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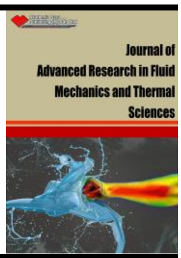

Hybrid Renewable Energy System for a Sustainable House-Power-Supply

Mohamed S. Emeara[1,*], Ahmed Farouk AbdelGawad[1], Emad Hamdy Ahmed[1]

[1] Mechanical Power Engineering Dept. Faculty of Engineering, Zagazig University, Egypt

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ABSTRACT

The main objective of the present research is to design a hybrid wind and solar energy-supply system for a rural residential building to meet its energy demands. The monthly averaged daily energy consumption for the dwelling was found to vary between 19 and 36 *kWh*. The system under consideration included some subsystems, namely: the hot-water service, the space-heating facility, and the power-utility system (wind electricity supply and storage system). The optimum design was obtained by carrying out a cost-benefit analysis for each of the subsystems. The hot-water system was designed to be based on solar flat-plate collectors, and a wind tree. The optimum hot-water facility is consisted of three flat-plate collectors, a storage heat exchanger with three coils, which are attached to flat-plate solar collectors, under-floor heating systems, and a wind tree power system. The large dimensions of the house were the limiting factor when investigating the feasibility of a solar-powered space-heating system. The existence of large windows made the space heating a very difficult and expensive task. The results show that the cost of the system is very expensive compared to the connection to the main grid. But on the other side, there will be a return investment value each year and the system will get all its costs after 14 years. Thus, if the average life of the system is 20 years old, the system will get profit after 14 years for six more years, in addition to the clean energy out from the system and the very beneficial positive effect on the environment.

1. Introduction
1.1 Motivation

The energy demands of any residential building can be studied by considering the total demand for hot water [1], space heating [2], and electricity for lighting and operation of various appliances [3, 4]. For urban dwellings, in general, natural gas is used for the first two and mains grid power for the latter; both of which are readily available. However, this is not the case for rural properties. The cost of connecting to the mains grid may render this option prohibitive since the power supplier has the responsibility of bringing the service to the property boundary nearest to the grid, then, the owner has to bear the cost thereafter. Therefore, renewable energy, *i.e.*, energy generated from

* *Corresponding author.*
E-mail address: memeara@gmail.com

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solar, wind [5], biomass [6], and/or hydro [7] might be an attractive alternative for rural properties [8].

The design in this hybrid system depends on the optimal use of solar energy by using high-efficiency panels with a design that takes into account the largest possible energy that can be generated through these panels. Many researchers have worked to develop many methods to raise the efficiency of these panels through design processes and also take into account the use of high-efficiency electrical transformers to ensure that the power losses are not increased [9-13].

The development of the use of solar energy has also been accompanied by a great development in the use of wind turbines and work to raise their efficiency to the extent required to generate sufficient energy. Many researchers and energy centers have focused their attention on choosing the appropriate site by scientific methods, as well as the optimal mechanical design of the wind turbine and the optimal shape of the turbine blade to generate the largest possible energy and to increase its efficiency and reduce energy losses [14-18].

1.2 Literature Survey
1.2.1 Solar energy systems

In addition to the mixing of energy sources, the use of equipment such as diesel generators and energy storage systems (*ESS*) as a backup system is conventional and leads to higher system reliability in remote areas [19]. The use of these storage systems provides the possibility for 100% renewable power generation in remote areas [20].

*1.2.1.1 T*SOL software*

T*SOL software from Valentin Software GmbH [21] is the professional simulation program for the design and planning of solar thermal systems. The program, which is a finite-element software, is capable of simulating temperatures and energy performance along a year down to a 6-minute resolution with a wide range of systems and components.

1.2.1.2 Flat-plate collector (FPC)

This type of collector is used to collect solar radiation in low ambient temperatures. It consists of a selectively coated flat-plate absorber, a transparent cover to protect the absorber and reduce heat loss at the top of the collector, a heat fluid to harness the energy from the absorber, tubes for the Heat Transfer Fluid (*HTF*) circulation, an insulation system to reduce heat loss, and protective casing to protect the components from surrounding harmful elements.

There are some important angles to be considered when using a flat-plate collector, Figure 1, which can be listed as [22]

- Tilt angle
  The angle between the horizontal plane and the solar panel.
- Zenith angle
  Solar zenith angle is the angle between the sun’s rays and the vertical. It is closely related to the solar altitude angle.
- Azimuth angle
  Azimuth angle is the angle between true south and the point on the horizon directly below the sun.

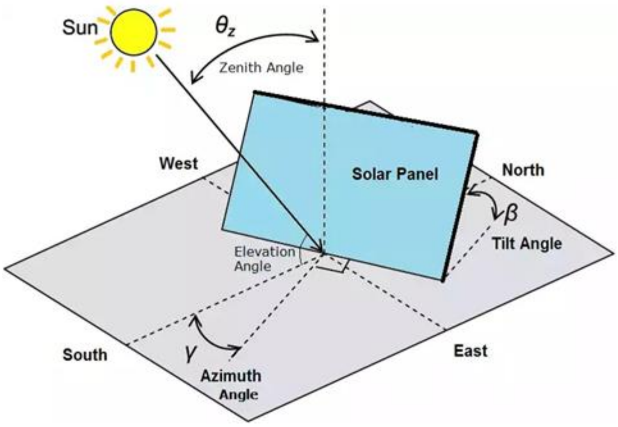

Fig. 1. Solar panel angles at high latitudes [22]

1.2.2. Wind trees

In 2018, Mohammadi *et al.,* [23] presented optimal planning of renewable energy resources for a residential house considering economic and reliability criteria. The system used mainly a *PV* system with wind turbines. Their method can be used to design a system to meet the demand in the various sectors taking the economic and reliability criteria into account.

1.2.2.1 Previous related work

Hayashi *et al.,* [24] implemented two types of control: constant rpm, and constant load-torque. They observed that when subjected to a step-change in wind speed from 10 to 11 m/s under constant rpm control, the VAWT torque responded almost instantaneously and attained a steady-state in less than 3 s. Raj [25] stated that VAWT **s**ystem can be installed on the median of the roads so that the wind from both sides of the median acts tangentially in opposite direction on both sides of the turbine, thereby increasing effective wind speed acting on the turbine. Kooiman and Tullis [26] experimentally tested a VAWT within the urban environment to assess the effects of unsteady wind on the aerodynamic performance. They indicated that independence of the performance in directional fluctuations was seen while amplitude-based wind speed fluctuations decreased the performance linearly.

1.2.2.2 Operation of wind tree

In this concept, wind energy is used to generate electricity with the help of aero-leaves. These aero-leaves are made of fiber and molded into specified shapes based on their needs. In the present study, an induction generator was used for each aero-leaf. Aero-leaves start to rotate with a minimum airspeed of 7 km/h (1.94 m/s). As aero-leaves were coupled to the generators, mechanical energy gets converted into electrical energy. All the generators were connected in series, so, the generated voltage was added. This output was given to the battery and was stored to be used to drive the load.

Switching techniques may be done by the source selector, i.e., by a microcontroller. The microcontroller is to be programmed in such a manner that the first preference must be given to the tree-model, while the second preference is given to the external power supply.

Analog to digital converter is to be used to measure the voltage and convert it to a digital signal for the LCD. The block diagram of the present control technique is shown in Figure 2.

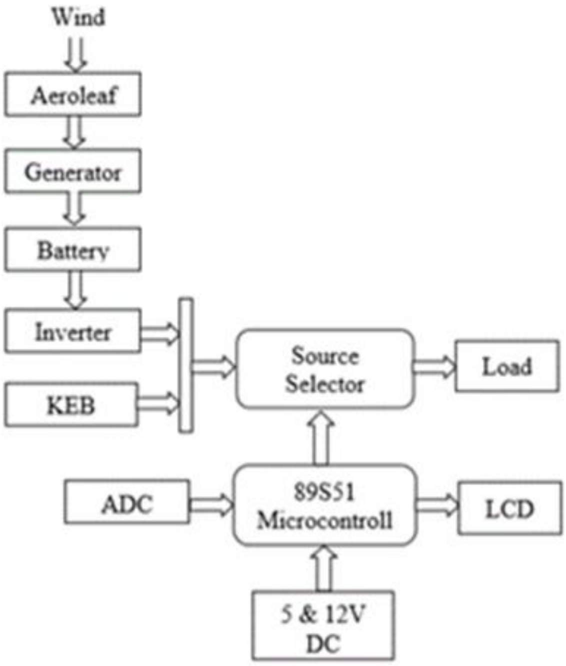

Fig. 2. Block diagram of the control technique [2]

In Figure 3, the power curve indicates the generation of power per aero-leaf depending on the wind speed. If the wind speed increases, the generation will also increase. The aero-leaf actuates at the wind speed of 7 km/h (1.94 m/s). If the wind speed becomes 12 m/s, the aero-leaf produces 30 W of power. When the wind speed is 18 m/s, each aero-leaf generates up to 100 W and reaches the saturation level because the peak capacity of an aero-leaf is 100 W.

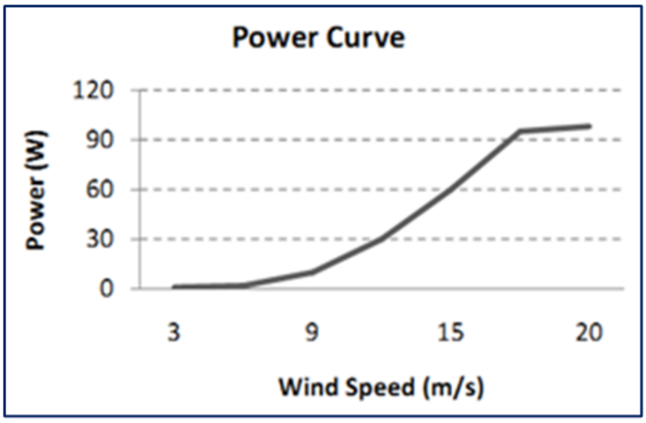

Fig. 3. Power curve of a single aero-leaf [2]

As shown in Figure 4, the single aero-leaf consists of the main blade which is designed to run with the air in any direction. This innovative blade is mounted on a shaft that is connected to a gearbox system. This gearbox is connected to a small generator that converts this rotational motion into electricity. The total efficiency of this system is based on the efficiency of these mechanical components especially gears and bearings.

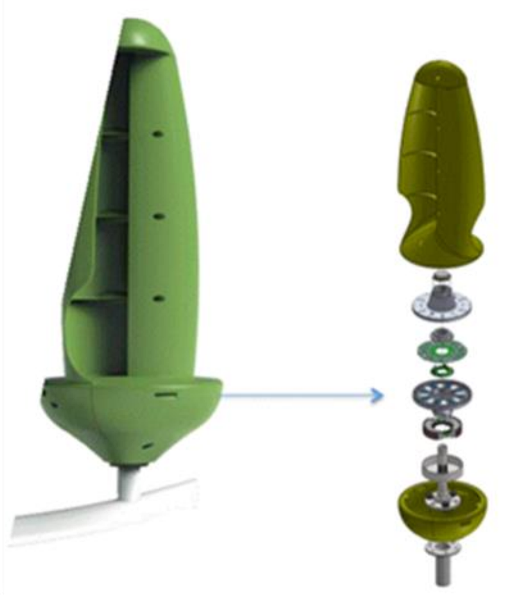

Fig. 4. Mechanical components of a single aero-leaf [27]

Lately, a new improvement is made to the wind tree system as a high-performance photovoltaic petal is mounted on each blade to add additional energy to the Aero-leaf. Positioned at the foot of each sheet, the petal is available as an option to equip the three models of Modular Shaft 18 A, 24 A, or 30 A. Light and thin (less than 800 g for 3 mm), it is also very resistant and waterproof. Thanks to its 5° inclination compared to the leaf, the petal allows an acceleration of the wind at the leading edge, making the leaf benefit from an energy gain of 5%. The hybrid aero-leaf is thus more efficient and at the same time more organic as shown in Figure 5.

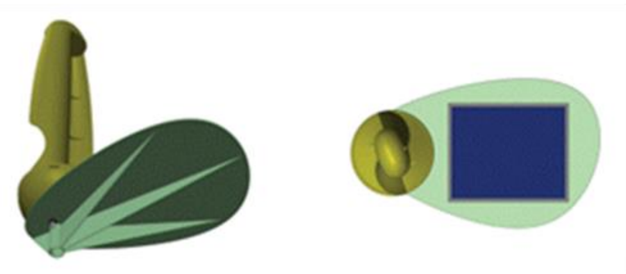

Fig. 5. A single aero-leaf equipped with photovoltaic petal [27]

1.2.2.3 Concept of wind tree

It was observed that by placing multiple turbines on a single tree, the power output could be increased. Therefore, wind tree is a concept based on vertical-axis wind turbines (VAWT) for power generation, in which several wind turbines are grouped in a single arrangement. Due to the reduced size of the blades, they can be easily rotated due to the impact of forced air. With the help of generators, power is generated and stored with the help of a battery.

1.2.2.4 Wind tree

There are two basic designs of wind electric turbines; horizontal-axis wind turbines (HAWT), and vertical-axis wind turbines (VAWT). Vertical-axis wind turbines can be further classified into two types Darrieus, and Savonius [28].

Darrieus type needs much less surface area. It is shaped like an egg beater and has two or three blades that are shaped like airfoils. Savonius turbine is S-shaped if viewed from the top. This turbine turns relatively slow but yields high torque. It is used for grinding grains and pumping water [9]. These VAWTs are powered by the wind coming from all 360 degrees, and even some turbines are powered when the wind blows from top to bottom. Because of this versatility, VAWTs are thought to be ideal for installations where wind conditions are not consistent, or due to public ordinances, the turbine cannot be placed high enough to benefit from steady wind [29].

In the present research, Savonius VAWTs are utilized to generate electricity with the help of aero-leaves. Several leaf-shaped aero-leaves are placed in the form of a tree, called Wind Tree as shown in Figure 6. Wind tree uses tiny blades housed in the aero-leaves to generate power from wind energy. These wind trees can generate power regardless of the wind direction and with a minimum wind speed of 7 km/h. Thus, a tree-shaped structure, covered with leaf-shaped mini turbines of Savonius type, is designed to produce the power.

Fig. 6. The wind tree shape [27]

All cables and generators are integrated into the leaves and branches. Artificial leaves operate as mini vertical turbines all around the tree. When the wind blows, the leaf turbines rotate and quietly produce the energy. The power generated from the wind tree is environmentally friendly, mainly, it generates power with the least noise and can be installed at different locations [27].

As shown in Figure 7, the wind tree system is connected to an electrical cabinet that is designed specially to take the output voltage generated by the wind tree's small turbines and store this energy into batteries connected to the system. After that this stored energy is converted to AC electricity to be used by the owner [30].

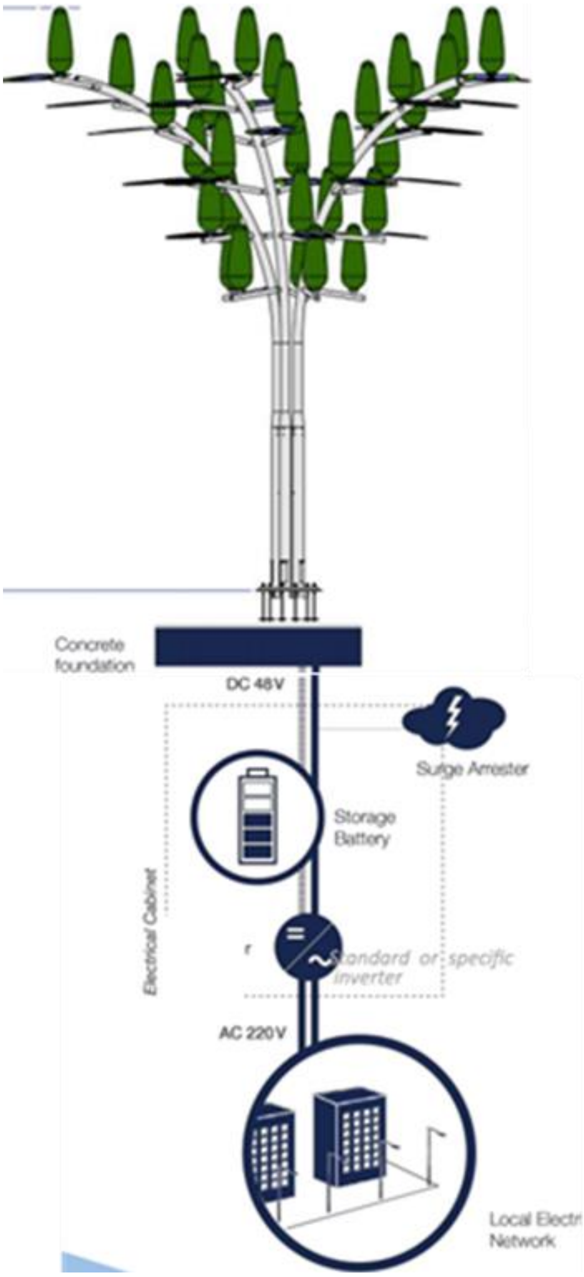

Fig. 7. The electric installation of a wind tree [31]

1.2.3 Hybrid wind-solar energy system

At the beginning of the twenty-first century, there was great interest in the importance of integrating renewable energies to obtain the highest possible efficiency using clean energy. Researchers have been interested in merging the use of solar panels with wind turbines to produce enough energy to operate a residential house and save a large part of the energy consumed. In 2006, Hessami [32] designed a hybrid wind and solar energy supply system for a rural residential building to satisfy its energy requirements. The system included the hot water service, the space heating system, and all the power requirements involving both electricity supply and a storage system. The optimum design was obtained by performing a cost-benefit analysis for each of the individual systems. But he found that the estimated total cost of the power-generation system was found to be higher than connecting to the mains grid. After that in 2008, a predesign study was presented for site selection with an assessment of the solar and wind potential [33]. They demonstrated that the study of the wind potential at the site indicated that the location of the wind system is not excellent for electric generation by the wind. However, assessment merely based on hourly average wind speed underestimates the wind energy potential of a site and may be misleading.

Large-scale renewable energy systems such as solar and wind farms mostly are connected to the grid and are used to supply the power of urban areas. In these systems, the main electricity grid is used as a backup system in the case of a power deficit. Also, in the case of excess power production, it can be sold to the main grid. In 2016, Zhang *et al.,* [34] presented a hybrid-renewable energy system developed for a net-zero energy low-rise residential building. This hybrid renewable energy system consisted of a water-based photovoltaic/thermal (*PVT*) collector and a ground water-source heat pump. The hybrid system was designed to produce heating, cooling, and electricity during both winter and summer by using solar energy and ground-surface water energy, respectively. The system was proved to be applicable on this on-grid zero-energy house, and hence has potential for low/zero-energy low-rise residential buildings.

Based on the above literature survey and to cover the gap of hybrid-renewable energy systems for sustainability, the present study was initiated. This paper starts with a discussion of the required solar and wind data. Then, it is followed by a general description of the hot water, space heating systems, and provision of power using the wind tree. Connection to the mains grid is discussed in the last section of the paper with an indication of solar energy consumption as a percentage of the total consumption.

1.3 Problem Statement

- We have solar-cell panels aimed at extracting solar energy.
- Use of a hybrid wind-solar system that can be used to provide the energy requirements for heating a rural apartment building.

1.4 Objectives

- Study the best orientation of panels to extract the best energy from the sun.
- This was done by changing the position of solar panels.
- Study the best shape of loops for ground heating that fits the solar panel system and gives the highest efficiency.

2. Methodology

This paper presents a hybrid wind and solar energy-supply system for a rural residential building in the Fifth Settlement, New Cairo suburb, Cairo, Egypt. The system is used to meet its energy demands. As shown in Figure 6, the water is heated inside the exchanger by solar panels. This is the main heating of the system.

Then, the water temperature inside the exchanger increases to the degree required by the heater by electricity generated by the wind tree. Solar water heating theory is based on the circulating pump that operates in a temperature difference between the plates and the exchanger, which is located on the control panel. The main control and regulation of the system aim to convert wind-tree power to electrical power for operating the heater and increase water temperature inside the exchanger. Also, it is an objective to operate and separate the circulating pump for under-floor heating as shown in Figure 8.

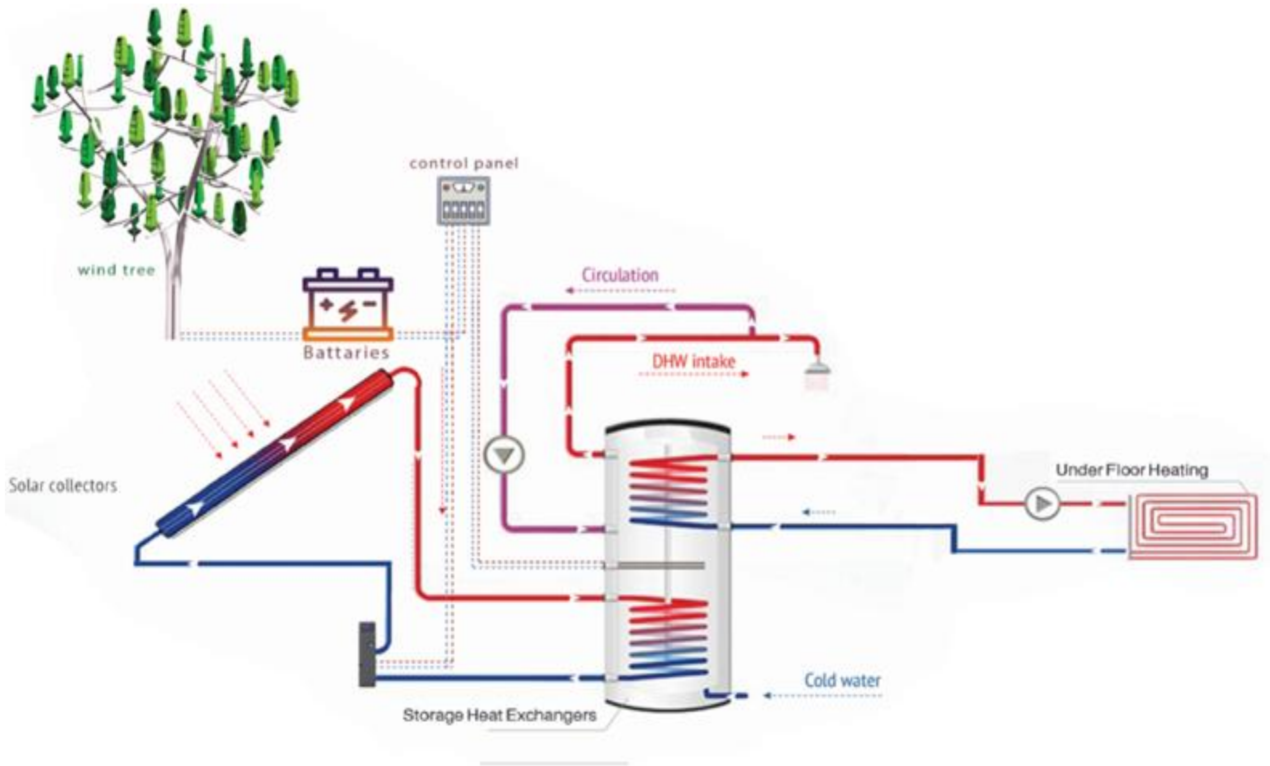

Fig. 8. Present heating system and domestic hot water by using solar heater and wind tree [35]

2.1 Present Dwelling

Based on the architectural drawings, Figure 9, the proposed dwelling has a floor plan of about 360 m^2, and a floor to ceiling height of 2.5 m.

The heat transferring wall and window areas for the different elevations of the building are estimated from the building plans and are provided in Table 1.

Table 1
Wall and window areas for each elevation of the proposed dwelling

Elevation	Walls (m^2)	Windows (m^2)	Total (m^2)
East	43.5	39	82.5
West	52.5	30	82.5
North	30	12.5	42.5
South	22.4	17.6	40
Total	148.4	99.1	247.5

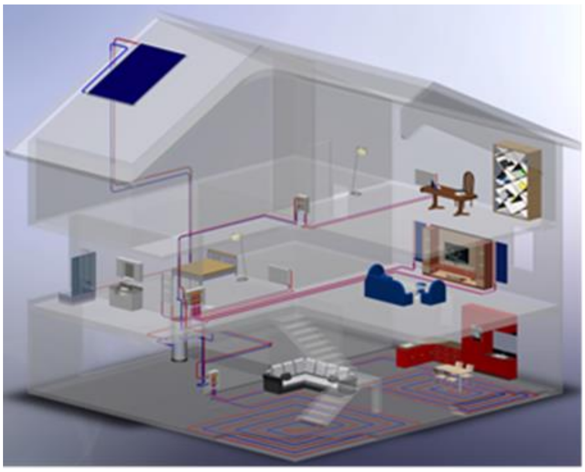

Fig. 9. Architectural drawings of the dwelling building by Solidworks software

2.2 Heating Systems by Using Hot Water
2.2.1 Background

Water is especially favored for central-heating systems because its high density allows for holding more heat. Moreover, the water temperature can be regulated more easily. The hot-water heating system consists of the storage heat exchanger, and a system of pipes connected to manifold panels, piping, and/or other heat emitters located in the rooms to be heated. The pipes, usually of polyethylene multi-layer pipes, feed hot water to the under-floor heating arrangement and give out their heat to the room. The water, now cooled, is then returned to the storage heat exchanger for reheating. Two important requirements of a hot-water system are: (i) Allowance for the expansion of the water in the system, which fills the storage tank, heat emitters, and piping, and (ii) Means for allowing air to escape by a manually or automatically operated valve.

Neither the gravity warm-air nor gravity hot-water systems could be used to heat rooms in an elevation below the furnace or boiler elevation. Consequently, motor-driven pumps are now used to drive hot water through the pipes, making it possible to locate the boiler at any elevation concerning the heat emitters. As with warm air, smaller pipes can be used when the fluid is pumped in comparison to gravity operation.

2.2.2 Performance of a radiant-floor heating system

Efficient radiant heating systems represent a promising technology for energy saving in commercial and building sectors together with improving occupant thermal comfort. However, the thermal performance of radiant systems in buildings has not been fully understood and accounted for in currently available building energy simulation software.

2.2.3 Governing equations

In the present paper, the effects of design parameters on the performance of a typical radiant-floor heating system were studied using a finite-element method. A radiant heating system comprises many pipes filled with hot water. Therefore, several design parameters such as pipe diameter, type (material), number, and thickness, as well as the cover of the system were considered. Thus, transient conduction, convection, and radiation heat transfer mechanisms were considered.

This calculation method takes into account the heat losses from the pipe and the heat losses from the water within the pipe. It is necessary to know the pipe diameters and pipe lengths for each section of the domestic hot water distribution system.

For every pipe section *i*, the maximum losses are given by

$$Q_{W,d,i} = \{\rho_W * C_{P,W} * V_{W,i} + C_{P,m} * M_{M,j}\} * \{T_{W,nom,i} - T_{int,i}\} * n_{tap} \quad (1)$$

where,
ρ_W : specific mass of water (*kg/m*^{3})
$C_{P,W}$: specific heat of water (*J/kg. K*)
$V_{W,i}$: volume of water contained in pipe *i* (*m*^{3})
$C_{P,m}$: specific heat of pipe material (*J/kg. K*)
$M_{M,j}$: mass of pipe *i* (*kg*)
$T_{W,nom,i}$: nominal hot water temperature in pipe *i* (*°C*)
$T_{int,i}$: average internal temperature around pipe *i* (*°C*)
n_{tap}: number of tapings per day using pipe section *i* (-)

Hot water losses at the user outlets, while the desired domestic hot water temperature has not been reached, are not included in this calculation method. If the heat losses from user outlets, *i.e.*, materials of showerheads or taps, are to be included, a further contribution is added to Eq. (1) taking into account the mass and specific heat of the user outlet material.

If heat losses associated with the thermal capacity of the user outlets are to be taken into account, the effect of different outlet types may be calculated from the following procedure. The heat loss due to the user outlets is

$$Q_{em} = \beta_e * n_{em} * n_t \quad (2)$$

where,
Q_{em} : total heat loss by outlets (*W.h*)
β_e: heat loss of the specific type of user outlet (*W.h*)
n_{em} : number of user outlets in the building
n_t: number of tapping cycles during the period considered

It is noted from the finite-element analysis that the type and thickness of the floor cover are the most important parameters in the design of radiant heating systems.

The heating-pipes arrangement depends on the nature of the room (its purpose, shape), cooling partitions distribution (internal walls, windows), floor structure, as well as adopted pipes assembly technique. In the present study, two basic patterns were applied: spiral and series as shown in Figure 10. The spiral pattern ensures the evenest heating surface temperature distribution because supply and return cables are arranged next to each other alternately. In the series pattern, the medium temperature is highest at the beginning of the coil, subsequent coil series temperature, due to the cooling, becomes increasingly lower, also the heating surface temperature decreases linearly. Therefore, the beginning of the series pattern coil should be arranged near the partitions with the highest heat loss (external walls, windows, terraces).

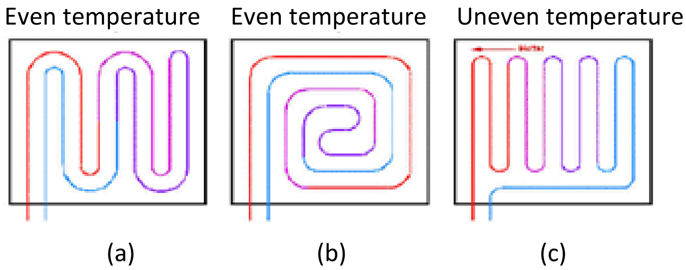

Fig. 10. Different shapes of design loops for under-floor heating; (a) spiral, (b) series, (c) linear [36]

Also, there is an effect of the temperature on the performance of the heating pump used as heat pumps are more energy-efficient if the water temperature is low, Figure 11.

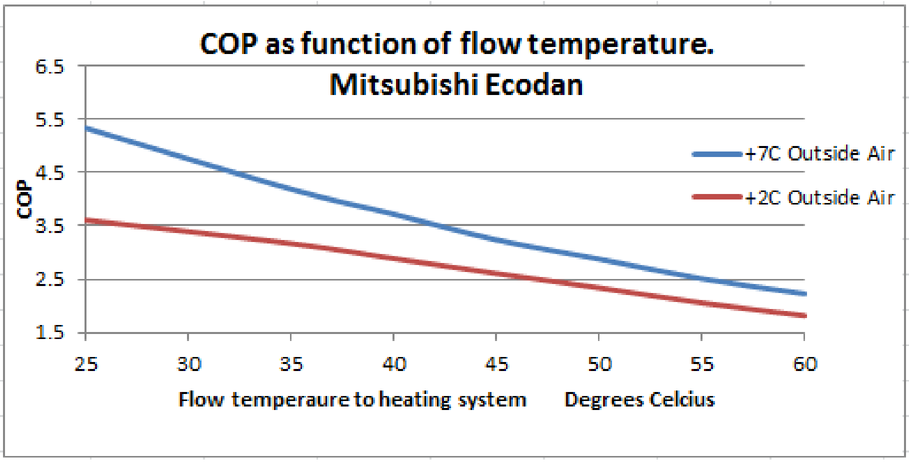

Fig. 11. Coefficient of performance of the pump versus the flow temperature [37]

The beneficial of a low flow-temperature is the units like this with electronic expansion valves are particularly efficient at very low water-temperatures.

2.3 Hot-Water System

The study of the proposed hot-water system was carried out using the commercially available equipment comprised of flat-plate solar collectors, the main tank, and an auxiliary electrical-heater coil, Figure 12. The main tank was selected to have a capacity of 500 *L* to satisfy the needs of a family of four persons. The total size of the collector was determined using the solar radiation data obtained from the system that was optimized by performing a cost-benefit analysis. Although the optimum tilt angle of the solar collector should be equal to the altitude at the point of installation as described by Duffle and Beckmann [38], for reasons of practicality, a tilt angle of 34° (equal to the pitch angle of the roof of the building) was applied. The solar hot-water system uses energy from the sun to heat water, thus, reducing the amount of natural gas, or in some cases electricity, needed for residential or commercial water heating. Solar hot-water systems are highly efficient; up to 87% of the solar energy that reaches a given section of the roof can be absorbed by the system's collector.

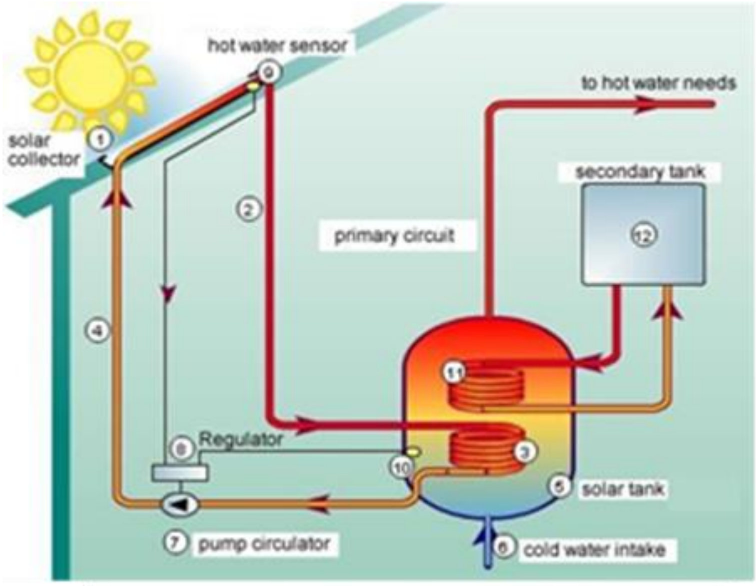

Fig. 12. Solar hot-water system [38]

The liquid in the collector, heated by the sun, is pumped to one or more storage tanks, thereby reducing or eliminating the need for conventional water heater fuel. Solar hot-water systems do more than just save homeowners money by decreasing natural gas and electricity usage. They are also act friendly to the environment. While solar hot-water systems save money over their lifetime, the upfront costs discourage many households from installing them. Appropriate policies, however, can increase public awareness while providing economically beneficial incentives to install the systems.

2.4 Electricity Supply

Due to the rural location of the building, the power demand of the property was envisaged to be met by renewable sources. The available alternatives are solar, wind, biomass, or a combination thereof. This section provides the details of the present procedure followed and the calculations performed to find the optimum system to suit the needs of the proposed building.

3. Results and Discussion

The purpose of this investigation was to design a renewable energy system for a rural property with a high level of reliability and total independence from the main grid. This was achieved by using solar and wind energies with a backup source powered by an electrical heater. The design of the system was based on the effects of the used area of the dwelling by calculating the actual area to be powered by the hybrid system and the outlet sources like windows or walls or taps.

The present system was investigated using a finite-element analysis software (T*SOL), which is considered an efficient tool to calculate the effective heat transfer in the system and the amount of power can be obtained through the system. All the input data was entered into the software including the specification of the PV collectors used and the wind tree characteristics. Also, the specifications of the under-floor heating system including the type of pattern, and size of pipes such as thickness and diameters. The used solar hot-water system was heated by three flat-plate collectors with an area of 4.92 m^2 each. The present system was integrated with a wind tree of Savonius VAWTs that were utilized to generate electricity with the help of aero-leaves. These wind trees can generate power regardless of the wind direction and with minimum wind speed.

The T*SOL software was provided with sufficient estimated data needed like those listed in Table 2.

Table 2
Results of annual simulation

Climate data (location)	Cairo
Domestic hot water's average daily consumption	0.16 m^3
Average desired temperature	50 ^oC
Gross surface area	14.76 m^2
Active surface area	13.14 m^2
Tilt angle	30^o
Orientation angle	180^o
Efficiency of the plates	15%
Combination tank	0.5 m^3
Auxiliary heating system nominal out put	9 kW

The solar energy consumption as a percentage of total consumption is considered one of the most important outputs of the valentine's software used in the proposed system. As it shows how much of the building's thermal needs could be met by solar water heater (SWH) during the year in each month. It could be seen in Figure 13 that, from May to September, nearly all the required energy is supplied by solar collectors. Also, the highest need for a boiler occurs in December and January when collectors have supplied 11% and 15% of heating loads, respectively.

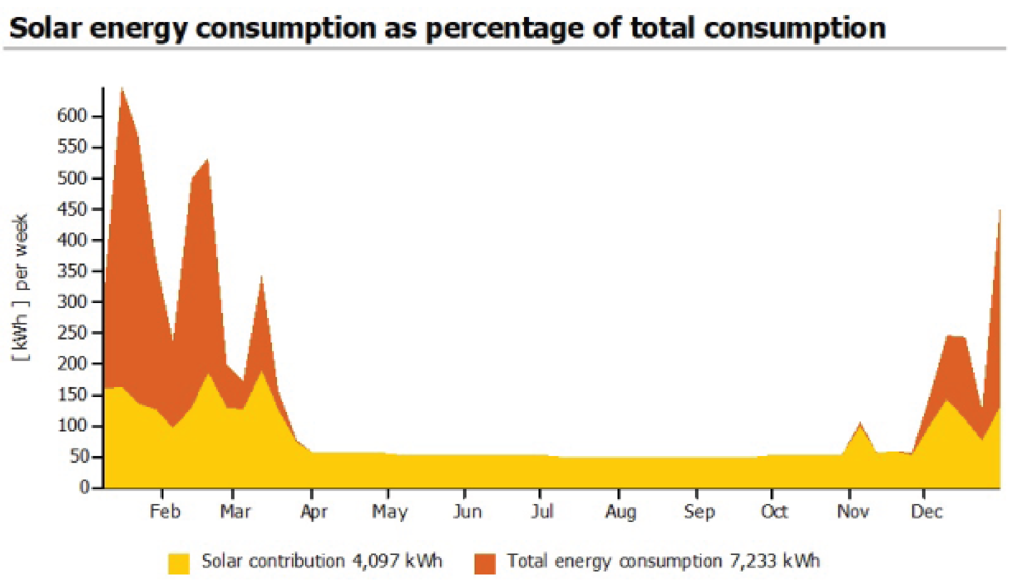

Fig. 13. Solar energy consumption as percentage of total consumption

All calculations were carried out using T*SOL 2018 (R3) simulation software for solar thermal heating systems. The results were determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can be deviated from these values due to fluctuations in climate, consumption, and other factors as shown in Figure 14.

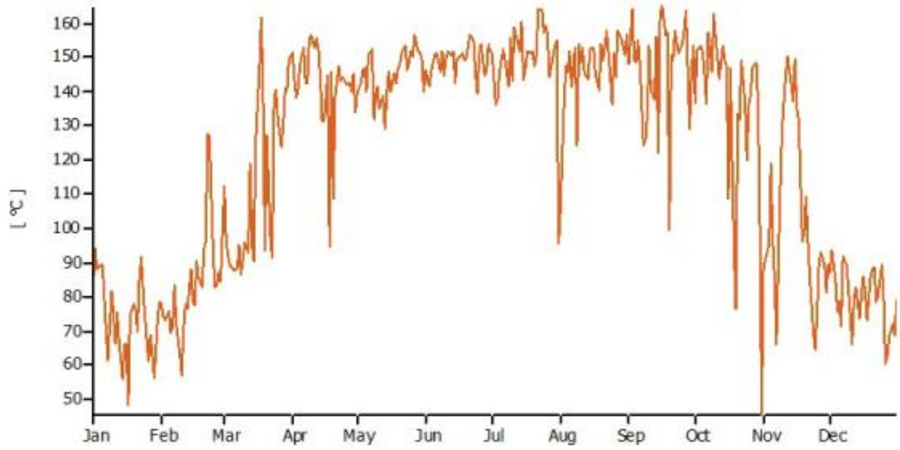

Fig. 14. Daily maximum collector temperature by the present study by T*SOL software

According to the global prices for wind tree and solar panels system, the total estimated cost of purchasing and installing the system [39] will be about 22,600 USD. The estimated total cost of the power generation system was found to be higher than connecting to the main grid. However, for reasons of environmental benefits and independence from the grid, this system was considered to be appropriate for this application. The financial output from the simulation software estimate that there will be a return investment after 14 years of the system life. The estimated life of the system is about 20 years for normal dwelling loads. Thus, based on the long expectation, using this system is very beneficial to the environment.

However, the high initial cost at the installation is high. Also, the software estimated the savings in first year only based on dividing the total cost over the total number of years of the life of the system to be 307$. This value will be fluctuating based on the estimated average power of consumption of the dwelling.

4. Conclusions

Present study introduces a detailed design of a hybrid solar-wind energy supply system used for a rural residential building to meet its energy demands. The system comprises mainly solar collector plates with 30^o inclination angle, a storage heat exchanger, under-floor heating system. A wind tree consists of many small turbines that are integrated into the system to be used as a backup for space heating. Solar collector, heat exchanger, pumping system, inverters, and the wind-tree were selected from known commercial sites with the desired efficiency. Under-floor heating system was studied in detail to select the appropriate pattern to get the desired heating energy. The solar panels characteristics were studied and the suitable inclination angle needed to get the maximum available energy from the sun during the daylight. The site location climate data was entered into the software and the performance of the system components to calculate the heat losses during the transfer through cables or user outlets. The initial and setup cost was calculated to be compared with the cost required to connect with the main electricity grid.

Based on the above illustrations and discussions, the following concluding points can be stated

i. By using an efficient software (T*SOL) for simulation and finite-element analysis of the hybrid system, accurate modeling was carried out to calculate the required energy needed to be supplied to the building and to show the usefulness of using this hybrid system.

ii. Wind tree can be selected to be integrated with small solar panels attached to its blades to get more power generated and increase the output energy from the system.
iii. The results show that the cost of the system is very expensive compared to the connection to the main grid. But on the other side, there will be a return investment value each year and the system will get all its costs after 14 years. So, if the average life of the system is 20 years, the system will get profit after 14 years, in addition to the clean energy out from the system and the positive effect very beneficial on the environment.

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