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The Passive Greenhouses

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1. Introduction

We are living in a great Greenhouse: our planet, the Earth. This sustainable system is almost closed, except the radiative energy received from the Sun. Understanding and respecting its principles is the only guaranty for a safe future of our species. The Greenhouse effect is a process by which a part of the incident solar energy is trapped by the lower atmosphere due to the action of some atmospheric gases, called greenhouse gases. A part of the Earth's surface infrared radiation, which would be otherwise lost into the space, is redirected back by the greenhouse gases and the clouds, so the temperature of the lower atmosphere becomes higher than it would be if direct heating by solar radiation was the only warming mechanism (IPCC, 2007). This effect has a certain similarity with the overheating of a proper greenhouse, which works by isolating warm air inside a transparent building, by reducing the convection heat flow.

The greenhouses were developed in order to cultivate plants under controlled conditions. They offer high productivity and efficiency, and remove much of the risks caused by the inappropriate weather and climate. A certain greenhouse surface can feed five to ten times more people than the same conventional agricultural terrain. That is why greenhouses are used from more than two millenniums, as we know from the Plinius the Elder reports on the culinary habits of the Roman emperor Tiberius, who was already aware of the vegetarian regimes' advantages (Janick, 2007). His favorite cucumbers were planted in wheeled carts, put in the sun daily and then taken inside at night. The cucumbers were stored under frames or in special houses covered with oiled cloth or with sheets of selenite. The first modern greenhouse structures were built in the 13th century at the Vatican in Rome. Along centuries the greenhouses issued a powerful industry, which nowadays is supporting powerful economies, like in the case of the Netherlands.

Although from the technological point of view greenhouses are well covered, they have to cope with the continuously increasing costs of the energy. Their main asset, the direct use of the solar energy, is not able to constantly ensure the temperature constraints demanded by plants, because of the hardly predictable weather conditions. That is why most greenhouses have to be connected to conventional energetic infrastructures: electricity, gas, warmed water, etc. Our purpose is to investigate a fundamental improvement of the greenhouse concept, with a huge potential to improve our lives: *the Passive Greenhouses*.

2. Greenhouses – the state of the art

2.1 The greenhouses of the third millennium

A greenhouse is nowadays a relatively complex technical system. Essentially they are built of glass or transparent plastic panels, single layered or double layered, sustained by a metallic structure. Controllable ventilation fans and/or opening roofs as well as vaporization devices are common features. Removable curtains are deployed over the plants when the solar radiation is too strong, in order to avoid the overheating produced by the greenhouse effect or during cold nights. Unconventional constructive solutions may be also found, as the convertible open-top greenhouses for example, which are using rolling flexible transparent films as covers (Richel, 2004). Very often the plants are cultivated on artificial soils, sand or perlite for instance. The water and the nutrient solutions are conducted towards the roots of the plants by special watering installations, which are dosing the fertilizers, mixing, dropping and re-circulating them. Specific devices can be used in order to furnish the necessary treatments against fungus, insects or diseases. The following photos were taken at the experimental greenhouse of the Southern University of Toulon-Var (see §2.2).

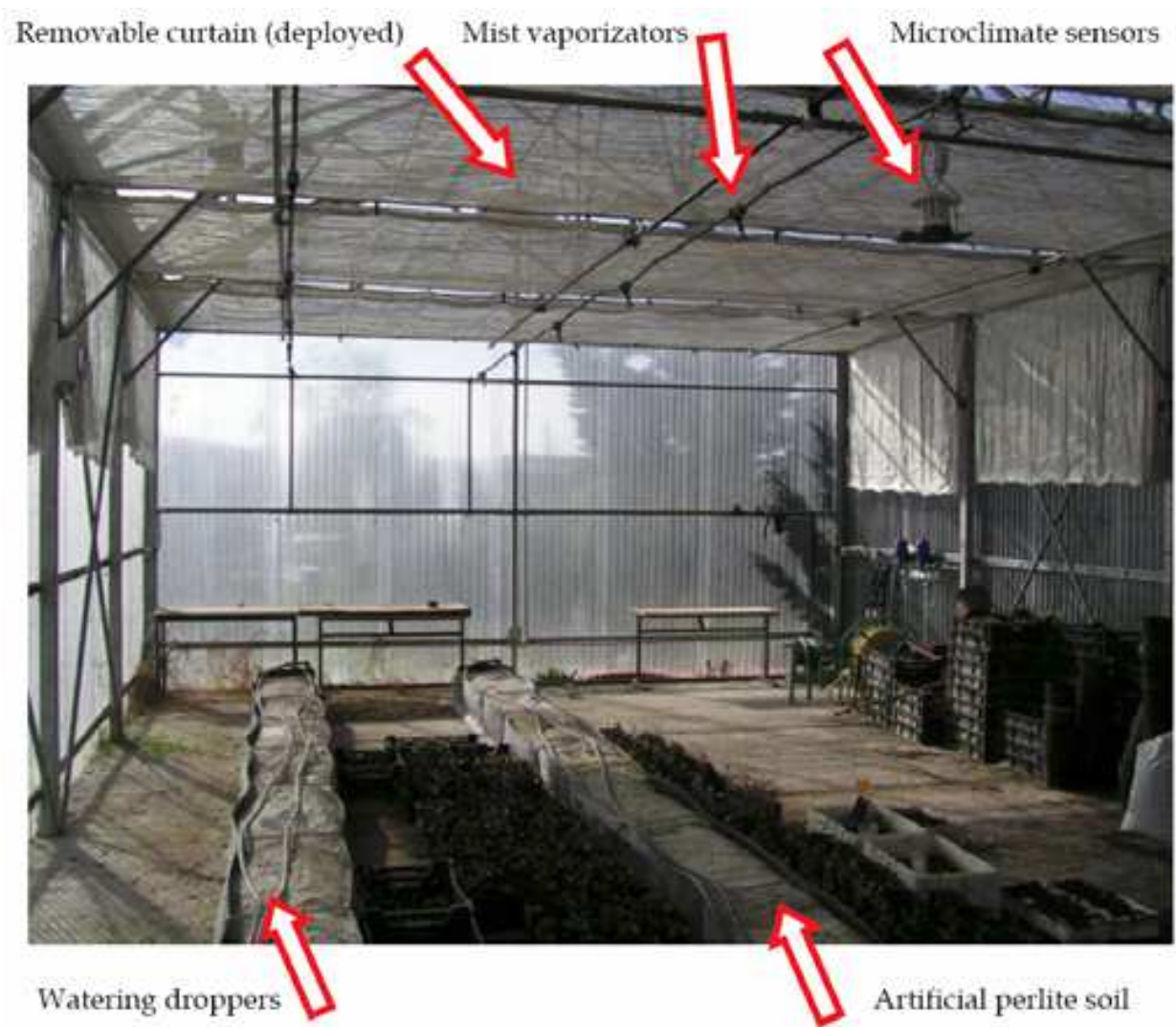


Fig. 1. The Toulon experimental greenhouse



Fig. 2. Opening roof and removable curtain (removed)

The artificial illumination and the carbon dioxide generators are also contributing to the economical efficiency of the greenhouses. Since photosynthesis converts carbon dioxide into organic compounds using the energy of the light, increasing the duration of the illumination and the carbon dioxide concentration in the air is substantially increasing the crop.

A wide range of control, monitoring, surveillance and telecommunication equipment is currently installed or connected to greenhouses. The typical greenhouse control is sequential, implemented by PLCs (*Programmable Logic Controllers*). Dedicated sensors are monitoring the main parameters of the microclimate and of the environment: the inside and outside air temperature and humidity, the soil temperature and humidity, the wind speed and direction, the solar illumination, etc.

The damages caused to the plants by the insects can be detected in very early stages by bio-electronic noses (Biologically Sensitive Metal-Oxide-Semiconductor Field-Effect Transistor - BioFET). For example the sensitive antenna of a Colorado beetle (*Leptinotarsa decemlineata*) may be connected to a MOS-FET. Thanks to the quasi-infinite impedance of the MOS-FET input gate, each electric impulse induced into the insect antenna by the odorant molecules emanated by the damaged plants may be amplified and measured (Schutz et al., 2000).

However, the essential components that decide the performance and the efficiency of the greenhouses are the heating/cooling installations. They use different conventional energy sources: electricity, gas, liquid fuels, coal or wood, as well as renewable energy sources such as hot geo-thermal waters.

Although the greenhouse is able in principle to directly use the sun energy for heating, this feature is not at all reliable, depending of the day-night cycle, the changing weather and the technical condition of the greenhouse. For example, when personnel work inside, the greenhouse system is changing a lot its parameters. That is why usual greenhouses still need a great deal of conventional energies. During the last decades the increasing energy price has affected the greenhouse industry in many parts of the world.



Fig. 3. A 55kW gas heater: extremely effective, but the gas is expensive and polluting

The scientific and technological research is continuously investigating different ways to increase the performance of the greenhouses:

- Constructive improvements concerning the materials, the shapes, the dimensioning of the components, etc.
- Improvements concerning the automate control: optimizations of the algorithms, smart/ intelligent features, embedding knowledge concerning the weather, the crop, etc.
- The elaboration of mathematical and computer models for the greenhouse system, able to assist the constructive dimensioning, the automate control, the automate diagnosis, etc.
- Introducing different renewable energy sources, in order to reduce the energy cost.

The following sections will illustrate some of the relevant achievements of the domain.

2.2 The experimental greenhouse of Toulon

The LSIS team (*Laboratoire des Sciences de l'Information et des Systèmes*) of the Southern University of Toulon-Var France initiated almost twenty years ago a project that issued a great deal of data and knowledge concerning greenhouses. Professor Gilles Enéa and his colleagues Jean Duplaix, Jean-François Balmat and others, built an experimental greenhouse (see the previous figures and <http://sis.univ-tln.fr/serre/>), provided with a Local Area Network control and monitoring system. More than twenty sensors measure the most important environmental and technical parameters. This platform and its Internet compliant technology supported numerous researches dedicated to the identification and the intelligent control of the greenhouses.

Both synthetic and structural models were approached. The synthetic modeling - neural networks, genetic algorithms, etc. proved to be very precise and efficient when dealing with very specific operating regimes: sunny or cloudy days, still or windy nights, etc. but encountered fundamental obstacles when trying to cover the overall greenhouse's performance (Lafont & Balmat, 2001; Bouchouicha, 2002). In other words, the synthetic models extracted from a sunny day recorded data are not properly working when applied for a cloudy day data. This is due to the complexity and high nonlinearity of the greenhouse system, and the only way that eventually produced good results was the fusion of several sub-models, each one aiming a particular operating regime: night, sunny day, cloudy day, rain, etc. The most comprehensive and precise synthetic model was obtained by a multi-model system supervised by HFL - Hierarchical Fuzzy-Logic (Pessel et al., 2009). The sub-models are implemented by neural networks. Although the synthetic modeling is a popular option nowadays, especially when the physical structure of the investigated process is unknown, such models are opaque; they are hiding any explicit knowledge about the system we are focusing on.

That is why, starting from 2003, the authors of this chapter engaged themselves on the other fundamental modeling strategy: the structural one. A structural identification is trying to catch the essential functional constraints that are governing the time evolution of the physical parameters. The complexity and the nonlinearity of the greenhouse as a mathematical item forced us to choose the simplest possible solutions, which are approximating rather roughly the reality. We avoided any computational complications: for instance, the inside greenhouse temperature was modeled by a first order differential equation (the Newton's law of cooling), with time varying coefficients and dead time, avoiding a partial differential equation system, that would have been the recommendable solution. Each coefficient of this key equation was determined on behalf of specific experimental tests, which were possible thanks to the experimental features of the Toulon greenhouse:

- The coefficient of the heat transfer through the walls was determined using the recorded data of a still night;
- The influence of the wind on the heat transfer issued out of a windy night data;
- The greenhouse effect was determined assuming that the heat transfer through the walls, previously determined for night conditions, will not change during daytime. The essential data for the identification of the greenhouse effect was recorded during a sunny day, keeping the greenhouse strictly closed, in order to avoid air changes with the exterior.

We can define two stages of the structural modeling:

- The elaboration of a "first guess", based on the theoretical analyze of the process and on training data;
- The optimization of the first guess model, based on validation data.

We applied this method mostly for the identification of the influences of the wind (Balas et al., 2008) and of the sun (Balas & Balas, 2008a). Our optimizations were carried on with the help of the genetic algorithms, but other choices are also legitimate.

The lack of precision of this method is largely compensated by its robustness, versatility and efficiency in terms of computational resources and developing time. Consider just the case of a new application, the synthetic modeling has to start from the scratch, while the structural one has only to be adapted and optimized for the validation. Of course, the greenhouse system is rather tolerant for the temperature variations, which is facilitating our task.

As a conclusion, the Toulon experimental greenhouse offered us the necessary conditions to elaborate a valid structural mathematical and computer model of a generic greenhouse. This model served us to explore new heating and cooling architectures for greenhouses, since the nature of the energy sources has a small impact on it.

2.3 The Wageningen solar greenhouse

The Netherlands plays a leading role in the greenhouse industry and horticulture. The scientific research that is supporting this industry is mainly located at the Wageningen University and it is inspired and supervised by Professor Gerrit van Straten. The Dutch Government promoted a fundamental research project dedicated to solar greenhouses and their optimal adaptive control (Dutch, 1999a & b), which was accomplished at Wageningen. This project was finalized by a doctoral thesis (van Ooteghem, 2007), that from our point of view, represents a milestone in the field. Here one can find the most detailed and complete structural model of a generic solar greenhouse, including the model of its developing crop. The Wageningen Solar Greenhouse, shown in Fig. 4, aims to minimize the fossil fuel consumption.

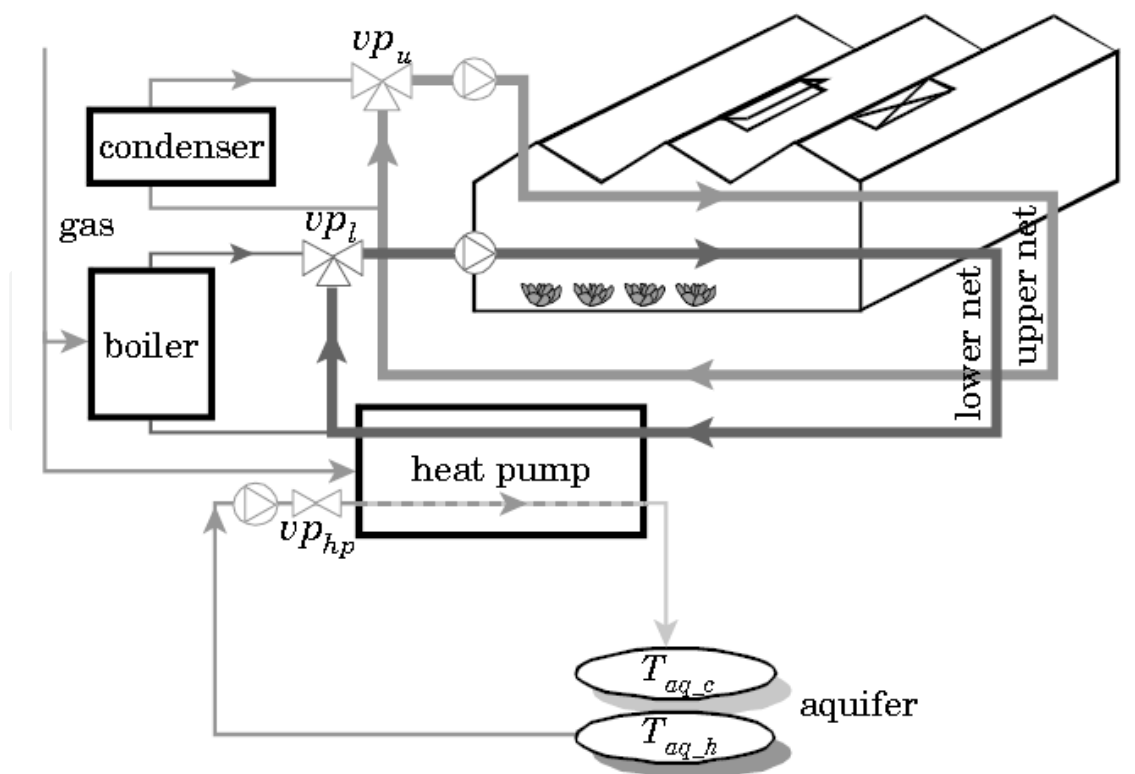


Fig. 4. The Wageningen solar greenhouse

Besides the solar effect, the greenhouse is warmed by a system consisting of a cold water heat pump, a gas boiler and a condenser. The heat pumps are able to extract energy from low temperature waters or air, by means of an external water circuit, and to inject it into an internal closed water heating installation. The energy is provided by the thermal radiation of the earth. Obviously this type of energy is available everywhere on the surface of the earth, it is free of any costs, it is very constant and it has no predictable time limits. The external circuit may be closed (pipes) or open. The open circuit needs an aquifer system with two water wells: a warm one (say 16°C) and a cold one (say 10°C).

Heat pumps need 15-20% of their nominal energy for the recirculation of the water. The heat pump of the Wageningen greenhouse is fired by gas. The heat pump can heat the lower net up to 33°C while the boiler can heat it up to 90°C.

Besides the warming system, the greenhouse is provided with a cooling heat exchanger, also connected to the aquifer and to its own upper cooling net.

The optimal adaptive predictive control is essential for the process (van Ooteghem, 2007). The predictive features are created with the help of the mathematical model that simulates over a time period of 6 days the effects of the disturbances: control actions (valve positions, ventilation windows aperture, etc.) and weather forecast. The model takes account of the crop growth effects. The receding horizon optimal control (RHOC) has been implemented. A goal function is formulated to minimize fossil energy use and maximize crop yield. With the goal function the costs are calculated based on the predicted process dynamics and the control inputs are altered to find the minimum costs.

The van Ooteghem model is the most comprehensive model communicated so far. All the greenhouse components and the associate physical effects are treated in a detailed manner: inside temperatures (air, walls, soil, etc.), curtain's effect, ventilation, heating and cooling, as well as the developing crop: evapotranspiration, photosynthesis, respiration, etc.

Although heat pumps can produce much higher temperatures, the gas boiler is still needed because the heat pump is highly inertial, unable to perform a fast control action. As in the case of the Toulon greenhouse, a powerful gas heating device is considered necessary.

2.4 The closed greenhouse and the watergy

Persons living in temperate or cold climate consider greenhouses mainly as energy manipulation technical items. However greenhouses can do much more than this. The management of the water resource – the Watergy – becomes essential in hot and arid regions that require large quantities of water for irrigation. The Closed Greenhouse, a concept of TerraViva Tec S.L., excludes the external aeration, preserving the initial water supply (TerraViva, 2004).

A tower with an internal cooling duct is placed into the centre of a greenhouse. Heated air humidified by the plants rises to the tower driven by natural buoyancy. From the upper end of the duct, the air is constantly cooled down by a heat exchanger. As it becomes colder, the air falls down through the tower and back into the greenhouse. This generates in the same time cooled and dehumidified air and condensed water. Besides the food production, closed greenhouses can turn wastewater or saltwater into irrigation and even drinking water.

Obviously, the Closed Greenhouse may become an Advanced Life Support item, making possible the habitation of remote areas like the desert and the polar regions and even the long term journeys in space.

3. The Passive Greenhouse

3.1 What is a Passive Greenhouse?

Starting from 2004 we began to investigate a new concept: *the Passive Greenhouse* (Balas et al., 2004). This term stems from *Passive House*, which defines a building with a reduced ecological footprint. Although this might open some controversies, we decided to consider the term *passive* in the sense of *free of conventional energy, relying exclusively on sustainable energy*.

A Passive Greenhouse is independent of any conventional energetic infrastructure (gas, hot water, electricity, etc.) The concept is close to the Solar Passive Greenhouse, which uses only solar radiation and natural ventilation (Bellows, 2003). If provided with renewable energy sources as geo-thermal water, wind, photovoltaic, etc. a Solar Passive Greenhouse becomes a Passive Greenhouse. We can appreciate a Passive Greenhouse as a radicalization of the Wageningen Solar Greenhouse, in the sense that we renounce at any sort of conventional energy - gas and even electrical network. As we are about to see, although from the constructive point of view a Passive Greenhouse is not much more than a Passive House, major difficulties appear because of the intrinsic characteristics of the renewable energy sources: the geo-thermal energy is highly inertial while the sun and the wind are inconstant and not reliable. That is why we will be forced to replace the idea of the optimal adaptive predictive control with the *expert adaptive predictive control*. We can afford to drop the optimization constraint because of the strategic advantage of the Passive Greenhouses: *the zero cost energy!*

The construction of a Passive Greenhouse is quite banal; all its components have already developed their own markets. On the other hand, putting together several renewable energy devices, with contradictory technical and economical constraints, gives birth to a new systems engineering item, with unexpected and promising interdependences and synergies.

Before describing the Passive Greenhouse, we prefer to discuss its potential impact on our future. This way the readers interested rather in ecology or economics will not be forced to bear the technical details. Anyway, the technological support of the Passive Greenhouses is expected to constantly change for the better, what is really essential is to understand the principle and to assume its consequences.

3.2 The Passive Greenhouse sustainable agricultural system

For the time being conventional greenhouses have to be located near the existing infrastructures of our towns or villages. Assuming solved the technical problems, besides their free energy, the essential feature of the Passive Greenhouses is *the full independence of any conventional energetic infrastructure*. They can be installed virtually anywhere we dispose of natural or even artificial aquifers. Thanks to this feature, the extensive use of Passive Greenhouses offers us the opportunity to reconsider the global structure of the agricultural terrains (Balas, 2008; Balas et al., 2009a).

The Passive Greenhouses could be concentrated into remote locations, out of other immediate interest. Such sacrificed arias will look perhaps as the ugly mountainous zones that are currently occupied by solar greenhouses near San Remo, Italy (see Fig. 5). However these unpleasant looking greenhouses, located on artificial terraces, are producing the splendid flowers that are decorating the Italian Riviera! Inspired by this image, we will borrow a chess strategy: sacrificing a humble pawn - passive greenhouse concentration regions - for the final victory: a global ecological reconstruction of our environment.

The reason standing behind this idea is simple: a certain greenhouse aria can feed five to ten times more people than the same conventional agricultural terrain. The unshackled surfaces

resulted after replacing a great deal of the agricultural terrains by Passive Greenhouses can be ecologically reconstructed and converted into natural environments: forests, pastures, orchards, pounds, etc. and all the consequent benefits.

Our alimentation is accomplished by two basic food chains:

- a. A three level trophic chain: *plants* → *animals* → *humans*
- b. A two level trophic chain: *plants* → *humans*

Much energy is lost into the environment at each transfer from one trophic level to another. That is why the food chain a) needs much more agricultural surfaces and energy than the food chain b). If, as a consequence of the extensive use of Passive Greenhouses, the animal growing will turn over the use of natural pastures instead of the actual cereal feeding, we can count on a significant bias of the trophic chains balance in the favor of the food chain b).

Besides any theoretical speculations, replacing conventional agricultural terrains by greenhouses has a doubtless carbon offset effect. We know that the CO₂ consumption of trees is much higher than for cereals (Tuzhilkina, 2006). The CO₂ consumption in a greenhouse is similar to a forest (Voican, 1998; Horgos, 2003), due to the high density of the plants and to the ideal growing conditions. So, in the end, more greenhouses means less CO₂ in our air.



Fig. 5. Greenhouse concentration near San Remo, Italy (satellite view)

3.3 The Passive Greenhouse generic structure

In our previous papers (Balas et al. 2004; Balas & Duplaix, 2008d) we proposed a generic passive greenhouse structure that aggregates three renewable energy sources: a cold water heat pump (Ochsner; Olivier, 2001), a dc wind generator (NREL, 2006; IEC, 2006; SECO, 2008; Texas, 2010) and a matrix of orientable photovoltaic panels (Bradford, 2006; Texas, 2010). The roles played by the components of the Passive Greenhouse are the following:

- ≈ The heat pump is the main heating/cooling device;
- ⇒ The wind generator produces the energy needed by the heat pump for recirculation;
- ⊗ The orientable photovoltaic panels produce recirculation energy for the heat pump and also replace the removable curtain, shading the plants when the solar radiation is excessive; this idea might seem too expensive, but the panels' prices are constantly decreasing.
- ☒ The dc accumulator stocks wind and photovoltaic energy in order to supply the electric recirculation pump of the heat pump and also to supply all the control, driving and communication systems needed by the greenhouse.

The aggregation and the stocking of the disposable energy amounts in the accumulator are our first weapons against the energetic unreliability of the wind and the sun.

Another item that can help the renewable energy sources aggregation during exceptional cold weather is a supplementary gas/bio-gas burner. Since such extreme weather periods are rather seldom, this is a good method to reduce the investment costs, avoiding the overdimensioning of the other energy sources. Gas burners are anyway useful in greenhouses in order to increase the carbon dioxide concentration in the air. The electric energy of the accumulator can be used as well for heating for short periods, in emergency cases.

Comparing to the Fig. 4 greenhouse, we need only the lower net, used for both heating and cooling. The low position of the heat exchanging net is normal for heating but may appear as inadequate for cooling. However, we must recall that the overheating greenhouse effect is produced essentially at the ground level, so cooling the soil is very effective, not to mention the cost reducing. The heating-cooling switching of the heat pump is not a critical issue.

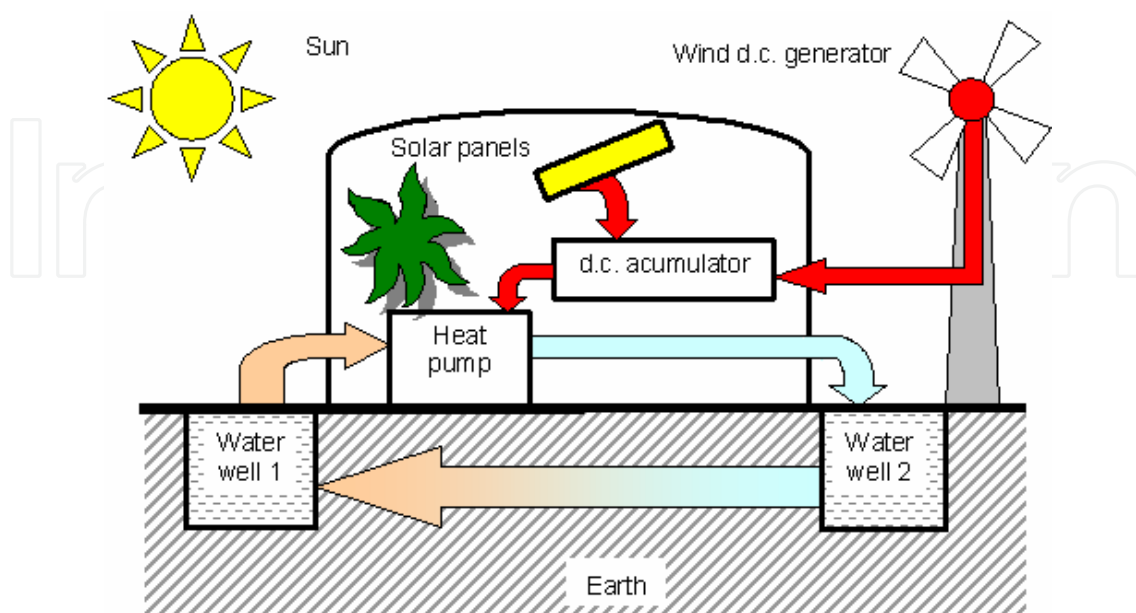


Fig. 6. The generic Passive Greenhouse

4. Modeling the Passive Greenhouses

Although all its parts are wide spread industrial products, the Passive Greenhouse is a novel product by its functionality and is not materialized yet. A pilot Passive Greenhouse has to be built as soon as possible. For the time being our research tool is a structural mathematical model enabling us to perform any theoretical task concerning the design and the development of the Passive Greenhouse. However this model resulted just by replacing the power of the gas heater of the Toulon experimental greenhouse with the power developed by the previously described renewable energy sources assembly, so we have no reasons to doubt the conclusions of the research. The model is tuned for the Toulon greenhouse but as a structural model, it can be adapted to any other greenhouse, after the experimental or theoretical identification. The model is essential for the Passive Greenhouses development because it can be easily adapted for different purposes.

One future application of this model is intended to address and the essential issue of the investment costs. Simulations performed after relevant scenarios may help us to optimize the energy sources balance that minimize the costs but ensures the desired operation.

4.1 The structural model of the Passive Greenhouse

According to the purpose of the future simulations we can use different arrangements for the greenhouse mathematical model. For the Passive Greenhouse our interest is to emphasis the contribution of each energy source over the overall internal temperature T_I :

$$\frac{dT_I(t)}{dt} = \frac{dT(t)}{dt} + \frac{dT_{PC}(t)}{dt} + \frac{dT_W(t)}{dt} + \frac{dT_{ES}(t)}{dt} \quad (1)$$

The detailed elements of the model are the following:

- a. $T(t)$ [$^{\circ}\text{C}$], the basic inside temperature due to the environment influence, embedding the effects of the heat flow through the walls and of the natural or forced ventilation:

$$\frac{dT(t)}{dt} = [k_a(t) + k_v \cdot F(t)] \cdot [T_E(t) - T_I(t)] \quad (2)$$

where $k_a(t)$ [s^{-1}] is the coefficient of the heat flow through the walls, k_v [m^{-3}] the ventilation coefficient, $F(t)$ [m^3/s] the ventilated air flow and T_E [$^{\circ}\text{C}$] the external temperature. $k_a(t)$ is a nonlinear parameter, embedding several functional influences: constructive (shape, dimensions, material of the walls), of the wind, etc. The model considers the two major physical effects characterizing the heat flow through the walls, the radiation and the convection, by two specific coefficients, k_{aR} [s^{-1}] and k_{aC} [m^{-1}]:

$$k_a = k_{aR} + k_{aC} \cdot V_W \quad (3)$$

where V_W [m/s] is the speed of the wind. The ventilation coefficient k_v , which is considered constant for the moment, could also be treated as nonlinear, influenced by the shape and the dimension of the ventilation fans, the wind, etc.

- b. The equation of the heat pump is:

$$\frac{dT_{PC}(t)}{dt} = k_{PC} \cdot P_{PC} \quad (4)$$

with $T_{PC}(t)$ the temperature amount added to $T(t)$ by the heat pump, k_{PC} [$^{\circ}\text{C} \cdot \text{s}^{-1} \cdot \text{W}^{-1}$] the heat pump coefficient, and P_{PC} [W] the power of the heat pump.

c. The equation of the wind generator is:

$$\frac{dT_w(t)}{dt} = k_W \cdot P_W \tag{5}$$

where $T_w(t)$ is the temperature amount added to $T(t)$ by the wind generator if connected to the electric heating device, $k_W[{}^{\circ}\text{C}/\text{m}]$ the wind coefficient and P_W the power supplied by the wind generator. We are considering a generic wind generator modeled by the following equation (Iowa):

$$P_W(t) = 0.5 \cdot \eta_W(V_W) \cdot \rho \cdot \pi \cdot r \cdot V_W^3 \tag{6}$$

where η_W is the efficiency coefficient of the wind generator, $\rho \text{ [kg/m}^3\text{]}$ is the density of the air and $r \text{ [m]}$ is the radius of its helix.

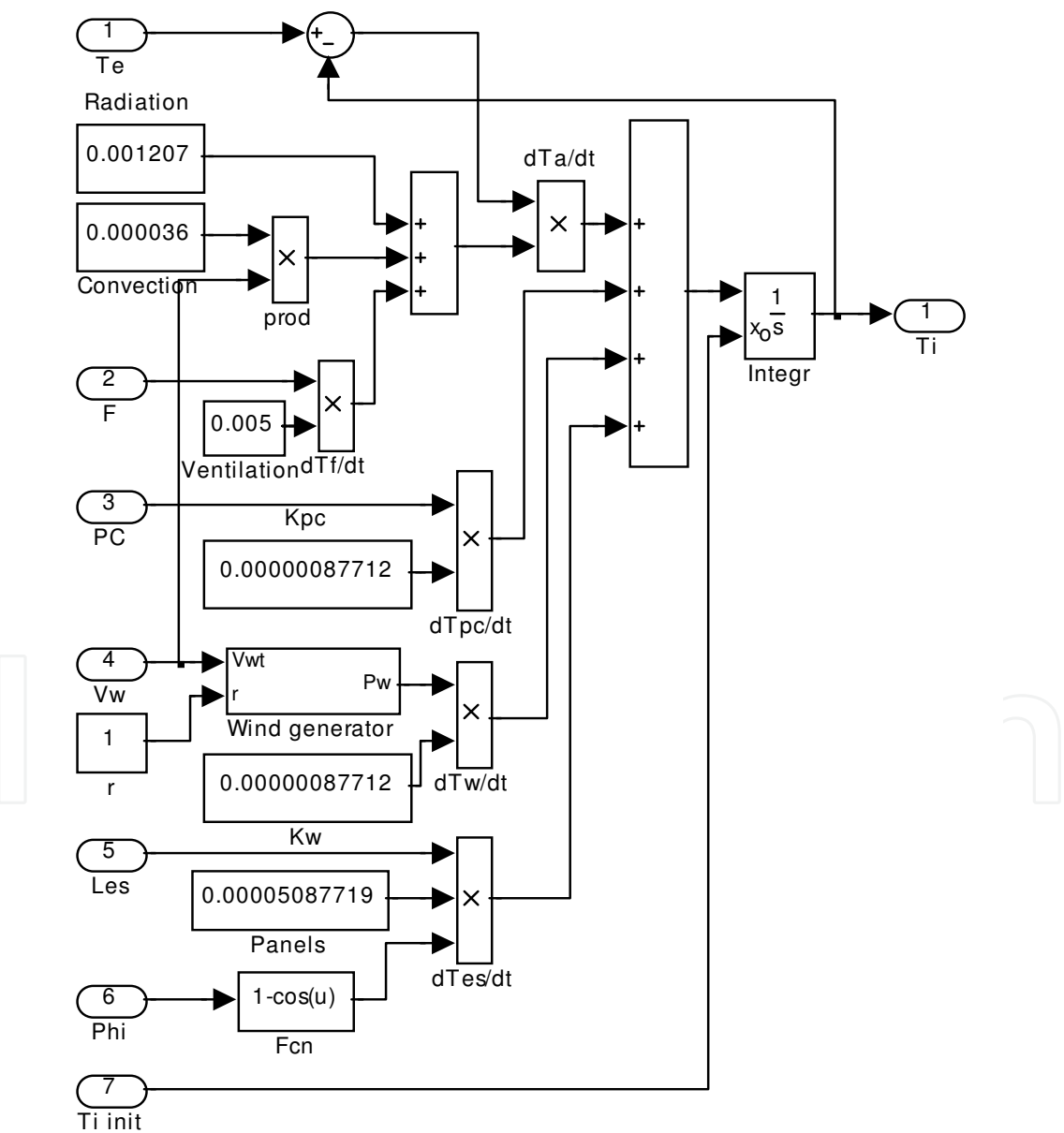


Fig. 7. The Simulink-Matlab implementation of the Passive Greenhouse model

- d. The equation of the greenhouse effect is:

$$\frac{dT_{ES}(t)}{dt} = k_{ES} \cdot L_S \quad (7)$$

where $T_{ES}(t)$ is the temperature amount added by the sun, $k_{ES}[^{\circ}\text{C}\cdot\text{m}^2\cdot\text{s}^{-1}\cdot\text{W}^{-1}]$ the greenhouse effect coefficient and $L_S[\text{W}/\text{m}^2]$ the intensity of the solar radiation (Balas & Balas, 2008a).

The coefficients k_{aR} , k_{aC} , k_{PC} , k_W and k_{ES} are tuned according to the results obtained in the previous papers concerning the Toulon greenhouse. For k_V experimental data are missing so far and we use a plausible value. The numeric values of the parameters used for the simulations to find in the next section are the following:

$$\left\{ \begin{array}{l} k_{aR} = 0.001207 \text{ s}^{-1} \\ k_{aC} = 0.000036 \text{ m}^{-1} \\ k_V = 0.005 \text{ m}^{-3} \\ k_{PC} = (250 \cdot 4560)^{-1} = 0.87712 \cdot 10^{-6} \text{ W } ^{\circ}\text{C s}^{-1} \\ k_W = (250 \cdot 4560)^{-1} = 0.87712 \cdot 10^{-6} \text{ W } ^{\circ}\text{C s}^{-1} \\ k_{ES} = 50.87719 \cdot 10^{-6} \text{ m}^2 ^{\circ}\text{C s}^{-1} \cdot \text{W}^{-1} \end{array} \right. \quad (8)$$

The Simulink-Matlab implementation of the model is presented in Fig. 7.

4.2 Direct applications of the model

- a. The assistance of the design and the optimization of the nominal parameters of the energy sources. The simulations are helping us to verify the sizing of the constructive components according to different simulation scenarios specified by the users.

Consider the following situation: we want to install a Passive Greenhouse identical to the Toulon experimental greenhouse in a region where the lowest winter temperature is -20°C , the mean winter temperature is 0°C , and the mean wind speed is 5 m/s . Which heat pump should we choose if we want to keep a minimum T_I of 10°C ? A simulation for $T_E = -20^{\circ}\text{C}$, shows that we need 47 kW to stabilize T_I at 10°C . The same simulation for $T_E = 0^{\circ}\text{C}$ indicates only 16 kW . Since the extreme temperatures are very seldom, we can choose a $16\text{--}20 \text{ kW}$ heat pump and an emergency gas burning device.

- b. A simulation performed over a certain time horizon, using the current input data, extrapolates instantly the current evolution of the system. This kind of predictors can help us to avoid the damaging of the crop (freezing or overheating) or to diagnose damaged walls.

Let us consider the following situation: $P_{PC} = 15 \text{ kW}$, $T_E = 0^{\circ}\text{C}$, initial $T_I = 20^{\circ}\text{C}$ and $L_S = 10 \text{ W}/\text{m}^2$ (a cold night, with no ventilation). We measure a -0.02°C decrease of the temperature per minute. A simulation over two hours starting with this input data is indicating that T_I will stabilize at 8°C . If the greenhouse's crop consists for instance of tomatoes we can accept this situation, taking into account the fact that the plants can tolerate such short time cool periods. If we cultivate tropical flowers that are not tolerating low temperatures, we must take appropriate measures to avoid the damage, for instance to burn biogas until morning, when the sun will begin to heat the greenhouse. The power of the gas burner can be tuned as well with the help of the model.

Imagine now, that for the same conditions, the walls are damaged, resulting a $0.5 \text{ m}^3/\text{s}$ air flow. After two hours, T_I would stabilize at 3.5°C that is not tolerable. The decreasing of T_I

in 60 s in this case is -0.056°C . Since this value is significantly exceeding the normal -0.02°C decrease we are usually measuring in these conditions, we are able to diagnose the damaged walls after just one minute, and we can produce immediately the necessary interventions.

4. The expert adaptive predictive control of the Passive Greenhouses

Controlling the Passive Greenhouse is not a trivial task, because of the extremely slow action of its main energy source, the heat pump, comparing to a conventional energy source (Balas & Duplaix, 2008d; Balas et al., 2009b). The control algorithm may cope with this strong inertial behavior only by strong predictive features. This kind of applications (highly nonlinear, demanding Artificial Intelligence elements, but with no strong accuracy constraints) may be conveniently treated with *the expert control*. The expert control is a control application involving expert systems. An expert system is a software that attempts to provide an answer to a problem the same way as a human expert would do it. An expert controller is essentially composed by a control rule base and an inference method. The control rules are elaborated by experts. If the control rules are modeled by fuzzy sets and the inference uses the fuzzy logic we obtain fuzzy expert systems. The fuzzy control was previously applied for the natural ventilated buildings (Dounis et al., 1996). The fundamental advantage of the intelligent control (fuzzy expert included) over the conventional/ optimal control is that the control rules may be formulated by experts in horticulture with absolutely no IT skills but having a deep understanding of the greenhouse system.

Our personal approach relies on the fuzzy-interpretative expert systems that may be implemented by look-up tables with linear interpolations, or with any other software or hardware interpolative networks (Koczi et al., 2005). Some of the control rules we used in our simulations for the Passive Greenhouse control may be linguistically described as follows:

1. IF outside is cold THEN the heat pump is turned ON (heating regime).
2. IF outside is cold AND inside is colder than desired THEN the ventilation is OFF.
3. IF outside is not cold AND inside is too warm THEN the ventilation is on.
4. IF the wind is strong AND the accumulator is not loaded THEN the wind turbine is loading the accumulator.
5. IF the accumulator is not loaded AND there is sun THEN the solar panels are ON.
6. IF the solar light is weak THEN the solar panels are OFF (let the light get to the plants).
7. IF outside is cold AND inside is cold AND the wind is strong THEN the wind turbine is directly heating the greenhouse. This is an emergency situation.
8. IF outside is cold AND inside is cold AND the accumulator is loaded THEN the accumulator is heating the greenhouse, etc.

Our simulations are clearly proving the efficiency of this approach, as the following case study is pointing (Balas & Balas, 2008b). Consider a very bright day, when the greenhouse effect would produce overheating. Fig. 8 presents the Toulon experimental greenhouse data recorded between 7 a.m. and 19 p.m. in 2004.02.09. One observes that the internal temperature T_I is reaching 38°C while the external temperature T_E is less than 22°C . We need to avoid overheating and to maintain T_I around 20°C . We try to control T_I by only two energetic passive control actions:

- The natural ventilation. We considered a typical $3\text{ m}^3/\text{s}$ mean ventilated air flow that can be switched between two positions: ON and OFF.
- The shading of the plants. The orientable photovoltaic panels can be switched between two positions: ON when the plants are shaded and the panels are charging the accumu-

lator and OFF when the panels are parallel to the solar radiation and the plants are in full light.

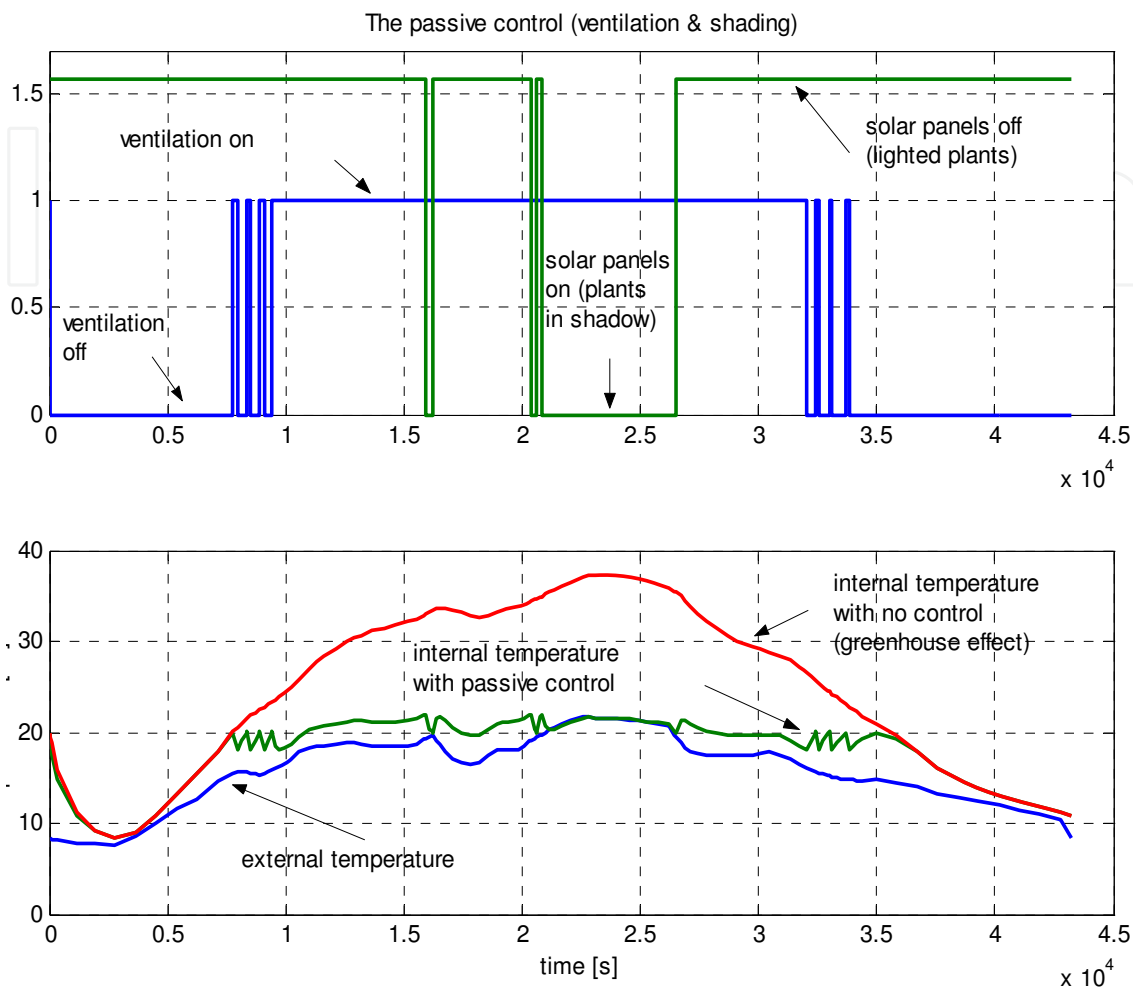


Fig. 8. Expert control performed by energetic passive actions: ventilation and shading

As shown in Fig. 8, our control problem can be easily solved, simply by setting appropriate numerical values at the fuzzyfication block of the controller.

During the first half of the day, when $T_E < 20^\circ\text{C}$, the natural ventilation is able by itself to cool the greenhouse. When T_E is exceeding 20°C the shading of the plants interferes as well. For much higher external temperatures the intervention of the heat pump, in the cooling regime, becomes necessary. Meanwhile the solar panels are not just controlling the temperature but also charging the accumulator!

Due to the high flexibility and adaptivity of the expert control, other situations, even contradictory or needing predictive decisions, can be conveniently handled by the same controller. For example, if we are aware that during cold mornings the greenhouse is naturally heated by the rising sun, by a small number of appropriate rules we can save about 20% of the daily energy consumption. Such control rule clusters can be addressed to any operating regime.

A particular constraint that is associated with the Passive Greenhouse is the remote control and monitoring. We performed experimental tests with a general use Programmable Logic Controller, able to control a generic greenhouse, which was connected to an Internet Ethernet network, with excellent results.

5. Conclusions and future research

This Chapter introduces the Passive Greenhouses, free of burned fuel energy and of conventional energetic infrastructures, and relying exclusively on renewable sustainable energies. We defined a generic Passive Greenhouse structure and proposed a corresponding mathematical model. This model adapts renewable energy sources (a cold water heat pump, a wind generator and a matrix of orientable photovoltaic panels) to a previous valid model of an experimental greenhouse, existing in Toulon.

Passive Greenhouses benefit of free energy and can be installed virtually anywhere we can find or build aquifers. They have the potential to reconvert a great deal of the existing agricultural terrains and give us the chance to ecologically reconstruct our environment.

This approach continues some existing concepts, as the Wageningen solar greenhouse, and relies exclusively on already existing renewable energy sources and technologies. The novel contribution of the work is the reconsideration of the solar greenhouse way of operating. Providing solar greenhouses with a sustainable aggregation of renewable energy sources they can become fully independent of any energy infrastructure.

The main technical difficulty to be coped is the extremely slow action of the heat pump. We can deal with this problem with the help of the expert adaptive predictive control, as our simulations are showing.

However the main obstacle against the Passive Greenhouses development is the high investment costs. We address this problem by optimizing the energy sources balance that can be performed by relevant simulations.

The Passive Greenhouses research project need a lot of future work:

- The refining of the mathematical model, applicable to any virtual or existing greenhouse;
- The development and the implementation of a comprehensive control algorithm;
- The study of the Internet remote monitoring and control of the greenhouse;
- The elaboration of a dedicated data base, with key information on Passive Greenhouses: materials, renewable energy sources (heat pumps, wind generators, photovoltaic solar panels) and accessories (accumulators, electronic converters), with technical data, prices and purchasing information;
- The elaboration of a design method able to optimize the investment costs;
- The implementation of a Internet site, containing our knowledge on greenhouses, a software able to assist a user at the dimensioning of its own Passive Greenhouse, tutorials, and other related information;
- The development of a Computer Aided Design application for greenhouses, etc.

Most of all, we need to build an experimental passive greenhouse!

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The world's reliance on existing sources of energy and their associated detrimental impacts on the environment- whether related to poor air or water quality or scarcity, impacts on sensitive ecosystems and forests and land use - have been well documented and articulated over the last three decades. What is needed by the world is a set of credible energy solutions that would lead us to a balance between economic growth and a sustainable environment. This book provides an open platform to establish and share knowledge developed by scholars, scientists and engineers from all over the world about various viable paths to a future of sustainable energy. It has collected a number of intellectually stimulating articles that address issues ranging from public policy formulation to technological innovations for enhancing the development of sustainable energy systems. It will appeal to stakeholders seeking guidance to pursue the paths to sustainable energy.

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