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Solar Energy for Water Conditioning

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***Abstract*—**Shortening of natural resources will impose greater limitations of electric energy consumption in various fields including water treatment technologies. Small water treatment installations supplied with electric energy from solar sources are perfect example of zero-emission technology. Possibility of solar energy application, as one of the alternative energy resources for decontamination processes is strongly dependent on geographical location. Various examples of solar driven water purification systems are given and design of solar-water treatment installation based on ozone for the geographical conditions in Poland are presented.

***Keywords*—**solar energy, water purification, ozone water treatment

I. Introduction

In spite of the fact, that near-equatorial places called "sunny belt" are so far much more favorable and cost-effective for solar installations, constant growth of fuel prices in the last decade caused rapid development of solar technology across Europe, including its northern parts. The average insolation of Europe territory is presented in Fig. 1. [1]. The average annual insolation on Poland's territory amounts to about 1100 kWh/m^2 (3500MJ/m^2) per year on a horizontal area, which corresponds to the calorific value of 120 kG of theoretical standard fuel (29300 kJ/kg of hard coal, 41860 kJ/kg of petroleum). Fig. 2 depicts insolation map of Polish territory. The insolation of this area is characterized by a big annual diversification. For example, the annual amount for the City of Lublin is about 1107 kWh, and while over 15% of (year) annual energy reaches Lublin in August, in December it is only 1,6% of annual amount. [2]. The typical daily insolation in Lublin area in Summer is depicted in Fig. 2 [3]. In Europe solar thermal collectors are primarily used for hot water production and space heating (use of solar energy for cooling is rather limited). According to EUROBSERV'ER, the solar thermal panel area installed in the EU during 2009 was 4166056 m^2 giving 22786,1MWth of the accumulated installed solar thermal capacity [4]. against each other left out in the fresh air- 148347 m^2 installed in 2009 in Europe). In 2010 Europe also continued photovoltaic plant installation reaching over 80% of global installed capacity and generating 22,5 TWh of photovoltaic power. The additional installed capacity in the EU over the twelve months to the end of 2010 ranged 13023,2MWp (growth of 120,1%).The cumulated predicted photovoltaic capacity of EU in 2010 is presented in Fig.4 [5].Average photovoltaic power per inhabitant in European Union in 2010 was 58,5 Wp/inhab, with leading Germany and Czech Republic with 212,3 and 185,9 Wp/inhab., recpectively. The most of 2009-2010 electricity production from this source took place in Germany (12000 GWh) and Spain (6302 GWh). In Poland it was only 1,8 GWh. [5]

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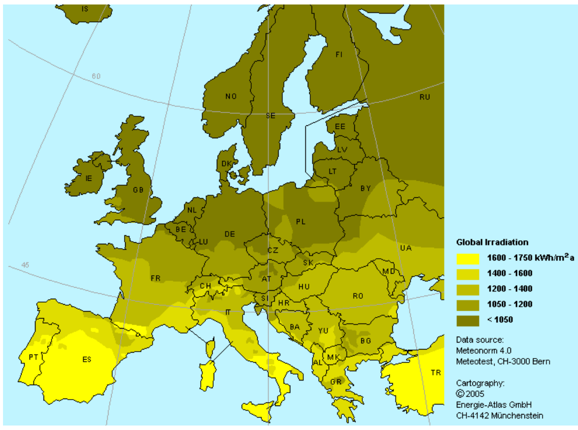

Fig. 1 Global irradiation in Europe [1]

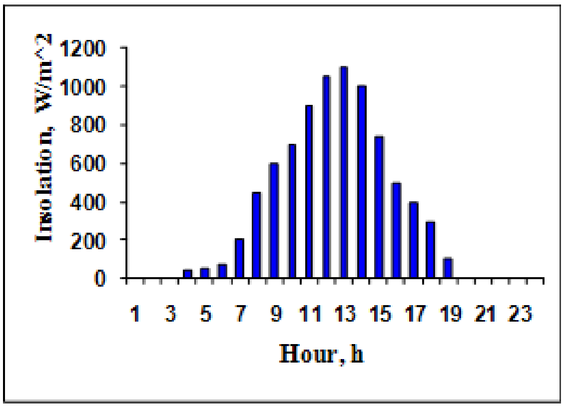

Fig. 2 The chart (day and night) insolation in Lublin between 1-3 June 2002, [3]

II. Solar energy in water treatment

Inadequate access to clean water and lack of its sanitation are persistent world-wide problems affecting humans on each continent (according to UN number of people who lack access to safe drinking water will increase from over 1 bilion to over 1.8 billion in in 2025). Moreover, industry and agriculture also require huge amounts of water of certain quality causing further deterioration of water quality in the region, which secondary may lead to its scarcity. There are many conventional technologies of water decontamination, which with growing environmental pollution are sometimes insufficient and energy-consuming. These technologies often require addition of suplemental chemical compounds, which lead to secondary pollution. Ozone based technologies combined with advanced oxidation processes (AOP), already investigated and tested for three decades proved to be a good alternative to traditional methodes. However, AOP methodes are sometimes considered expensive and power-consuming. Thus combining treatment technologies with alternative enegry sources can be a perfect solution allowing for optimum purification due to combination of variety of decontamination techniques. In this part applicationof solar power for water desalination, drinking water and wastewater treatment is described.

Availability of drinking water is an ultimate condition for the inhabitation. Extraction of water from air (EWA) [6] is the solution in the case of lack of primary source of water. The total quantity of water contained in 1 km^2 of atmospheric air, that is, in most regions around the globe, 10,000 to 30,000 m^3 of pure water. In the state of the art technology, the refrigerator is operated by an electricity driven compressor. The cold fluid that goes into the heat exchanger is produced by a reverse compression-expansion thermodynamic cycle. (Fig. 3). It is claimed by the manufacturers that approximately one liter of diesel fuel operating the electrical generator can provide four liters of water from air. In fact system integration with PV panels could make it more reasonable from economy point of view.

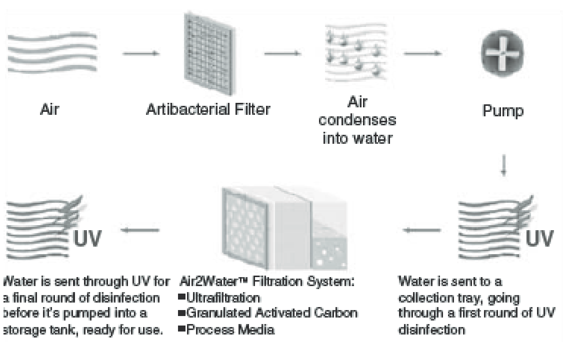

Fig. 3 Typical EWA plant for potable water production (condensation occurs by passage of the air on the cold coils of a heat pump) [6]

In the developing countries, where sophisticated water purification methods are not available solar water disinfection (SODIS) reveals a great potential to reduce the global diarrhoeal diseases burden, which affects over 1.8 million people [7], [8]. According to extensive microbiological investigation, 30^{o}C water temperature, a threshold solar radiation intensity of at least 500 W/m^2 (all spectral light) is required for 3-5 h for SODIS to be efficient for destruction of diarrhoea-causing pathogens in contaminated drinking water. Water can be stored in any transparent container. Since the year 2000, SODIS is being promoted in developing countries through information and awareness campaigns and currently used in 33 countries (Fig. 4) by more than 2 million people and decreasing diarrhoea outbreaks by 16–57%. A large body of microbiological research followed, that assessed and demonstrated the effectiveness of SODIS in destroying diarrhoea-causing bacteria, viruses as well as Giardia spp. and Cryptosporidium spp. [9-16].

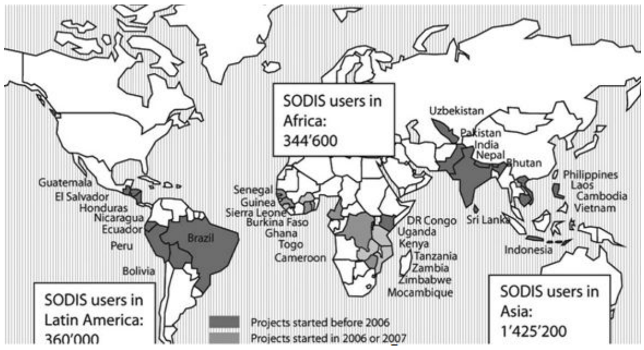

Fig. 4 More than 2 million users currently practise SODIS in 33 countries [7-16]

During Haiti experiments, one-day exposure achieved complete bacterial inactivation 52% of the time, while a 2-day exposure period achieved complete microbial inactivation 100% of the time [17].

Single-basin, solar stills, for the removal of a selected group of inorganic, bacteriological, and organic contaminates were investigated [18] and turned to be efficient in removing non-volatile contaminants from the water. Removal efficiencies of more than 99% were noted on salinity, total hardness, nitrate, and fluoride. The stills were also successful in removing bacteria by more than 99.9% from the water if care was taken to avoid cross contamination from the raw water source. Stills had mixed success when it came to the removal of volatile organic compounds (VOCs), such as pesticides.

Solar distiller built using local materials used for reducing the fluoride content from underground waters was used in Anaafobiisi, Ghana. From an initial concentration of 20.6 mg/l of fluoride in the water from a local borehole, this was reduced to an average of about 0.7 mg/l, which is below the WHO acceptable limit for fluoride in drinking water when the solar distillation unit was used to purify it [19].

Different approach for sanitation of drinking water with chlorine was proposed by Appleyard [20]. Ferric tannate-sensitized n-(ZnO, SnO_2)/Cu photoelectrochemical cells were constructed using recycled waste materials and household chemicals and utilising Fe^{2+}–Fe^{3+} and Cu^{2+}–Cu redox couples for charge transfer. The solar cells, which were constructed in recycled clear plastic tubing and drinking straws in a home environment, produced an open-circuit voltages of 0.4–0.6 V and a short-circuit current densities of 1–2.5 mA/cm^2. Chlorine was produced at a rate of 4 mg/h from a 1% salt solution using an array of cells with a combined voltage of 5 V and a current of 200 mA.

In areas where water is heavily contaminated standalone systems, which were used for desalination might be not sufficient. AOP methods and catalytic processes can bring rapid improvement of the effluent water quality. Many research groups were investigating the catalytic systems based on titanium compounds and Fenton process.

Tests of water heavily contaminated with Escherichia coli (K-12) were carried out in real sunlight using laboratory scale reactors to determine the collectors' performance of different tubular reflector profiles [21]. The reactors were constructed using Pyrex tubing and aluminium reflectors of compound parabolic, parabolic and V-groove profiles. Compound parabolic reflector turned out to be most efficient in inactivation of bacteria.

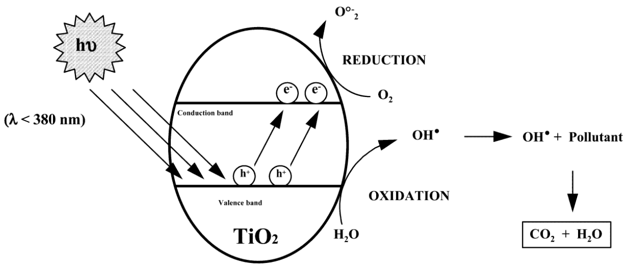

Fig. 5 General mechanism of the photocatalysis [22].

The group of Sixto Malato is investigating the solar photocatalysis and proposing various innovations in the process for more than decade. Mechanism of solar driven photocatalysis is depicted in Fig. 5. [22].

TABLE I
COMPARISON OF TiO_2 AND PHOTO-FENTON PROCESS ASPECTS RELEVANT TO THE PHOTOREACTOR'S DESIGN REQUIREMENTS. [24]

TiO_2-persulfate photocatalytic system ($\lambda < 390$ nm)	Photo-Fenton method (H_2O_2 and Fe^{2+}) irradiated in the UV–vis range ($\lambda < 580$ nm)
$TiO_2 + h\nu \rightarrow e^-_{CB} + h^+_{VB}$	
$h^+_{VB} + H_2O \rightarrow {}^\bullet OH + H^+$	$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + {}^\bullet OH$
$S_2O_8{}^{2-} + e^-_{CB} \rightarrow SO_4{}^{\bullet -} + SO_4{}^{2-}$	$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + H^+ + {}^\bullet OH$
$SO_4{}^{\bullet -} + H_2O \rightarrow {}^\bullet OH + SO_4{}^{2-} + H^+$	

Malato group is often using compound parabolic collectors (CPC), however variety of shapes and solutions including trough reactor (PTR), thin-film-fixed-bed reactor (TFFBR), double skin sheet reactor (DSSR, pilot plant in Wolfsburg factory of the Volkswagen AG), etc. are employed [23]. Solar driven photocatalytic oxidation processes are presented in Tab 1. [24].

EU supported several different projects with the aim of developing a cost effective technology based on solar photocatalysis for water decontamination and disinfection in rural areas of developing countries: SOLWATER and AQUACAT [24].

In Europe huge solar driven photocatalytic plant was built in Almeria, Spain under the ''SOLARDETOX'' project [25] (Solar Detoxification Technology for the Treatment of Industrial Non-Biodegradable Persistent Chlorinated Water Contaminants). Nowadays facility allows to investigate following technologies [23-25]:

(a) Solar Desalination, from two different approaches, combined solar power and desalination plants (MW range), and medium to small solar thermal desalination systems (kW range).

(b) Solar Detoxification, by making use of the near-ultraviolet and visible bands of the solar spectrum (wavelengths shorter than 390 nm for TiO_2 and 580 nm for photo-Fenton) to promote a strong oxidation reaction by generating oxidizers, either surface-bound hydroxyl radicals ($OH^\cdot$) or free holes, which attack oxidizable contaminants, producing a progressive break-up of molecules yielding CO_2, H_2O and dilute mineral acids.

(c) Solar Disinfection, which applies the detoxification techniques mentioned above, using a supported photocatalyst, to generate powerful oxidizers to control and destroy pathogenic water organisms.

Solar-driven electrochemical and photocatalytic installation using a boron-doped diamond electrode and TiO2 photocatalyst for removal of volatile organic compounds and pesticides from water was developed [26]. In a treatment test of river water samples, large amounts of chemical and biological contaminants were totally wet-incinerated by the system. This system, could provide 12 L/day of drinking water from the Tama River (Japan) using only solar energy. Authors estimated cost of the water as 26 yen/L.

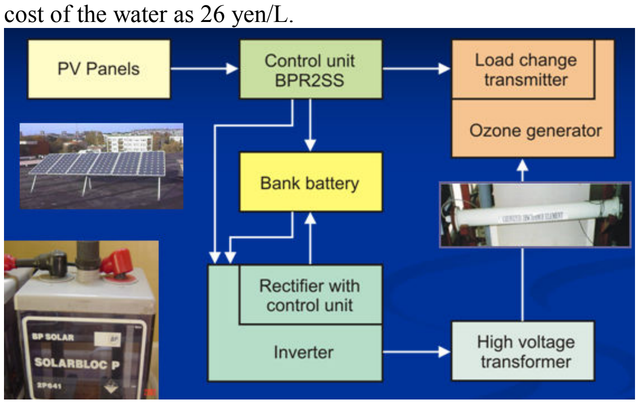

Fig. 6 Integrated PV water/gas/soil conditioning system based on ozone

Advanced oxidation technologies (AOTs) using UV lamps (UV_{254}, UV_{350}), UV/H_2O_2, UV/Fe(III) as well as photo-Fenton and heterogeneous photo-catalysis with TiO_2 were also investigated for treating aqueous solutions of pesticides (Vydine) [27]. Slight degradation of pesticide in aqueous solution was observed upon using simple photolysis process. However, the combination of H_2O_2 or Fe(III) with these illumination sources were more efficient than photolysis process alone. UV_{350} was less efficient than that UV_{254}.The degradation rate of pesticide was strongly accelerated by photo-Fenton and TiO_2 processes regardless of the illumination source. Increase in solar radiation intensity accelerated the degradation rate of pesticide. AOTs can be efficiently used with solar radiation to either mineralize the organic matter or convert hardly biodegradable organics to more biodegradable waste.

Integrated PV system based on AOP and application of ozone (Fig. 6) for water and gas conditioning was developed by Stryczewska group [28-31]. System was applied for conditioning of the pool waters, soil and gas.

III. PROTOTYPE INSTALLATION OF AIR, WATER AND SOIL TREATMENT ENERGIZED FROM PV PANELS OLAR ENERGY IN WATER TREATMENT

Autonomous water treatment installation energized from PV panels and installation for air, water and soil treatment were developed in Lublin University of Technology in cooperation with Japanese partners. Set-ups were extensively described [2, 28-33].Small water treatment installations with ozone generation using electric energy from renewable energy sources could be the good solutions to variety of environmental problems. Fig.7 depicts a small household water ozonation installation. Proposed system was made of three basic sub-systems: electric energy power system, ozone production system and water treatment system. It was totally autonomous, designed for a constant work in difficult climatic conditions. The devised technological solution is excellent to be utilized in remote terrains, which are distant from electroenergetic network or in the places where the electroenergetic main is unstable and fallible.

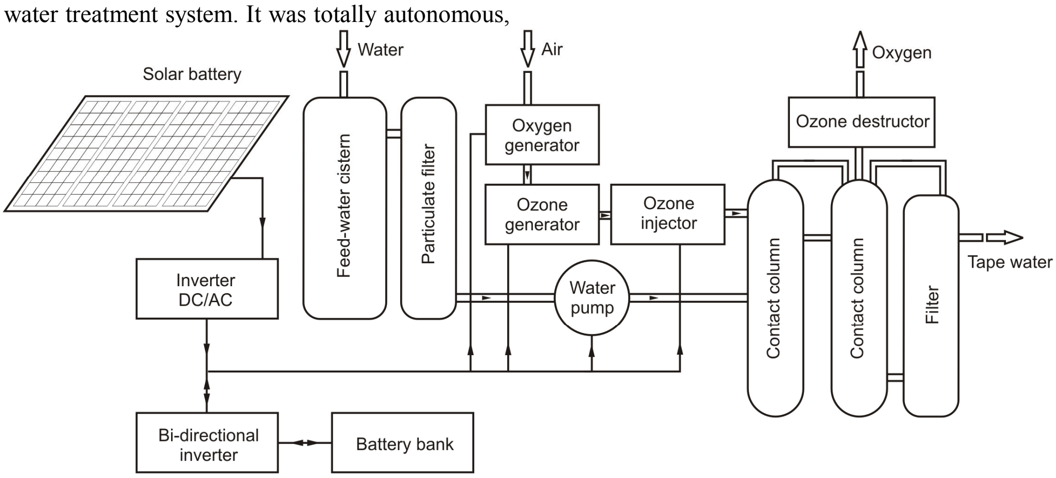

Fig. 7 Water ozonation system

Currently, the total cost of generating electrical energy from solar batteries is one order of magnitude higher than in case of nuclear energy. However, the application of solar batteries becomes profitable, as far as the demand for electrical energy is small. The correctly selected system should cover about 95÷100% of electrical energy demand during summer.

Ozone generation took place with the usage of corona discharge. The ozonizer was powered with high frequency supplier with pulse control and amplitude modulation. The basic part of ozone generator were titanium electrodes (one of the covered with ceramic dielectric material). In order to lower the ozonier's consumption of electric energy, the complex system of radiators was used, electrodes were efficiently cooled with atmospheric air. The utilized ozone generator operated with both: pure oxygen and atmospheric air as substrate gases. With atmospheric air and pure oxygen used as substrate gases, 1.5 g/h and 6 g/h of O_3 was generated, respectively. Gas flow ranged 3,3-4,7 l/min with 180 W of power consumption.

The appropriately made contact container has a fundamental influence on stability and final quality of water ozonation process. In the majority of ozonation systems ozone is added to water in the form of bubbles through diffuser. The effectiveness of such a process is low because ozone is not evenly mixed with water, and when in large quantities, ozone evaporates from water into ozone destructors, from where the unused oxygen is blown out to the atmosphere. To reduce influence of factors mentioned above innovative WOFIL system was used. In this solution, raw water was initially aerated and oxidized with the oxygen mixed with ozone, which evaporated from the contact container. This solution enabled the increase of ozonation process' efficiency by almost 30% (in comparison with the competitive ideas) without the increase of electrical energy consumption. It also resulted in reduction of amount of gas which was blown out to ozone destructors and in lower values of residual ozone after the contact container. In order to remove the excess of the produced and the residual ozone the catalytic destructors were used. System is presented in Fig. 8.

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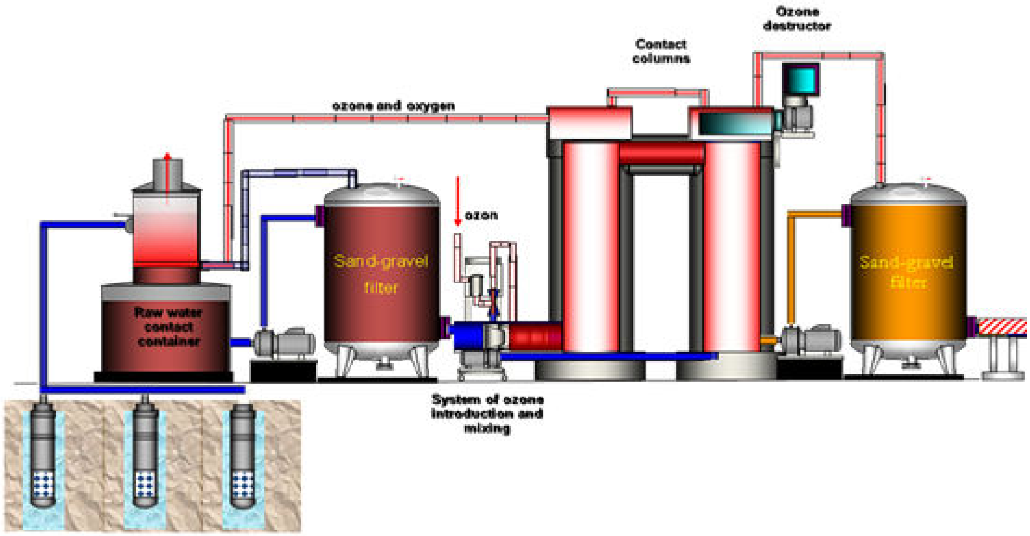

Fig. 8 WOFIL water ozonation system

The main element of the circuit was bi-directional inverter, administering loads, the flow of energy and the work of accumulators. Inverter provided 24 V grid of DC voltage and a typical grid of AC voltage 110 V/60 Hz or 230 V/50 Hz. Thus, it enabled integration ranging from electric generators to energy receivers.

Photovoltaic systems, air turbine, generators with diesel motors, water-power plants are connected together with load on the side of alternating voltage. The batteries of accumulators, fuel cells and DC receivers, however, are integrated on the side of DC voltage. The connection of solar batteries on the side of alternating voltage required application additional DC/AC inverter, what allowed to avoid using an expansive DC wiring and additional adjustment.

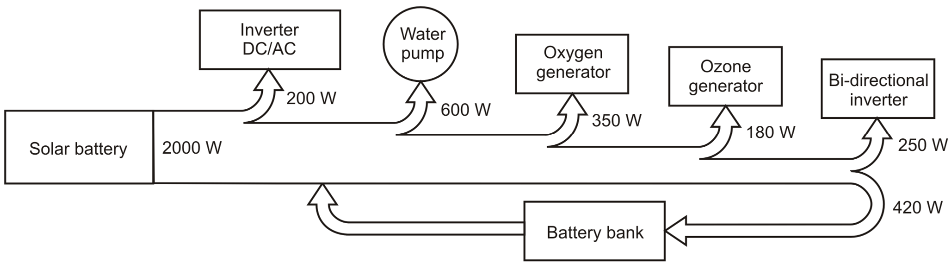

Fig. 9 Electric energy consumption in the system

Limited power value received from photovoltaic cells poses the main problem in designing an efficient treatment system. Power consumption of individual electric elements in integrated ozonation system is shown in Fig. 9.

When the whole system is accurately aligned, usage of some of electronic elements, utilized in pilot installation, which are responsible for controlling functioning of the system might be omitted. Thus, power consumption could be lowered to several hundred Watts.

IV. Conclusions

Usage of solar power via thermal collectors or photovoltaic panels to the water treatment is an environmental-friendly and cost-effective solution.

The presented water and air/water/soil ozonation set-ups are currently being prepared for implementation procedures. Since being fully autonomic systems of modular construction, they could be easily adjusted to individual needs. Power from PV panels could cover up to 95-100% energy needs in summer period in optimized integrated system.

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