Small-scale Off-grid Energy Supply System Architecture for Sustainable Greenhouses

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***Abstract*— Electricity is needed for the operation of additional infrastructures to support farming. Generating electricity separately from the public grid and providing it from diverse sources means high reliability for self-sufficient and sustainable crop production. This article presents architectural options optimized for efficiency and cost in terms of heat and electricity supply for a small scale, off-grid greenhouse.**

***Keywords*— hybrid renewable energy system, energy storage system, sustainable energy supply, off-grid greenhouse, greenhouse energy supply**

I. Introduction

The greenhouse is a building covered with translucent material for the cultivation of plants from a foreign climate or for the production of plants at unusual times. There is also a practical gardening in a greenhouse, the most important work of which is propagation and sprouting.

In temperate climates and continental climates, in the case of hard winters, where the thermometer is often in the red, heating in the greenhouse is absolutely necessary for the successful production of summer vegetables. Depending on the climatic conditions and the gardening objectives, there are several heating options that differ in their efficiency, environmental footprint and cost of entry and maintenance.

The proposed architecture is based on modular subsystems, due to easier modifiability [1-5]. The optimization of the HRES structure is considered according to the following papers [6-8]. Real time data monitoring and logging is also a significant part of the work [9-12]. One of the effective ways of control the operation is closed-loops and compensation of disturbance [13-15]. The electronic circuit implementation aims at serviceability and robust operation [16-19].

A. Greenhouse types

The most common greenhouse structures are the geodesic dome, quonset (tunnel), A-frame, gable roof, gothic arch, slant-leg, semi-pit, or lean-to. Under snow loads the rounded top greenhouses are standing poor. Snow can easily settle on it, and under the weight of the accompanying snow load, the structure can collapse during a storm. Gothic arch greenhouses are also inexpensive to purchase and assemble. They also do not require a foundation, have very good lighting through the season and they have excellent snow removal because the top comes up to a point, so the snow slides down the sides. Too much snow buildup along the sides of the greenhouse, and that can buckle up and collapse it from the sides, so during storms it is needed to clear the area. Larger structures are usually start using poles and trusses to strengthen the greenhouse, it is excellent to distributing the weight and wind forces.

Greenhouses can be built by metal pipe, PVC pipe or wood frame. In cold conditions PVC can be very brittle, wood frames can degrade with time, but they are much more cost effective in the short run. Aluminum or galvanized steel pipe structures are much more long-standing, but a costly solution.

The most common greenhouse coatings are glass, plastic film, polycarbonate or acrylic coatings. Foil needs to be replaced in every few years. Film covered greenhouses are expensive to heat because of the poor U-value (heat transfer coefficient). Polycarbonate and higher U-value coverings have higher energy efficiency, but they are more expensive. [20]

B. Greenhouse heating

In off-grid power supply, solar energy and wind energy can be used to supply greenhouses with energy from renewable sources. Solar energy can be used in both passive and active modes in the greenhouse.

Passive solar energy is one of the most cost-effective ways to grow crops in a winter greenhouse, but in some cases additional heating is required at night. The key to the utilization of passive solar energy is the use of materials with a high heat storage mass in greenhouses.

For passive greenhouse heating - beside the correct orientation and structure - a solar assisted ground-source heat pump or a heatsink can also be used. The solution uses one-third of the floor area of the greenhouse, but with fan air circulation it is a good additional heating solution in a negative outdoor temperature range. [21]

In active mode, in addition to solar energy, wind energy can also be used to generate electricity. To generate and to store electrical energy is relatively costly, so its effective use is recommended. Electricity can be used for lighting, watering, airing, and for heating. Heating is the most energy intensive process, so it is proposed to use a solution with a COP (Coefficience Of Performance) factor higher than 1 or some other additional energy source for heating. A heat pump can be an energy efficient, but costlier solution.

With the poor greenhouse insulation (greenhouses are designed to maximize the influx of light), heating the air is not always the best solution. It is proposed to store the generated heat in a solid or liquid medium. In the case of electric heating, one possible solution could be to use oil radiators, so that the air dries out less than using heating resistors, and the heat storage medium also increases significantly, the heat dissipation will take considerably longer. It is one of the simplest constructions, it is suitable for climatic conditions where there is only an occasional cold wave.

Solar collector heating is another way to harness the energy of the sun to heat a greenhouse. The collected heat is stored in an uninsulated water tank placed in the greenhouse, which radiates heat, heating the air in the greenhouse. The advantages of the water tank are similar to those described for the oil radiator. In the case of a heat-insulated hot water tank, pipes for heating the soil can be placed directly in the beds. Water tanks can also be heated with heating filaments, heat pumps and with wood stoves. The needed mechanical equipment is well scalable depending on needs and financial resources. The operation of mechanical equipment still requires the provision of electricity.

The wood-burning stove or mixed-burning stove is simple and well-suited for primary or auxiliary heating. The disadvantages are the need for continuous manpower and the possible large fluctuations in temperature and humidity, as well as the need for adequate oxygen supply in the case of small, well-sealed greenhouses. Pellet stove can slightly reduce the manpower requirement for producing heat energy.

By using the installed fossil fuel tank, a large amount of heat can be generated, well automated and does not require manpower to operate, but the cost of installation and operation is also significant. High-cost solutions are relevant if they include the function of using other off-grid functions, outside the small-scale greenhouse. Additional heat and power supply from a generator is a possible option, with the disadvantages of non-renewable fuel consumption and operating noise.

During composting, a significant amount of heat is also produced, i.e. indoor air can also be heated with a compost tank placed in the greenhouse. If the poultry is fenced and housed in a greenhouse or if the hen house has a common wall with the greenhouse, it can also help a lot to stabilize the night temperature. Feasibility depends largely on the breed of animal and the design of the greenhouse.

C. Additional techniques

A greenhouse could be too big for heating with the available resources, so it could be a good practice to use a tunnel inside a greenhouse on the soil or on heated raised vegetable garden beds for growing seedlings. Another solution could be the hotbed, fenced on four sides of deep, rectangular stack (filled with manure) in which early plants can grow (seedling cultivation) and, on the other hand, protect plants from the colder outside air.

The heat flowing upwards can easily leave the greenhouse through the high-transmittance cover. It is advisable to transfer the heat energy to the soil or to raised beds. It is also advisable to direct the rising warm air to the plants or through the beds with fans and ventilation pipes. It is a good idea to set the propellers to a low setting so that the air just circulates and does not cool the plants.

Another factor contributing to the utilization of heat is the selection of the right plants for the conditions created. For example, summer plants like peppers and tomatoes need plenty of warmth and light. Carrots, beets, spinach, onions, peas, cabbage, broccoli, brussels sprouts, etc. prefer a cooler environment and thrive in limited sunlight.

The increased heat storage mass in the greenhouse helps to achieve a balanced ambient temperature if the heat storage mass is able to absorb and dissipate the heat energy. The heat storage mass can be water, brick, stone, gravel, concrete, earth, etc. The heat storage mass can gain energy from the sun, hot water heating, fire stove, electric heating or from the ground. The design of raised garden beds is a good practice to increase the heat storage mass.

Thermal insulation on the north side of the greenhouse only slightly reduces the amount of incoming light but helps to retain heat. The wall of another building can also be part of the thermal insulation. Covering the inner opaque wall surface of the greenhouse with thermal mirror film is also a good passive technique for raising the temperature. The whitewashed wall surface also helps to reflect heat and disinfects the wall surface.

The easiest way to insulate the soil and the plants in it is by mulching with straw, grass, bark, etc. Covering the plants with veil foil will also help protect against frost, preserve moisture, prevent sunburn, etc. thus prolonging the spring and fall seasons.

II. Realization

A. Modular design

Modular design is a design principle that divides a system into smaller parts called modules. These can be created, modified or replaced with other modules independently of each other. The modules are understood as units that can be scaled in their discrete electrical parameters. The benefits of a modular system are customizability without system overhaul, ease of maintenance and serviceability, and cost-effective quality and functional upgrades. Adding a new type of solution or feature, with replacing or connecting a module. The modular platform system offers benefits such as reducing development costs and time to market. [22]

In general, the complexity of designing a modular system is significantly greater than the complexity of a platform system. It requires experience in product development and market strategy. To achieve modular benefits, system flexibility and the depth of modularity must be well configured. The depth of modularity determines the possibility of customization.

Solar panels have 2-dimensional modularity (can be connected in series and in parallel). Charge controllers, energy storages, power converters and consumers add additional dimensions to modularity. In the case of an off-grid power supply chain, the modular system architecture and the proper definition of the modules contribute to customizability, and the matching user needs and available resources. Customizable modular systems can gain a significant competitive advantage in the market. [23]

B. Hybrid Renewable Energy System Concept

High reliability is a basic requirement for an off-grid power supply system. It is advisable to base it on several different types of input energy sources, which can be built separately from modular, redundant system components. [24]

The system plan shown in Fig. 1 shows three input sources from which electricity can be generated and the figure outlines five options as input heat sources. Energy is stored using a battery array, a buffer tank, and a water tank.

Additional electrical and mechanical elements such as photo voltaic breakers and isolators, battery breakers and isolators, positive and negative DC bus bar, DC distribution and breaker box, AC bus bar, AC distribution and breaker box, battery management system controller, power meter system, contactors, connectors, air vents, expansion vessels, expansion valves, isolation valves, control valves, heat exchangers, three-way valves, heat traps, etc. are also part of the design, but are not shown in Fig. 1 due to complexity.

C. *Wind power*

The wind generator, in addition to the solar system, is an excellent solution for grid-independent power supply. The horizontal shaft wind turbine is characterized by high performance and a design similar to a conventional propeller. It is capable of producing energy at relatively higher wind speeds. A unit with gold-plated sliding contacts allows protection against twisting the wires. [25]

In the case of a vertical wind generator, the blades rotate on an axis perpendicular to the ground on an axis common to the generator, so that the slip ring contact can be omitted. The vertical wind wheel is characterized by quiet operation and self-protection against overspeed, it breaks itself at high wind speeds due to its aerodynamic design. Its peculiarity is that it can produce energy even at relatively low wind speeds, but its efficiency is lower than a horizontal-axis wind turbine.

The protection and braking of wind generators against overspeed can be solved by applying an electrical load to their output. Uncharged batteries are usually a sufficient load for the wind generator. At high wind speeds, additional loads can be applied to the system, which can be used primarily for useful work, such as pumping water from a well to a surface water storage tank, heating water with heating wire, or electrical heating.

If the wind speed is too high, the wind generator need to be stopped by loading and short-circuiting its outputs and securing the rotor with an electromagnetic and / or mechanical brake.

D. *Solar energy*

In the solution presented in the paper, redundancy also appears in the case of solar cells, in the form of a smaller and a larger solar array. Reliability can be further increased if the solar panels connected to the charge controller and can be disconnected. Using DC switches also increases efficiency. More solar cells than the capacity of the charge controller can be placed, so in low sunlight, the increased surface area will indicate increased incoming power without overloading the charge controller. In strong sunlight, the DC switch disconnects the excess solar panels so that the charge controller is not overloaded.

It is advisable to install a larger and a smaller capacity, critical-performance module in the system, be it a solar cell array, a solar collector, a wind generator, a battery array, an inverter, or other equipment.

If reliability and robustness is a strong consideration, it is a good practice to build the system from lower capacity components. If a battery fails [26] the power lost is less, replacing the module is cheaper and easier to do as well. It is advisable to keep stock of critical system modules.

Smaller panels are less sensitive to possible distortions in the roof structure. If a component of a battery pack with lower voltage and capacity connected in series and in parallel fails, the system module will still be operational and will be easier to service.

E. *Solar collector*

In the case of mechanical equipment, the system may also be able to produce domestic hot water with the appropriate accessories. Depending on the system in the application environment, it is advisable to choose the type of flowing antifreeze or water medium and the type of heat exchangers. [27 ,28]

It may be advisable to choose a hybrid solar module that has a dual function. The first part of the collector has a solar cell that generates electricity and heats up in the process. Warming reduces its efficiency. Integrated on the back surface of the panel is a flat plate collector that takes in the heat and cools the solar cells. This increases the performance of the solar panel while producing hot water like a conventional solar collector. With a good approximation, a solar collector unit has half the heat generation capacity of a solar collector of a similar size. [29-31]

F. *Control circuit*

The control circuit is a microcontroller based embedded system, based on PIC24FJ256GB110 microcontroller. A hybrid electronic circuit (see on Fig. 2) built around the microcontroller matches the signal levels of the sensors and actuators to the outputs and inputs of the programmable controller. Port expansion has been solved with bidirectional analog and digital multiplexers. Some of the input and output pins are galvanically isolated, and feedback LEDs are also integrated.

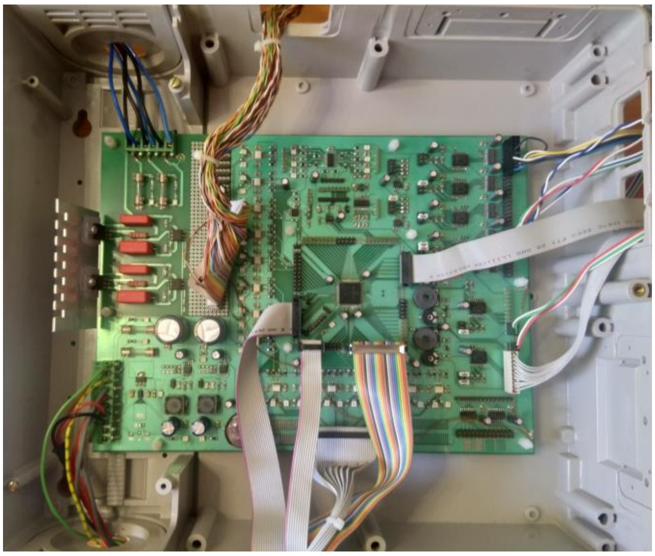

Figure 2. The main control circuit

In terms of software control, the use of working batteries takes precedence when storing energy, followed by the pumping of water for watering. In the case of overproduction, solar and wind energy sources can be switched off and the power produced can be converted into heat. Any excess heat can be removed with heating pipes or radiators and fans. [32]

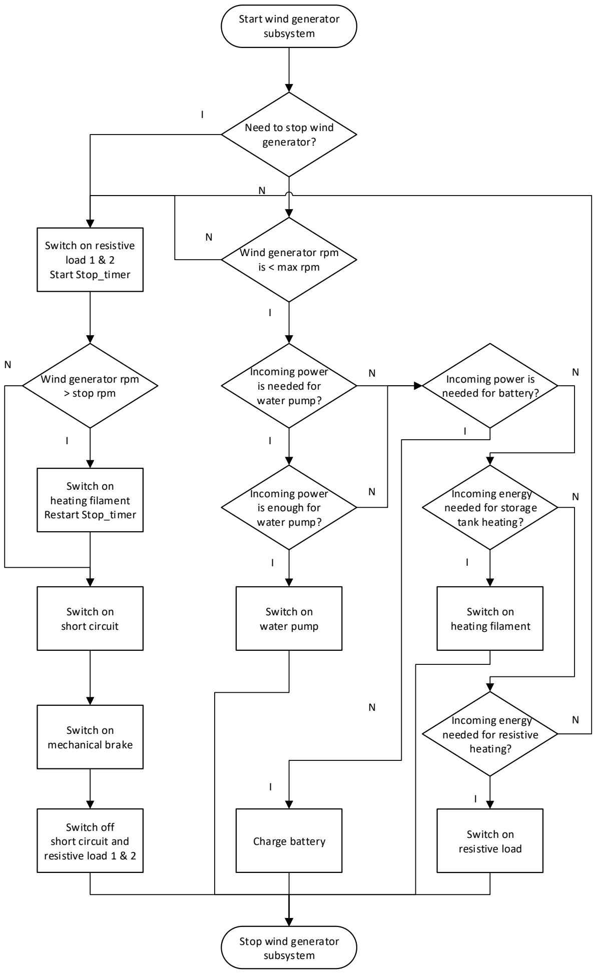

Figure 3. Wind generator subsystem flowchart

G. Operation of the system

Taking into account the needs of the plant, a specific priority and decision list can be defined:

- If the water level in the water tank is low, turn on water reservoir or well water pump.
- If battery array is full or wind is too high, break the wind generator.
- If the wind generator needs to be braked, turn on the buffer tank heating filament or other resistive loads.
- If the wind generator needs to be stopped, first break it, than switch it to short circuit, than use mechanical brake.
- If battery array is low and energy balance is negative, turn on the fuel generator.
- If the water temperature in the water tank is low, and external heat source is available, turn on the solar collector, the ground loop heat exchanger or the well water pump, or turn on the gas burner or the heat pump, or send message for the user (it can use the fire stove).
- If the water temperature in the water tank is high, and external cooling medium is available, turn on the ground loop heat exchanger or the well water pump, or turn on the heat pump, or send message for the user (it can accept to change the water in the storage tank with draining).

The different subsystems are equipped with independent control subroutines [33-35]. In summary, a flowchart shows the subsystem operation in Fig. 3. and Fig. 4 The specific comparison levels were determined based on technical specifications and empirical experiences.

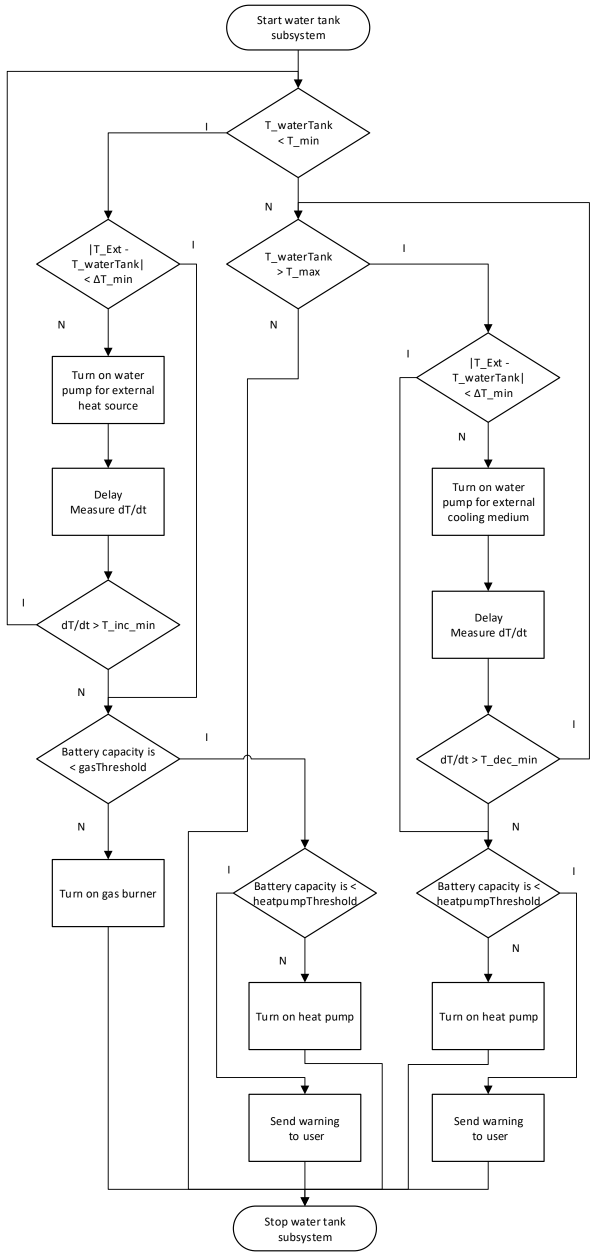

Figure 4. Heating subsystem flowchart

III. Conclusion

From the point of view of heating a greenhouse, it is most expedient to use several of the different solutions mentioned above at the same time. Applying different heating techniques and using practices like using mulch, increasing the heat storage weight, and planting the right plants can allow to create something in the greenhouse even in wintertime.

The current paper aimed to show an optimized sustainable off-grid hybrid renewable energy system. The design contains two different renewable energy resources. The most suitable ones are solar and wind. The shown modular design can also be used for other off-grid applications. The proposed architecture is easily scalable, user-friendly, and robust. The article describes the relationship between the system components and includes an algorithm that demonstrates the control options.

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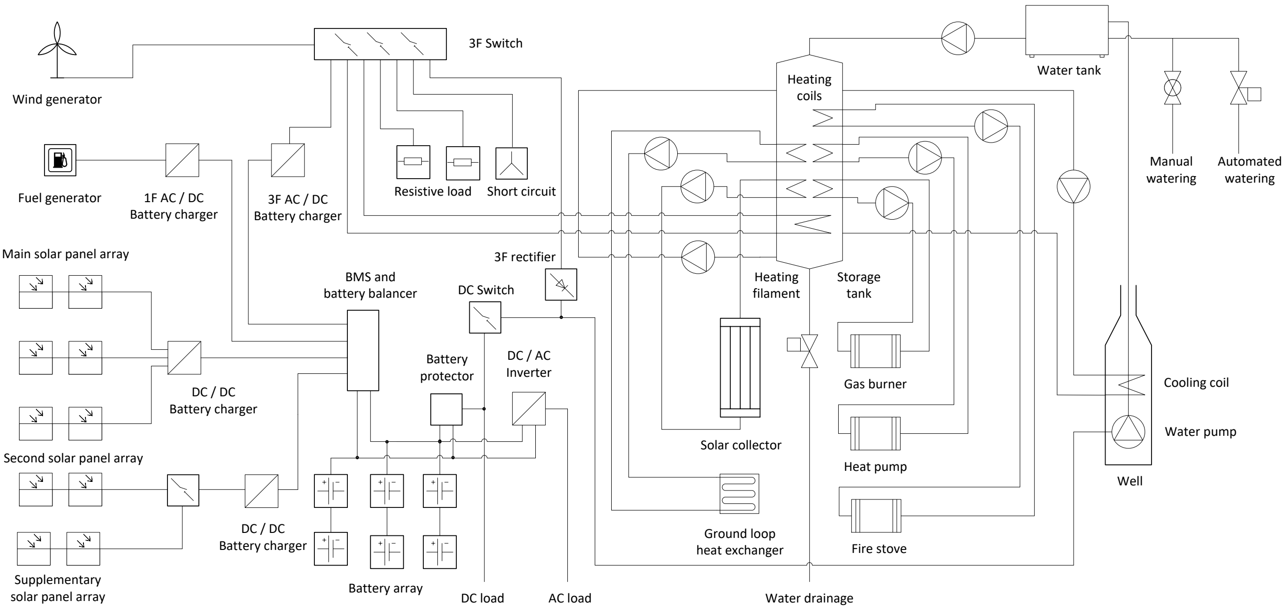

Fig. 1. Small-scale hybrid renewable energy system architecture

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