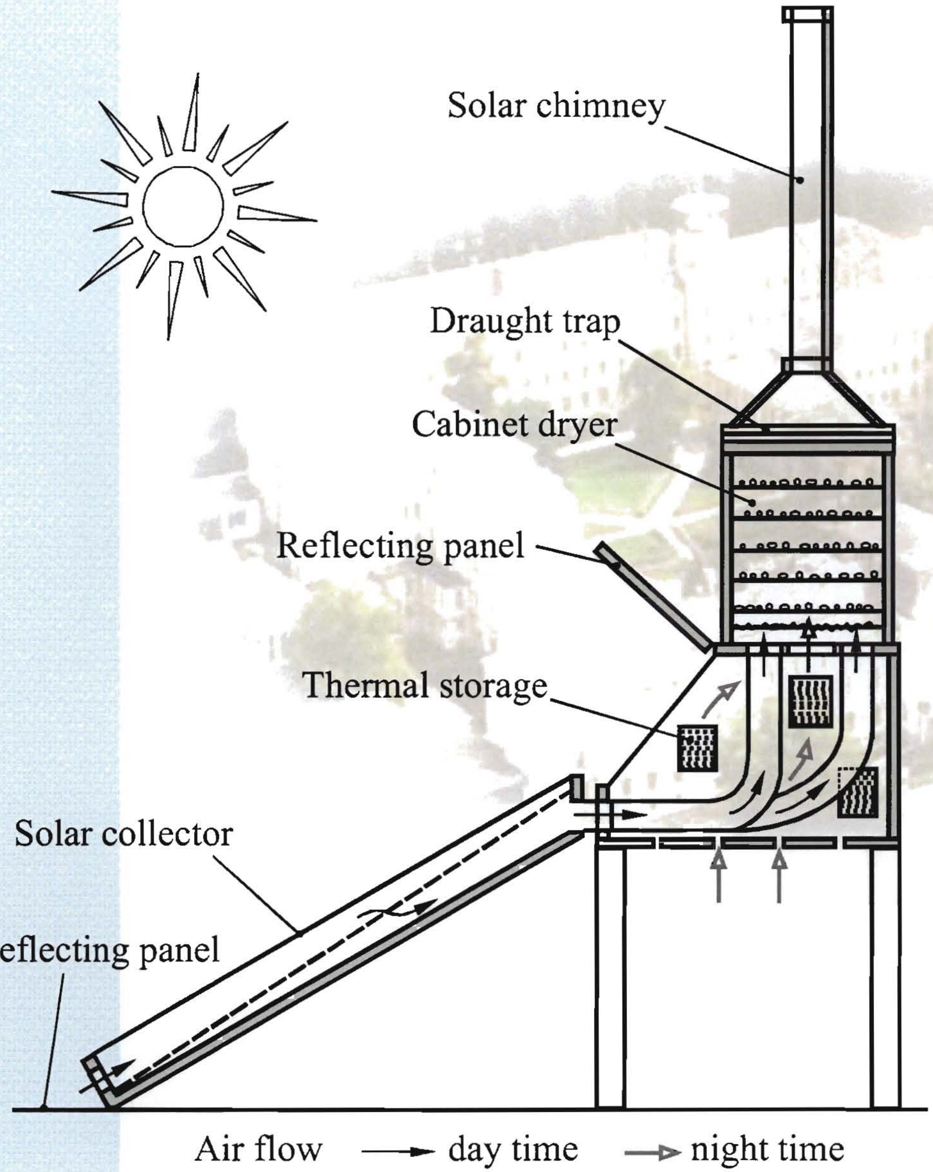
SOLAR CABINET DRYER FOR FRUIT DEHYDRATION (1/4)

- A solar cabinet type of dryer can be successfully used for drying of different fruits like apricots, peaches and apples (Puiggali and Tiguert, 1986).
- The dryer consists of the following main parts: solar collector as a warm air generator, thermal storage, cabinet type of drying chamber and chimney. The porous matrix bed solar collector has a surface are of 2,2 m^2.

SOLAR CABINET DRYER FOR FRUIT DEHYDRATION (2/4)

- The thermal charging of the heat storage water vessels can take place by direct solar radiation or by the heat recovery system.
- During the night the reflecting panels are dropped to insulate the transparent cover.
- The drying chamber can hold 5-10 trays supporting the thin layer drying of the different fruits.
- The chimney acts as a vertical flat-plate collector.

Scheme of a solar cabinet dryer



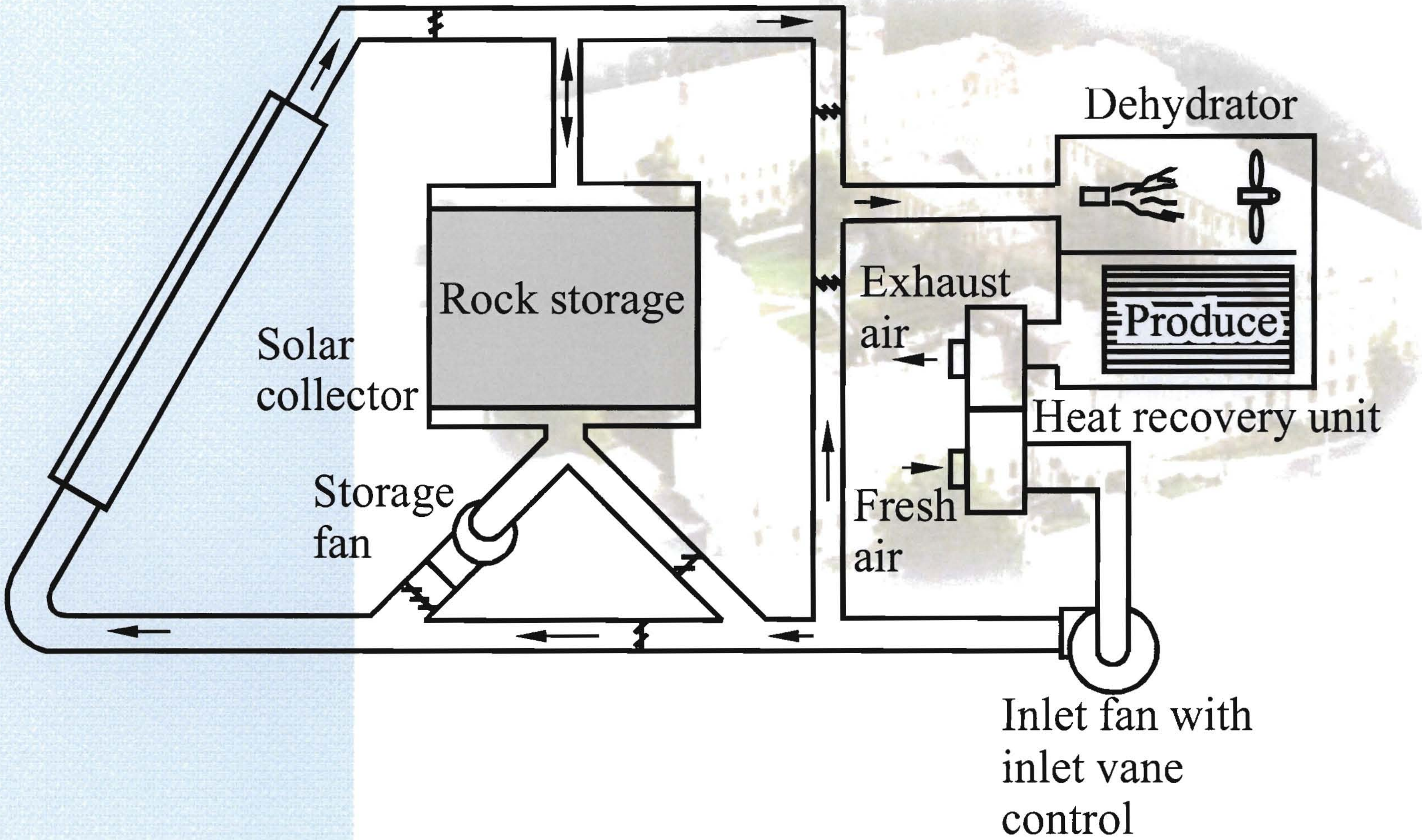
SOLAR CABINET DRYER FOR FRUIT DEHYDRATION (4/4)

- **During the experiments it was concluded that the different parts of the solar system have different contributions in the use of solar energy. The amount of the daily average cumulative solar energy was 72 MJ, giving a contribution ratio of 48 MJ by solar, 20 MJ by thermal storage and 4 MJ by the chimney.**
- **However, the ratio of chimney effect is not that high but it comes by a natural passive way, so its inclusion is fairly advisable (Boizan Justize et al., 1992).**

SOLAR FRUIT DRYING WITH BED STORAGE (1/5)

- **During use of solar energy the storage is essential.**
- **Solar-assisted large-scale fruit drying facilities equipped with bed storage and heat recovery unit are more beneficial through the varying the modes of operation.**

Scheme of solar fruit dryer with rock bed storage



SOLAR FRUIT DRYING WITH BED STORAGE (3/5)

- **The solar installation comprises a single-glazed flat plate collector of 1885 m^2, a rock bed storage unit of 354 m^3 and a rotary-wheel type of recovery unit along with automatic control of the entire system.**
- **The ambient air is first preheated by heat obtained from the moist exhaust air from the dryer using the heat recovery unit.**

SOLAR FRUIT DRYING WITH BED STORAGE (4/5)

The drying air can be heated in the following ways:

- by passing the air through the solar-heated rock bed storage unit when operating on storage
- by passing the air through the collector when operating on the collector
- by combination of the above methods determined by the availability of heat from the collector and the rock storage unit

SOLAR FRUIT DRYING WITH BED STORAGE (5/5)

- The control system divides the flow between the collector and the storage unit in a ratio to ensure that the two air flows are at equal temperatures, thus allowing the collectors to operate whenever solar energy is available.
- During the day, the collector output temperature is controlled by the base set point temperature of the dryer and the flow rate of the storage fan. If overheating occurs, the drying air is mixed with cooler air from the heat recovery unit in order to maintain the desired temperature.

MODULAR SOLAR FRUIT DRYER (1/11)

- There are several types and sizes of fruit to be handled during the drying process, using the same equipment.

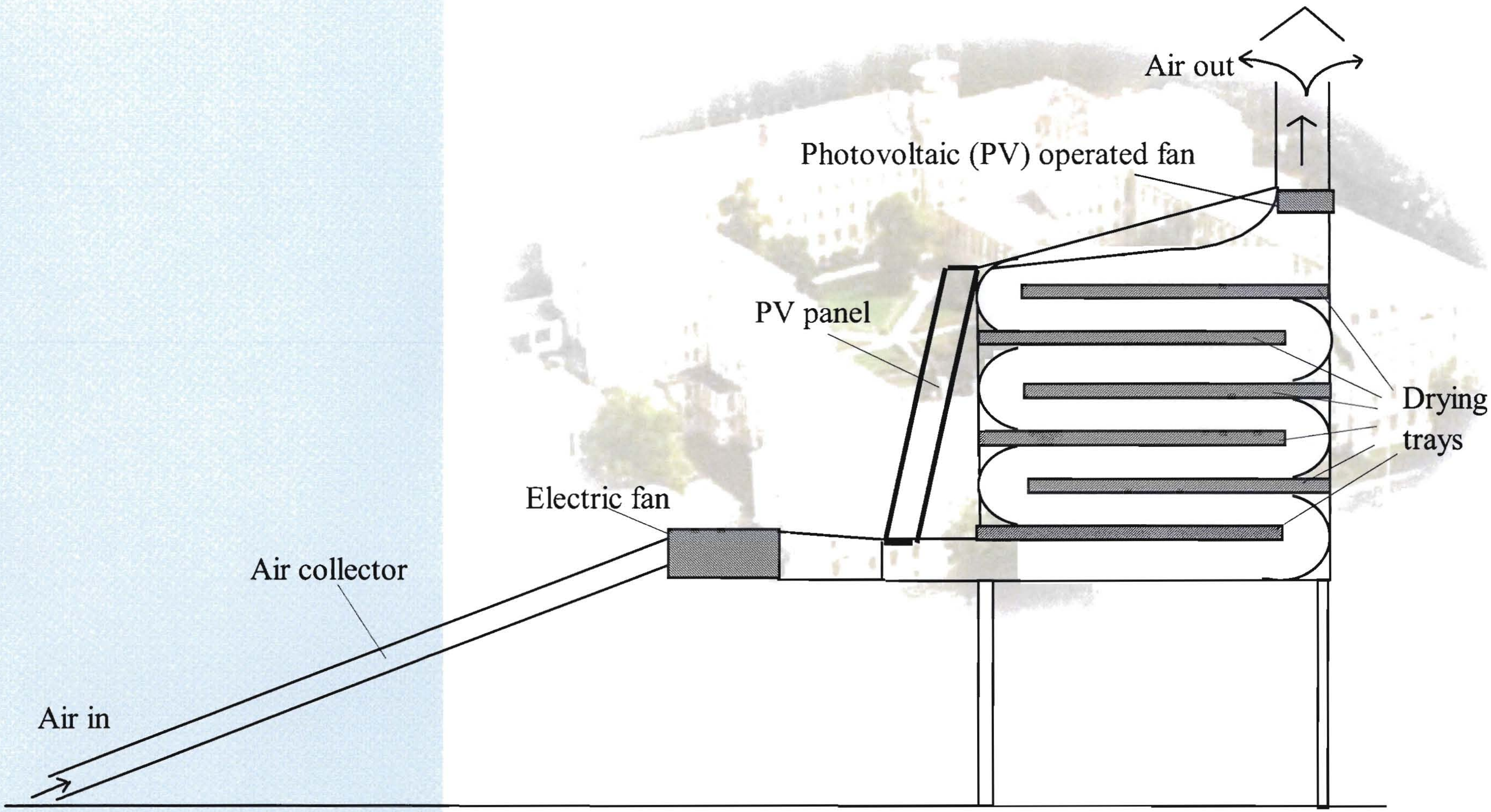
- At the same time, consideration to the involvement of the different solar energy resources must be given, to intensify the drying process and reduce the fossil energy requirement. These ideas gave the basis to construct a modular solar tray dryer (Farkas et al., 1996).

MODULAR SOLAR FRUIT DRYER (2/11)

- **Two basic variations were considered in accordance with the direction of the air flow inside the drying chamber. The first one is a surface dryer the other one is a batch or "overflowing" solution.**

- **The modular construction of the dryer means that the equipment does not need to contain all of these parts for the operation. It can be used with or without the solar collector, with natural (without fan) or forced airflow.**

Scheme of a solar surface dryer



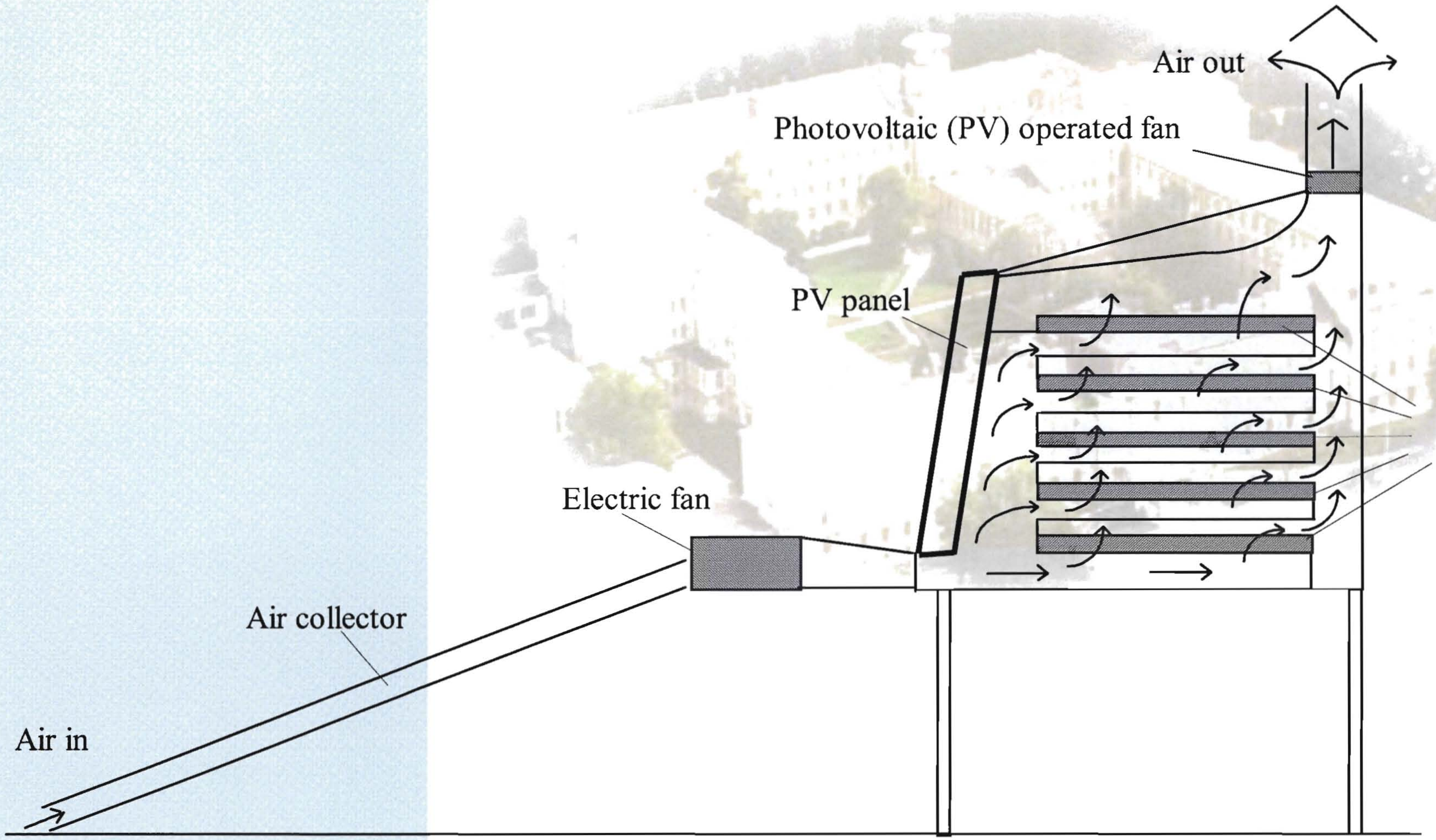
MODULAR SOLAR FRUIT DRYER (4/11)

- **In the course of this solution air becomes more and more wet during its route and the products on the higher trays do not dry so intensively than the lower ones.**
- **At the same time the bigger pieces of fruit could dry at lower intensity in this way.**

MODULAR SOLAR FRUIT DRYER (5/11)

- To solve this problem another solution was carried out in which the dry air enters uniformly to all of the trays.
- Such construction has an other advantage i.e. the air flow crosses the bulk layers so its drying efficiency is much higher compared to the surface drying, but this latter solution depends highly on the product to be dried.

Scheme of a solar tray dryer



MODULAR SOLAR FRUIT DRYER (7/11)

The solar drying equipment has four main parts:

1. **A dryer (drying chamber) with different trays for the different products to be dried. A tray holder with 4 trays stands for the surface drying, when the product is very fine size to flow the drying air through it. Another holder with 7 trays stand for bulk drying providing air flow through itself the product layers. Due to the weight and fixation of the trays holder units their changing for another one is rather simple. The drying chamber has a size of about 0.8 m x 1 m x 0.65 m and it has four legs with the height of 1 m.**

MODULAR SOLAR FRUIT DRYER (8/11)

2. A **PV module** with the maximum power of 2x20 Wp along with a same capacity of DC fan. The PV panel is installed in the front side of the dryer with changeable slope.

3. A 300 W capacity of **grid connected fan** can increase the rate of artificial drying.

4. A **solar air collector** unit of about 1 m^2 attachable to the dryer for preheating the inlet air with a value of 8-10 ^0C.

MODULAR SOLAR FRUIT DRYER (9/11)

Due to the modular construction of the dryer it can be operated in different modes:

1. **Natural ventilation by ambient air. To support this operating mode a chimney with a height of 2 m and across-section of 0.2 m x 0.2 m serves to strengthen the air flow through the drying chamber and through the material to be dried.**

MODULAR SOLAR FRUIT DRYER (10/11)

2. **Artificial ventilation of ambient air**, when the PV module and/or the grid connected fans are applied.

3. Artificial ventilation of the **drying air preheated by solar air collector**.

4. **Combined operation** including the above mentioned modes.

MODULAR SOLAR FRUIT DRYER (11/11)

- **During the drying experiments, several types of fruit were considered e.g. apple, grape, peach, plum, cherry and sour cherry but, and blackthorn.**
- **Some of them were used as a basic component of fruit tee or taste additive for different foods (muesli, etc.) or just for preserving.**

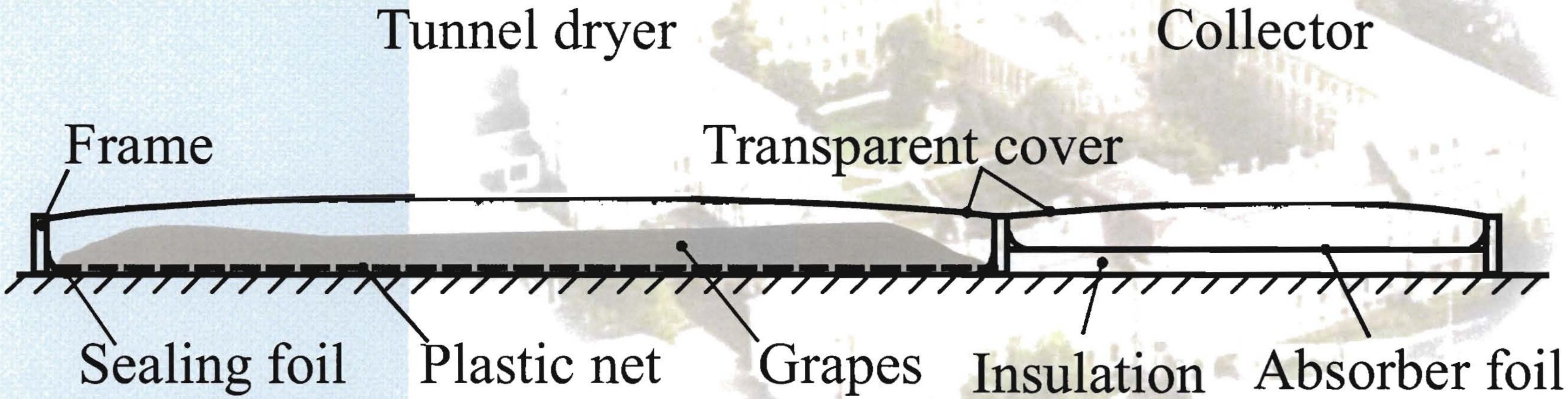
SOLAR GRAPE DRYING (1/6)

- Natural solar drying of grapes in order to get raisins of about 85% dry matter content has been known for thousands of years.
- The most critical factor is the long drying time along with elimination additional disadvantages, e.g. quality degradation, contamination, wind-blown pollution, splitting of the grain, insect infection, etc.
- Using solar energy for grape drying leads to substantially improved economics for the process.

SOLAR GRAPE DRYING (2/6)

- A solar tunnel dryer with integrated collector can serve as a low cost system.
- The equipment can even be fabricated either by small-scale industries or farmers them selves using simple tools and relatively cheap materials. (Lutz and Mühlbauer, 1986).

Scheme of a solar tunnel raisin dryer



SOLAR GRAPE DRYING (4/6)

- The collector and tunnel dryer are arranged parallel and oriented north-south.
- The size of the collector is 20 m x 1 m while the dryer is the same length but double (2 m) in width.
- The collector and tunnel dryer are covered with a high UV-stabilised transparent air-bubble foil.
- The drying air is forced by a fan through the flat plate collector, heated, turned by 180 degrees and mounted to the dryer.

SOLAR GRAPE DRYING (5/6)

- **Approximately 1000 kg of fresh grapes can be spread out inside the dryer.**
- **To prevent discoloration and spoilage the dryer has to be operated continuously during the first two days. During this period a relatively high airflow rate of about 1200 m^3/h is required.**
- **After that critical period the airflow can be reduced to 600 m^3/h and ventilation is no longer necessary during night.**

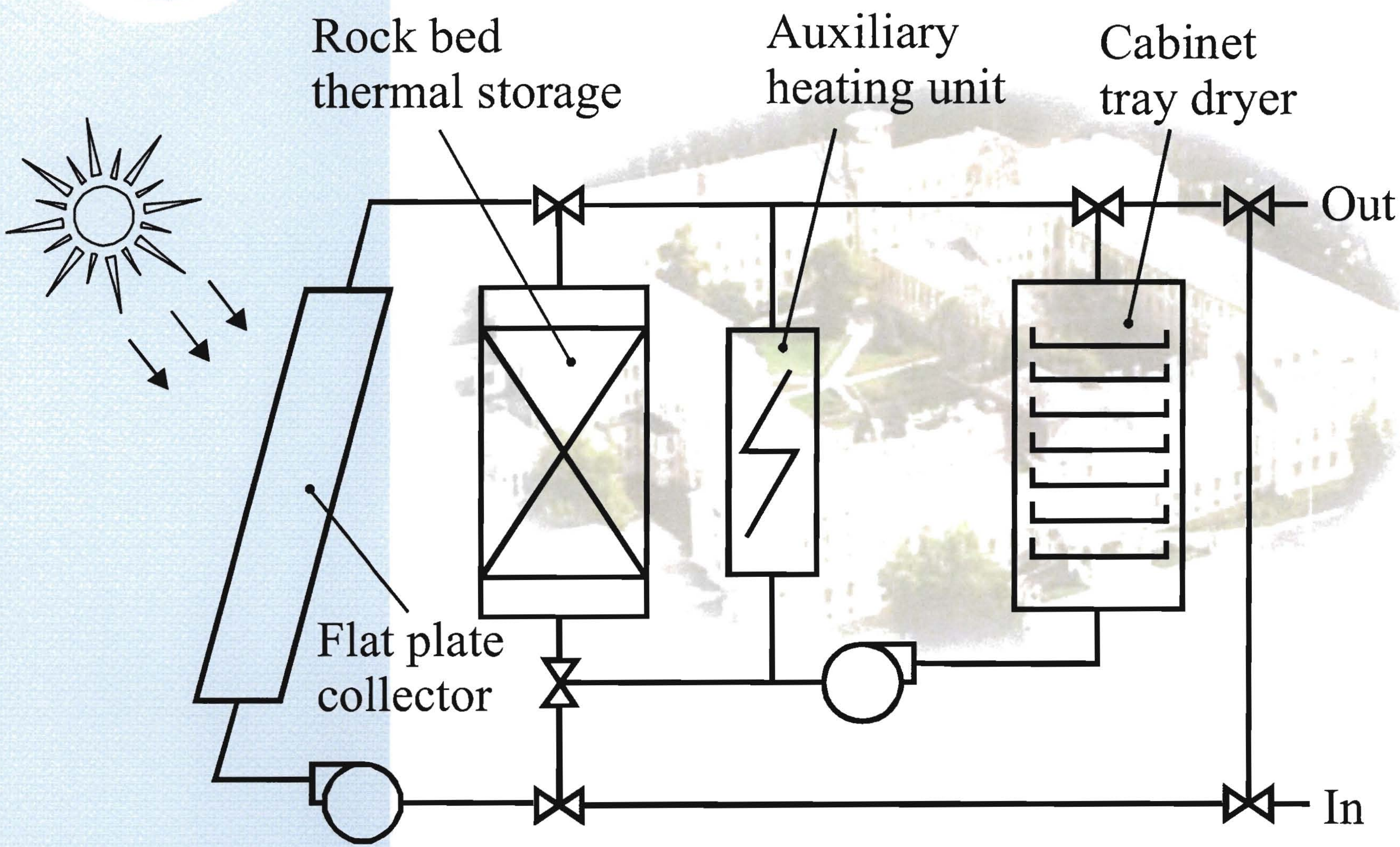
SOLAR GRAPE DRYING (6/6)

- Depending on the weather conditions, 1000 kg grapes can be dried within 4 to 7 days, compared to 8 to 12 days through natural sun drying.
- According to the drying capacity, the solar drying system can be successfully applied to farms with a size of 0,5-1 hectare.
- The payback time of the system is less than one year.

SOLAR GRAPE DRYING WITH STORAGE (1/5)

- **The solar dryer extended with thermal storage bed and auxiliary heating can improve significantly the quality issues of the dried raisins (Raouzeus and Saravacos, 1986).**

Scheme of a solar cabinet raisin dryer



SOLAR GRAPE DRYING WITH STORAGE (3/5)

- **The installation consists of a flat plate solar collector, a thermal storage bed a cabinet dryer and an auxiliary heater. The size of the black-painted absorber surface is 3 m x 2 m. A glass cover of 3 mm thick is placed at a distance of 40 mm above the absorbing plate.**

- **The thermal storage bed consists of concrete spheres 4 cm in diameter, packed in a cylindrical vessel of 0,5 m in diameter and 1 m high with an effective volume of 0,2 m^3.**

SOLAR GRAPE DRYING WITH STORAGE (4/5)

- **The cabinet dryer was constructed of iron sheet and it was 1,2 m high with a cross section of 0,5 m x 0,5 m. Two centrifugal fans with a capacity of 1,2 and 0,5 kW circulated the air through the solar heating, thermal storage and drying sections. An auxiliary electrical heater rated at 4 kW capacity was used.**

- **The installation could be operated as a one-pass or as a re-circulation system, with the use of auxiliary heater intermittent or in continuous mode of operation.**

SOLAR GRAPE DRYING WITH STORAGE (5/5)

- The drying experiments were carried out with ripe Sultana seedless grapes within 4-5 days using intermittent operation (Dincer, 1996).
- Even shorter drying times (1-2 days) can be achieved under continuous operation with the use of the thermal storage bed and/or the auxiliary heater.
- Under the same conditions 8-16 days of open-air sun drying would be required.

CONCLUSIONS

- The solar drying process plays a rather important role in influencing energy savings, quality of end-products and also environmental issues.
- Different types of solar drying technologies and drying apparatus can be successfully used for different sorts of materials of biological origin.
- The applicable temperature range and energy requirement for moisture removal are the most important parameters in designing a safe and cost-effective solar drying system.

THANK YOU

FOR YOUR KIND

ATTENTION!