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Application of Solar Energy in the Processes of Gas, Water and Soil Treatment

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1. Introduction

Shortening of natural resources will impose greater limitations on electric energy consumption in various fields including treatment technologies. Moreover, with increasing of environmental awareness in the society there comes the need of shifting industry and farmers towards clean and eco-friendly techniques, which allow to avoid formation of secondary pollutants during the treatment process.

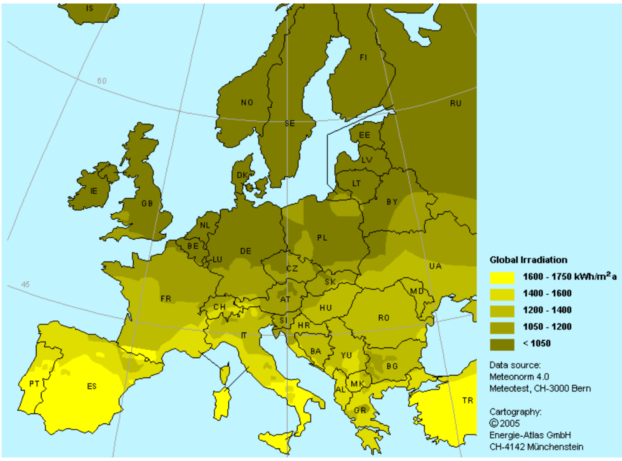


Fig. 1. Global irradiation in Europe (Energie-Atlas GmbH, 2005).

Small water, wastewater, gas and soil treatment installations supplied with electric energy from renewable energy sources are perfect example of zero-emission technology achieved with reasonable cost (Pawłat et al., 2011). Possibility of solar energy application, as one of the alternative energy resources for decontamination processes is strongly dependent on geographical location. Near-equatorial places called "sunny belt" are much more favorable and cost-effective for solar installations. However, 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. (Energie-Atlas GmbH, 2005).

Poland is situated in the moderate climatic zone between 49^o and 54.5^o of the northern latitude. Daily interval (time from the sunrise to the sunset) covers over 51% of 8767 hours in the average year, and this period is 24 hours longer in the northern parts compared with the southern ones. In winter, day is almost 1 hour longer in southern regions of Poland comparing with the northern regions whereas it is opposite in summer (Nalewaj et al., 2003).

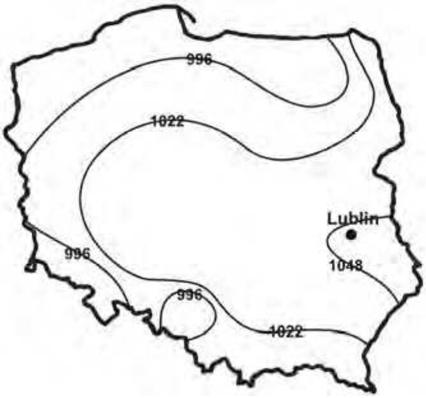


Fig. 2. Total radiation (KWh/m^2).

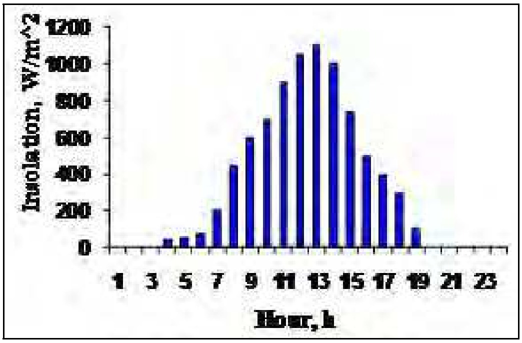


Fig. 3. Insolation in Lublin between 1-3 June 2002, (Nalewaj et al., 2003).

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 Lublin city is about 1107 kWh, and while over 15% of annual energy reaches Lublin in August, in December it is only 1,6%. The typical daily insolation in Lublin area in Summer is depicted in Fig. 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, 2010), the solar thermal panel area installed in the EU during 2009 was 4166056 m^2 giving 22786,1MW$_{th}$ of the accumulated installed solar thermal capacity. Prevailing technology is flat glazed collectors integrated into an insulated casing (heat transport fluid circulates in an absorber sheet placed behind a panel of glass- 3608711 m^2 and 106494 m^2 installed in 2009 in Europe and Poland, respectively) over the vacuum tube collector (fluid circulates inside a double vacuum tube and insulation is provided by the vacuum- 408998 m^2 and 37814 m^2 installed in 2009 in Europe and Poland, respectively) and unglazed collectors (matrix of black plastic tubes, stacked against each other left out in the fresh air- 148347 m^2 installed in 2009 in Europe).

The largest national collector bases were in Germany (12899800 m^2 and 9029,9 MW_{th}) and in Austria (4330000 m^2 and 3031 MW_{th}). The 10th place on the EU2009 list belonged to Poland with 509836 m^2 of collectors installed, giving 356,9 MW_{th}). Poland had 13,4 m^2 of solar thermal collectors installed per 1000 inhabitants and produced 9,4 kW_{th} per 1000 inhab. in 2009. Leaders per capita were Cyprus (873,9 m^2/1000inhab.and 611,7 kW_{th}/1000 inhab) and Austria (517,1 m^2/1000 inhab. and 362 kW_{th}/1000 inhab.). In UE on average 64,9 m^2 and 45,5kW_{th} were installed and produced per 1000 inhabitants, respectively (EUROBSERV'ER, 2010).

In 2010 Europe also continued photovoltaic plants' installation reaching over 80% of global installed photovoltaic's capacity and generating 22,5 TWh of photovoltaic power. The additional installed capacity in the EU over twelve months to the end of 2010 ranged 13023,2MW_p (growth of 120,1%).The cumulated predicted photovoltaic capacity of EU in 2010 is presented in Fig.4 (EUROBSERV'ER, 2011).

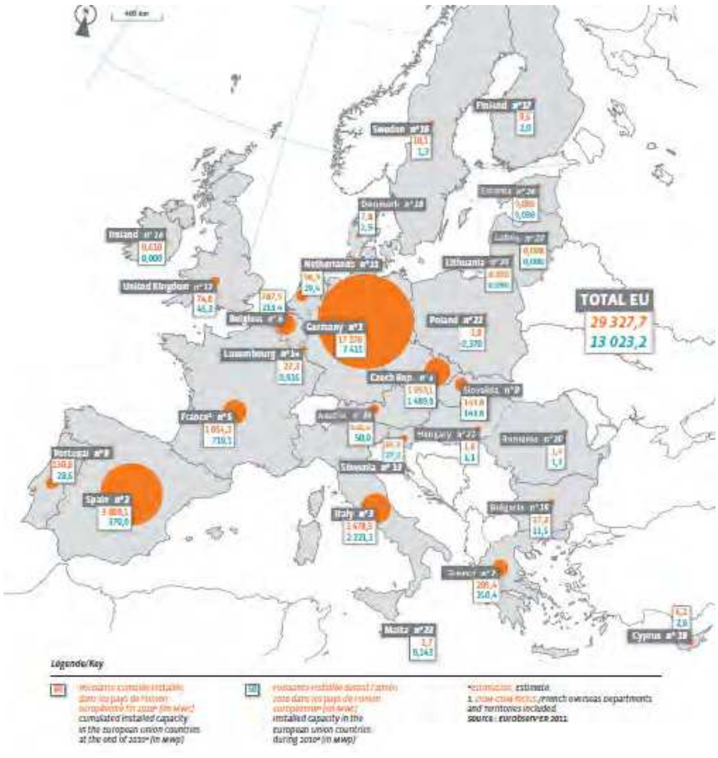


Fig. 4. Cumulated photovoltaic capacity in the European Union countries in 2010 (in MW_p) (EUROBSERV'ER, 2011).

Average photovoltaic power per inhabitant in European Union in 2010 was 58,5 W_p/inhab, with leading Germany and Czech Republic with 212,3 and 185,9 W_p/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 (EUROBSERV'ER, 2011).

2. 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 causing further deterioration of water quality and its scarcity in the region.

There are many conventional technologies of water decontamination but with growing environmental pollution they are sometimes insufficient besides being 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 also considered expensive and power-consuming. Thus combining treatment technologies with alternative energy sources can be a perfect solution allowing 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.

2.1 Solar desalination

Desalination aims to remove any salts and mineral from water to make it suitable for drinking or for industrial application. The most common process is thermal desalination, which uses boiling water and is based on evaporation and vacuum distillation. Energy required to evaporate water is 2.3 MJ per kilogram. The installations, which belong to this category are simple stills, MEH (Multi Effect Humidification), MED (Multi Effect Distillation), MES (Multi Effect Solar Desalination) and MSF (Multi Stage Flash). Novel desalination plants use reverse osmosis (RO), electrodesalinizion (EDI) and membrane distillation (MD). Despite of used method, desalination of water requires tremendous amount of energy. The main criteria for desalination system in developing countries are affordability, reliability, simplicity and good quality of output medium. Areas, where shortage of drinking water limits the socioeconomic development are often highly insolated. Thus, using solar power for desalinization purposes seems to be economically justified. Moreover, water can be obtained in environmentally-friendly process.

Two examples of small thermal desalinization installations for use in remote arid areas are depicted in Fig. 5 (Chaibi, 2000; Al-Kharabsheh and Goswami, 2003).

Solar powered humidification– dehumidification principle is evaporation of seawater and condensation of water vapor from the humid air in the unit at ambient pressure and at temperatures between 40°C and 85°C (Al-Hallaj et al., 2006). Simplicity of the set up made it popular in different parts of the world. Typical MEH desalination unit is presented in Fig. 6a.

Multi-effect distillation unit was developed in Germany (Muller-Hoist et al., 1999) and then applied on the island of Fuerteventura, where it is working for several years without almost any maintenance or repair. The optimized module produced 40 L/h of fresh water, but it was shown that production of 1000 L/d is possible when the unit was operated continuously for 24 h. Based on a collector area of 38 m², the daily productivity of the optimized module is about 26 L/m² of collector area for a 24-h run and with thermal storage under optimized laboratory conditions (Parekh et al., 2004).

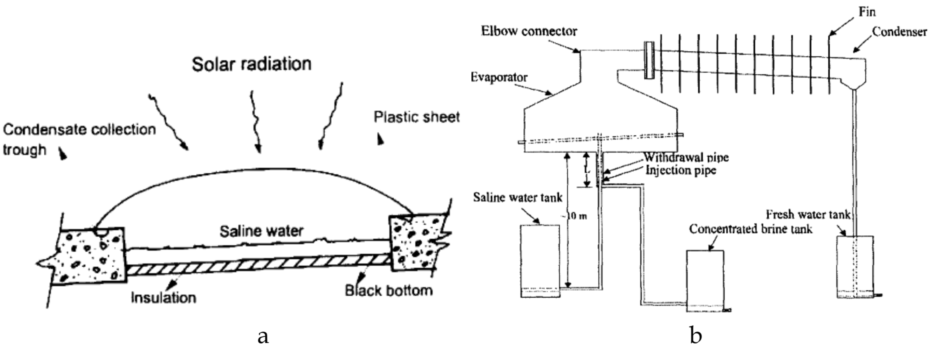


Fig. 5. Simple solar still (Chaibi, 2000) (a), desalination system using low-grade solar heat (Al-Kharabsheh and Goswami, 2003) (b).

Application of solar chimney to generation of energy and sea water desalination, which is shown in Fig. 6 is also an interesting approach. Through theoretical analysis, it has been demonstrated that the integrated system can significantly improve the solar energy utilization efficiency as well as the land resources utilization efficiency (Zuo, 2011).

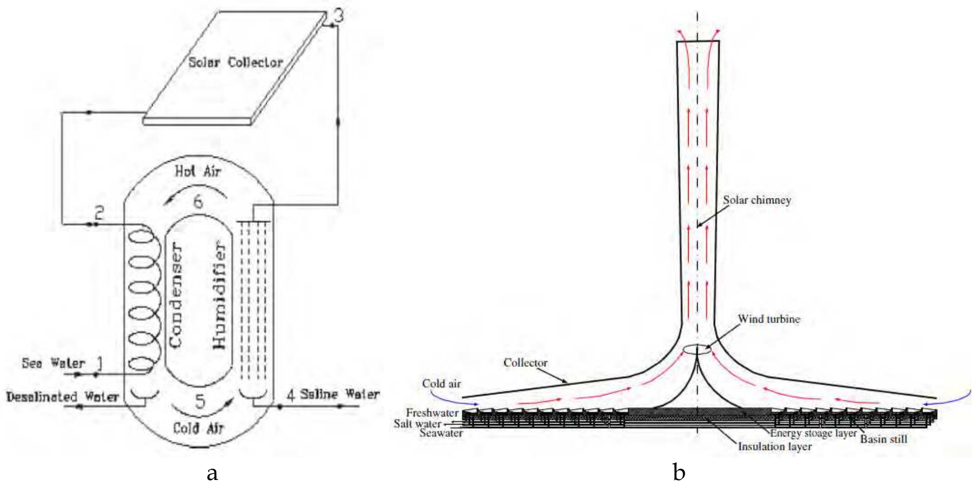


Fig. 6. Sketch of a natural draft air circulation MEH desalination unit (Parekh et al., 2004) (a), Schematic diagram of the integrated desalination system with solar chimney (Zuo, 2011) (b).

The Solarflow water treatment system for remote indigenous communities was invented at The Environmental Technology Centre, Murdoch University (the Murdoch ETC) in Perth, in the early 1990s and it is constantly modified since then (Dallas et al., 2009). The Solarflow is a self-contained solar-powered unit capable of producing 400 L/d of high quality drinking water from brackish water via reverse osmosis and requires only 120W of photovoltaic power.

Other project combining solar thermal and seawater or brackish water reverse osmosis is SOFRETES system, which was already in operation in the early 1980s (Delgado et al., 2007).

As an output of the project SMADES, employing membrane distillation and aiming in design of large solar powered desalination system, the pilot plant was built in Aqaba, Jordan in 2006. Feed water was seawater directly from the Red Sea (55,000 μS/cm) (Banat et al., 2007).

MEDSOL is an EU project on seawater desalination by innovative solar-powered membrane distillation system (Galvez et al., 2009). Commercial sea water purification system is offered by Blue Spring Company, (Fig. 7). Models EC-1MS, through EC-30MS with output capacity ranging from 1.2 m^3/d to 30 m^3/d can serve the fresh water needs of communities from 6 to 160 households.

Fig. 7. Blue Spring Solar desalination system.

2.2 Solar energy for water conditioning

Availability of drinking water is an ultimate condition for the inhabitation. Extraction of water from air (EWA) (Scrivani et al., 2007) 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, ranges from 10,000 to 30,000 m^3 of pure water.

In proposed solution, the refrigerator was operated by an electricity driven compressor and the cold fluid going into the heat exchanger was produced by a reverse compression-expansion thermodynamic cycle (Fig. 8). It was claimed by the manufacturers that approximately one liter of diesel fuel operating the electrical generator could provide four liters of water from air. In fact, system integration with PV panels could make it more reasonable from economy point of view.

In the developing countries, where sophisticated water purification methods are not available, solar water disinfection (SODIS) revealed a great potential to reduce the global diarrhoeal diseases burden, which affects over 1.8 million people (Meierhofer and Landolt, 2009; Acra et al., 1980).

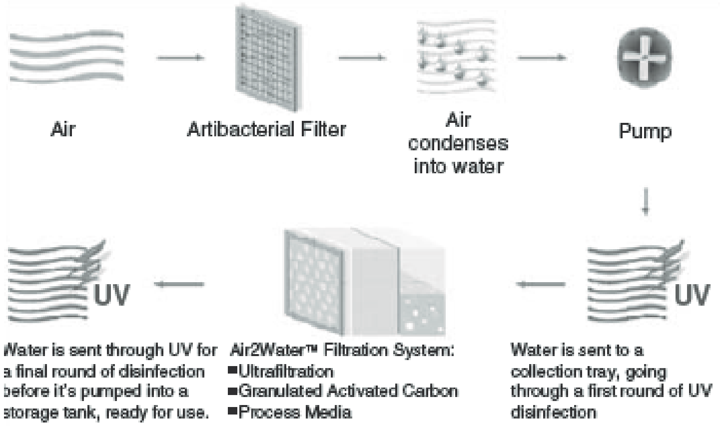


Fig. 8. Typical EWA plant for potable water production (condensation occurs by passage of the air on the cold coils of a heat pump) (Scrivani et al., 2007).

According to extensive microbiological investigation, 30°C water temperature, a threshold solar radiation intensity of at least 500 W/m^2 (all spectral light) is required for 3-5h 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. 9) by more than 2 million people and decreasing diarrhoea outbreaks by 16–57%.

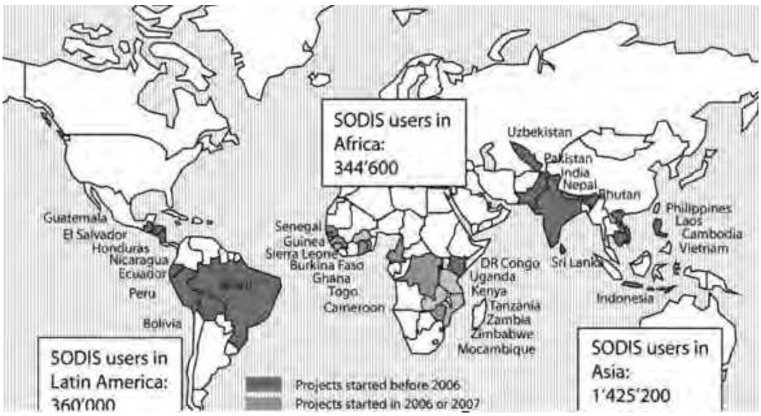


Fig. 9. More than 2 million users currently practise SODIS in 33 countries (Meierhofer and Landolt, 2009).

Single-basin solar stills, presented in Fig. 10 for the removal of a selected group of inorganic, bacteriological, and organic contaminates were investigated (Hanson et al., 2004) 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 group of Sixto Malato has been investigating the solar photocatalysis and proposing various innovations in the process for more than decade. Mechanism of solar driven photocatalysis is depicted in Fig. 11, (Robert and Malato, 2002).

Malato group was 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. can be employed (Bahnemann, 2004).

In areas where water is heavily contaminated standalone systems, which were used for desalination and simple light disinfection 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.

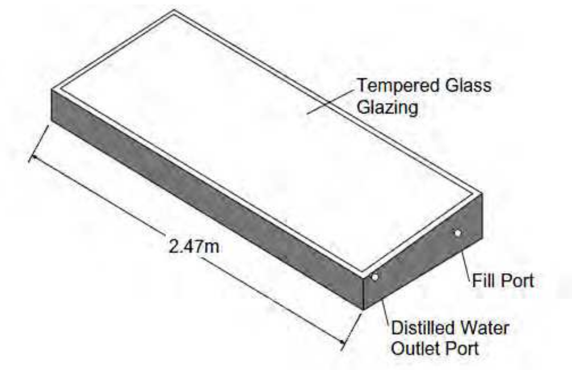


Fig. 10. Isometric view of El Paso Solar Energy Association still (Hanson et al., 2004).

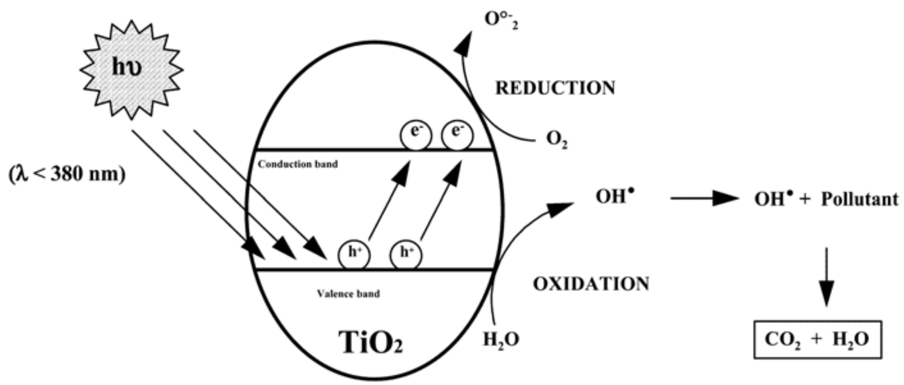


Fig. 11. General mechanism of the photocatalysis, (Robert and Malato, 2002).

Solar driven photocatalytic oxidation processes are presented in Tab. 1. (Blanco et al., 2009). Tab 2. (Malato et al., 2009) compares various factors, which must be taken into the consideration when TiO_2 and photo-Fenton process are used.

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)
$TiO_2 + h\nu \rightarrow e^-_{CB} + h^+_{VB}$	
$h^+_{VB} + H_2O \rightarrow {}^\bullet OH + H^+$	$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + {}^\bullet OH$
$S_2O_8{}^{2-} + e^-_{CB} \rightarrow SO_4{}^{\bullet -} + SO_4{}^{2-}$	$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + H^+ + {}^\bullet OH$
$SO_4{}^{\bullet -} + H_2O \rightarrow {}^\bullet OH + SO_4{}^{2-} + H^+$	

Table 1. Photocatalytic oxidation processes that can be driven by solar energy (Blanco et al., 2009).

	TiO_2	Photo-Fenton
Stress on reactor materials	Corrosive liquids: oxidative process, pH and salt concentration depend on application.	Corrosive liquids: oxidative process, H_2O_2, iron ions, usually acidic pH (2–3.5), salt concentration and temperature depend on application.
Cleaning procedures	TiO_2 may adsorb on the reactor walls preventing illumination, effective chemical cleaning agents are HCl, and mostly, H_2F_2.	Iron oxides may deposit on the reactor walls preventing illumination, effective chemical cleaning agents are chelating agents, such as oxalic acid and acidic pH.
Residence time in collector	Long residence time in the collector may cause dissolved O_2 depletion.	Long residence time in the collector may cause H_2O_2 depletion.
Temperature	Not relevant to process performance between 20 and 80 °C.	Strongly influential on process performance, beneficial if higher.
Reactor diameter/ depth—optical pathlength	Light distribution in the collector is largely governed by absorbance and scattering by the catalyst particle. A direct correlation between ideal catalyst concentration and diameter exists.	Light distribution is governed by absorbance of the solution, which is a function of catalyst concentration and wastewater. Absorbance varies strongly along the ‹treatment› due to the appearance and destruction of compounds.
Effective wavelength range	<390 nm for TiO_2, being approx. 4% of sunlight's irradiance power (sunny days).	Depends strongly on the presence of complexes, may be up to 550–600 nm being 28–35% of sunlight's irradiance power (sunny days).
Light intensity	Rate law changing from first through half order to zero-order dependency as the light intensity increases.	Little research performed, first order rate law suggested over a broad range of light intensity, applicable as long as ferric iron predominates over ferrous iron.
Dark zones	No reactions taking place in dark zones.	Fenton process takes place in dark zones, elevated temperature influences the reaction rate positively. Alternating dark and illumination intervals have shown to reduce the necessary illumination time.
Process control	Process control mainly includes the determination of ‹treatment› end.	Process control includes the determination of the ‹treatment› end. pH must be controlled to avoid iron precipitation.

Table 2. Comparison of TiO_2 and photo-Fenton process aspects relevant to the photoreactor's design requirements, (Malato et al., 2009).

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, for instance: SOLWATER and AQUACAT (Malato et al., 2009) (Fig. 12).

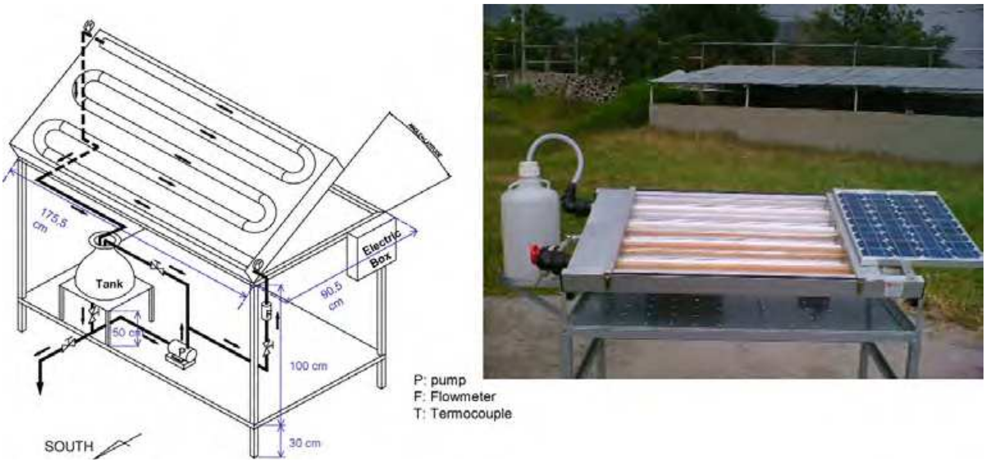


Fig. 12. Schematic diagram and photograph of the photoreactor developed in AQUACAT and SOLWATER projects for photocatalytic disinfection in developing countries (Malato et al., 2009).

Fig. 13. View of the solar detoxification demonstration plant erected by ALBAIDA at La Mojonera (Almerı´a, Spain), (Malato et al., 2007).

Huge solar driven photocatalytic plant, presented in Fig. 14, was built in Almeria, Spain under the ''SOLARDETOX'' EU project on solar detoxification technology for the treatment of industrial non-biodegradable persistent chlorinated water contaminants, (Malato et al., 2007). Nowadays, facility allows to investigate following technologies (Bahnemann, 2004):

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^-) 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.

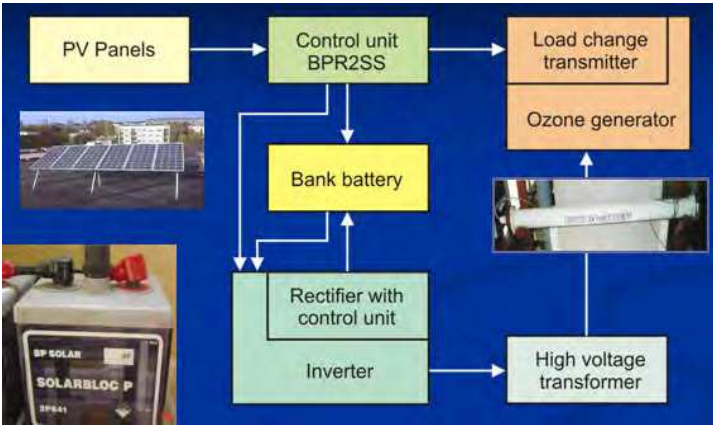


Fig. 14. Integrated PV water/gas/soil conditioning system based on ozone.

Integrated PV system based on AOP and application of ozone (Fig. 14) for water and gas conditioning was developed by Stryczewska group (Stryczewska, 2011; Komarzyniec et al., 2010; Pawłat et al, 2011a; Pawłat et al, 2011b). System was applied for conditioning of the pool waters, soil and gas. It will be further described in part 5.

2.3 Solar wastewater treatment

Wastewater treatment processes can be basically divided into 3 groups: mechanical, chemical and biological. They are used in various combinations depending on the type and concentration of pollutants. Some of discharged industrial impurities are not decomposable by conventional technologies, require tremendous amount of energy, thus, must be treated with alternative methods such as AOP. Those needs can be at least partly assured by using solar supported technologies. Examples of solar power employing in the processing of hardly-treatable compounds from various industrial branches such as pharmaceutics, chemical, semiconductor, dye, paper, food and for farms' and landfills' leachates are known.

Fig. 15 presents solar photocatalytic treatment plant developed to treat wastewater from recycling pesticide bottles (Albaida plant, Almeria, Spain) (Blanco et al., 2009). Water from washing the pesticide bottles was treated in batches until 80% of the TOC has been mineralized. At this point, the water was transferred to the post-treatment (iron precipitation, sedimentation and recuperation), and either reused for bottle washing or discharged for irrigation through an activated carbon filter to ensure discharge quality. About 75% of the total volume of the treatment circuit was continuously exposed to sunlight in 150 m^2 of CPC solar reactors.

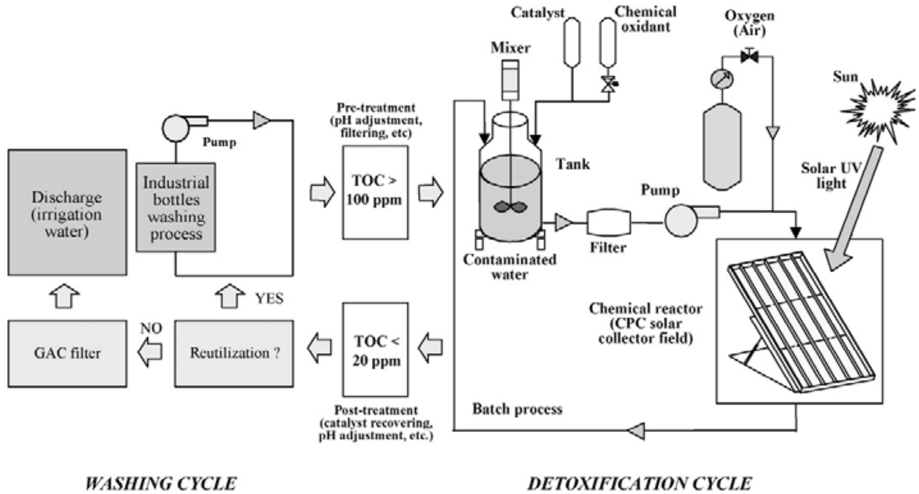


Fig. 15. Conceptual design of the ALBAIDA solar photocatalytic plant for the treatment of wastewater from washing shredded plastic pesticide bottles for recycling, (Blanco et al., 2009).

Another coupled solar-biological system at field pilot scale based on CPC and fixed bed reactor (Fig. 16) for the treatment of biorecalcitrant pollutants was developed in EPFL (Sarria et al., 2003). The photo-Fenton system was the most appropriate AOP for the degradation of a model biorecalcitrant compound, 5-amino-6-methyl-2-benzimidazolone (AMBI). The coupled reactor, operating in semicontinuous mode achieved 80-90% mineralization performance depending on the range of initial dissolved organic carbon.

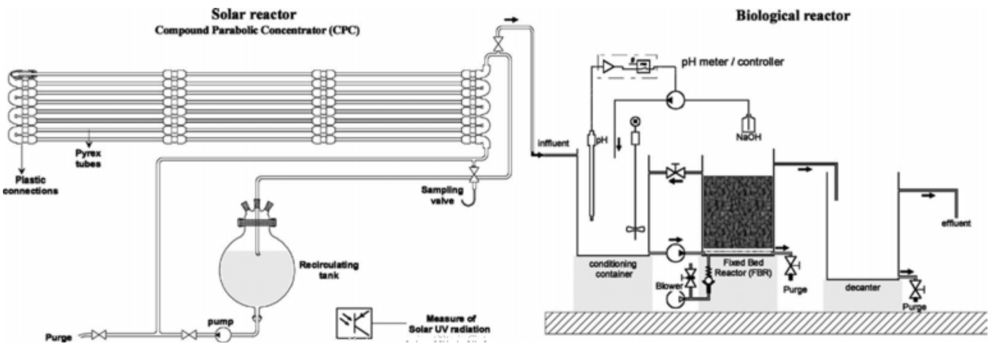


Fig. 16. Schematic representation of the coupled solar-biological flow reactor (Sarria et al., 2003).

100% of the cyanides and up to 92% of TOC in wastewater effluent from an Integrated Gasification Combined-Cycle was degraded in the cycle utilizing concentrated solar UV energy (UV/Fe(II)/H_2O_2) in a Solar CPC pilot plant (Duran et al., 2010) under the optimum conditions ([H_2O_2] = 2000 ppm, [Fe(II)] = 8 ppm, pH = 3.3 after cyanide oxidation, and [$(COOH)_2$] = 60 ppm).

Different solution was design of solar heated reactor for anaerobic wastewater or biological sludge treatment at temperatures higher than the ambient air temperature (Yiannopoulos et al., 2008). For the proposed reactor system, the solar energy absorbed by flat plate collectors was transferred to a heat storage tank, which continuously supplied an anaerobic-filter reactor with water at a maximum temperature of 35^{o}C. At this temperature the COD removal efficiency was approximately 80%.

3. Solar energy in conditioning of air and drying the crops

3.1 Cooling and air conditioning

There are two main ways to convert solar radiation into cooling or conditioning of air, based on PV panels and solar collectors combined with variety of thermodynamic processes (Fig. 17), (Henning, 2007). Solar buildings and using of gravitational ventilation is gaining more and more popularity in Europe but this topic will not be a subject of the present chapter.

Techniques allowing use of solar thermal collectors, which are currently prevailing over PV panels for air-conditioning of buildings can be basically divided into thermally driven chillers (to produce chilled water which can be used for any type of air-conditioning) and open cycles, also referred to as desiccant cooling systems, (for direct treatment of air in a ventilation system). Typical system based on thermal process is presented in Fig. 18.

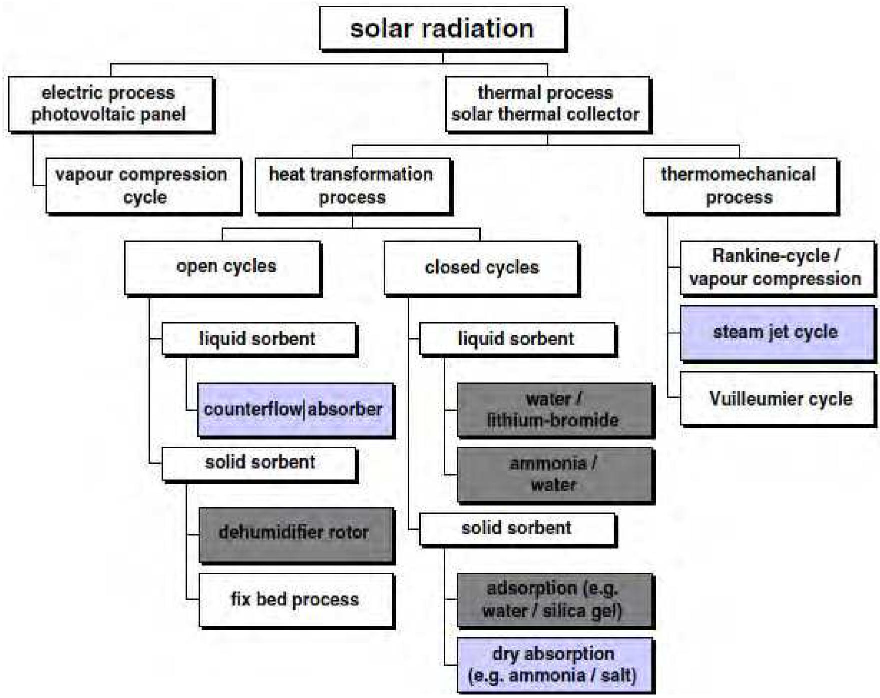


Fig. 17. Solar radiation for air-conditioning. Processes marked in dark grey: market available technologies which are used for solar assisted air-conditioning. Processes marked in light grey: technologies in status of pilot projects or system testing (Henning, 2007).

Following processes, depicted in Fig. 18 are taking place: 1- intake, 2-sorptive dehumidification of supply air; 3-pre-cooling of the supply air in counter-flow to the return air from the building; 4-evaporative cooling of the supply air to the desired supply air humidity by means of a humidifier; 5-the heating coil is used only in the heating season for pre-heating of air; 6-a small temperature increase is caused by the fan; 7-supply air temperature and humidity are increased by means of internal loads; 8-return air from the building is cooled using evaporative cooling close to the saturation line; 9-the return air is pre-heated in counter-flow to the supply air by means of a high efficient air-to-air heat exchanger, e.g., a heat recovery wheel; 10-regeneration heat is provided for instance by means of a solar thermal collector system; 11-the water bound in the pores of the desiccant material of the dehumidifer wheel is desorbed by means of the hot air;) 12-exhaust air is blown to the environment by means of the return air fan.

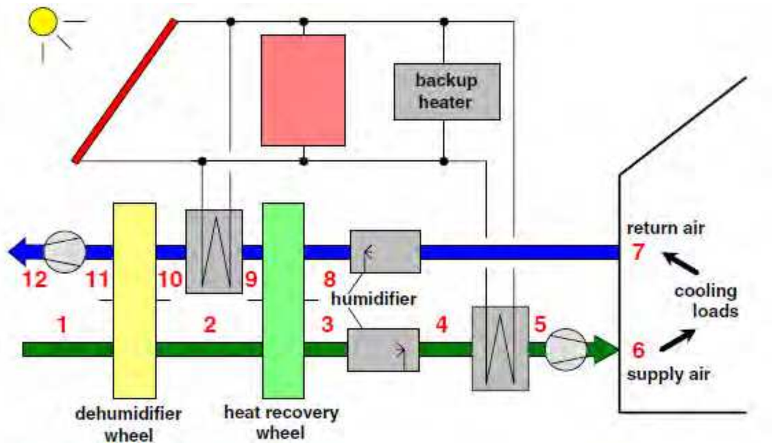


Fig. 18. Standard desiccant cooling cycle using a dehumidifier wheel with solar thermal energy as driving heat input, (Henning, 2007).

In Europe thermal systems are mostly installed in Germany and Spain. Large ones are installed at the Sarantis cosmetics factory in Greece and the federal office for environmental issues of Bavaria in Augsburg. In Freiburg/Germany a solar cooling system is operated by the University hospital for air-conditioning of a laboratory.

The system, presented in Fig. 19 consists of an adsorption chiller with a capacity of 70 kW and a field using evacuated tube collectors with an aperture area of 170 m^2 (Henning, 2007).

Integration of air conditioning especially for cooling purposes with PV panels is another eco-friendly approach as cooling is usually used in the period of high insolation. Thus, use of PV supplied energy could stabilize the grid. PV panels integrated with air conditioning system are already commercially offered on the market by LG (Fig. 20a). LG's solar-assisted air conditioner requires only 727 watts per hour of energy for cooling.

Another solution is a hybrid system (photovoltaic + solar thermal) proposed by SolarWall® PV/T , which provides up to 4 times the total energy from the same surface area. ICL Co Ltd, Mitsubishi Chemical Corp and Nippon Fruehauf Co Ltd co-developed the air conditioning system "i-Cool Solar" (Fig. 20b), which stores electricity via the photovoltaic panels in special on-board batteries and uses the stored energy to power the cabin air conditioner when the truck is idle.

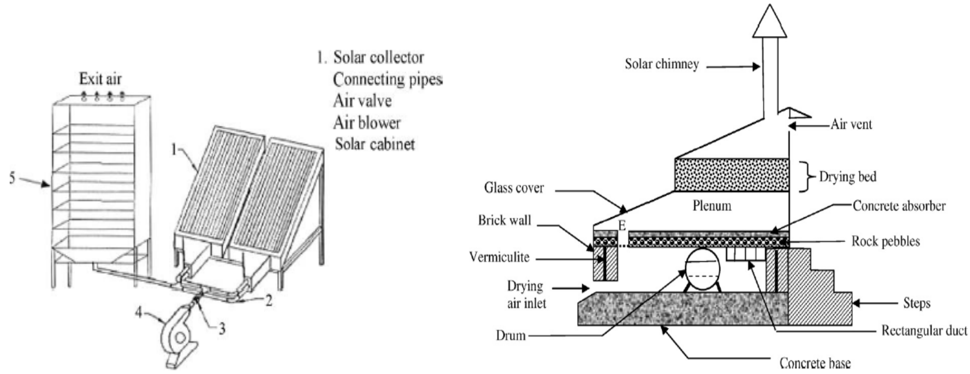
Fig. 19. Solar collector field (evacuated tubes) installed in system at University hospital in Freiburg (Henning, 2007).

a b

Fig. 20. LG solar hybrid air conditioner (a), ICL Co Ltd, Mitsubishi Chemical Corp and Nippon Fruehauf Co Ltd solar cooled truck (b)

3.2 Drying of crops

Application of solar energy for drying crops, clothes, building materials is one of the oldest one. The first installation for drying by solar energy was found in South France and is dated at about 8000 BC. Two basic moisture transfer mechanisms are involved in drying: migration of moisture from the mass inside to the surface and transfer of the moisture from the surface to the surrounding air, in the form of water vapor. Drying by solar radiation can be divided into direct, or open-air sun drying, the direct exposure to the sun and indirect solar drying or convective solar drying, (Belessiotis and Delyannis, 2011; Leon et al. 2002). Selecting the perfect conditions for drying is not easy as the food materials are very sensitive and their color, flavor, texture or nutritional value should not be seriously affected. According to (Belessiotis and Delyannis, 2011) outdoor sun-air heating suits to fruits because of high sugar and acid content but vegetables have low sugar and acid content increasing the risk of spoilage during sun- and open-air drying. The basic classification of solar drying modes is summarized in Tab. 3. Basically, direct solar dryers, indirect solar dryers, mixed-mode dryers and hybrid solar dryers can be distinguished (Fudholi, 2010). Fig. 21 gives examples of basic design of solar dryiers.



a b

Fig. 21. Examples of solar crops dryers: indirect-mode forced dryer, (Al-Juamily et al., 2007) (a), indirect type natural convection solar dryer with an integrated thermal mass and a biomass-backup heat, (Madhlopa and Ngwalo, 2007) (b).

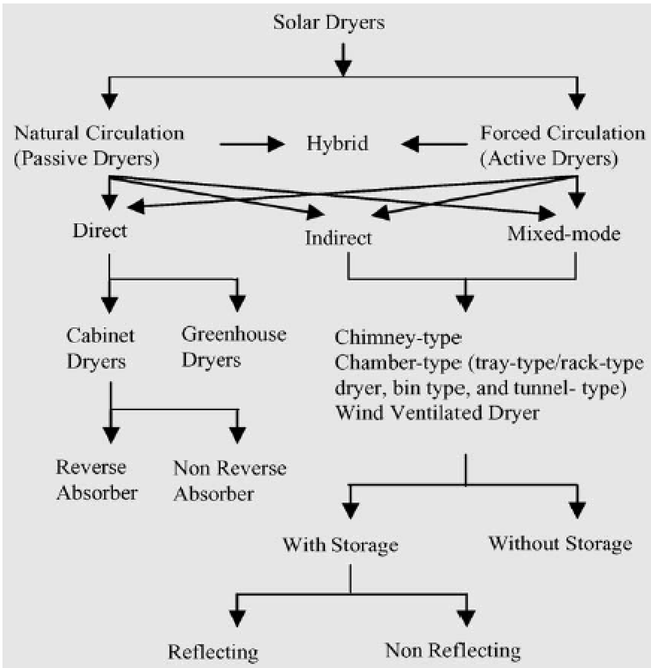


Table 3. Classification of solar dryers and drying modes (Fudholi, 2010).

4. Solar energy for wastes and solids treatment

Solar energy might be used in processing of solid and liquid wastes on several stages of their treatment. PV panels might be used for generating of electrical power for each devices but commonly rather thermal solar power is used to maintain or increase the temperature required for the treatment process.

Solar power can be used in the process of gasification of carboniferous materials including wastes of high carbon content. Solar steam-gasification of biomass makes use of concentrated solar energy to convert solid biomass feedstocks into high-quality synthesis gas (syngas) – mainly H_2 and CO – applicable for power generation in efficient combined cycles and fuel cells, or for Fischer-Tropsch processing of liquid biofuels (Lede, 1999; Perkins and Weimer, 2009; Melchior, 2009). Conventional auto-thermal gasification requires a significant portion of the introduced feedstock to be combusted with pure O_2 to supply high temperature process heat for the highly endothermic gasification reaction. For example, the energy required to gasify bituminous coal of LHV 34 MJ/kg is supplied by burning 35% of the injected coal mass (Piatkowski and Steinfeld, 2008). In contrast, the solar-driven gasification eliminates the need for a pure stream of oxygen (Melchior, 2009).

Solar-driven steam-gasification is free of nearly all combustion by-products and produced syngas has a lower amount of CO_2 (calorific value is over that of the original feedstock by an amount equal to the enthalpy change of the reaction).

The solar hydrogen technology can be divided into water thermolysis (needs a high temperature heat source at above 2500 K), thermochemical cycles for water-splitting, and hybrid solar/fossil fuels processes.

Thermochemical gasification of tires and plastic bottles into synthesis gas using ZnO as a donor of oxygen in the infra-red furnace and concentrated solar energy was studied (Matsunami et al., 1999). Another solution for concentrated-solar supported gasification was two phase biomass char (biochar) steam gasification in a bubbling fluidized bed (Fig. 22). Hydrogen was the principal expected product followed by carbon monoxide (Gordillo and Belghit, 2011).

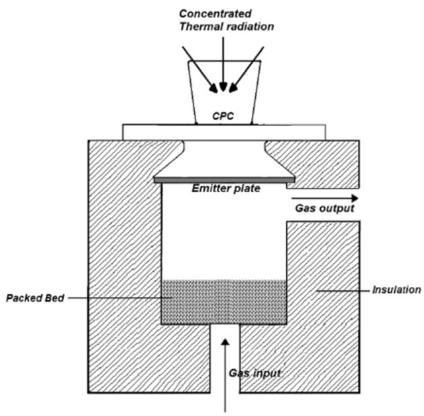


Fig. 22. A bubbling fluidized bed gasifier with concentrated thermal radiation as source of energy (Gordillo and Belghit, 2011).

3kW solar reactor prototype was invented for continuous steam-gasification of biochar (ultimately for the biomass feedstock) (Melchior et al., 2009). High-temperature thermochemical reactor, depicted in Fig. 23, used cavity-type configuration to capture effectively the incident concentrated solar radiation entering through a small opening (aperture) and multiple internal reflections.

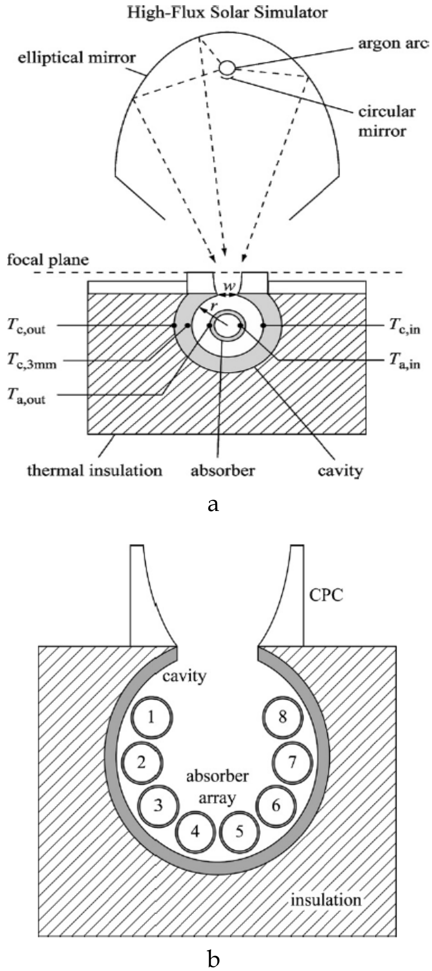


Fig. 23. Schemata of the solar chemical reactor configuration (cross-sectional view) at ETH's High-Flux Solar Simulator (a), and of scaled-up reactor consisting of a cavity-receiver containing an array of 8 tubular absorbers (b), (Melchior et al., 2009).

A novel system of hydrogen production by biomass gasification in supercritical water (SCWG) using concentrated solar energy has been constructed, installed and tested with biomass model compounds (glucose) and real biomass (corn meal, wheat stalk) (Chen et al., 2010). The system's schema is shown in Fig. 24.

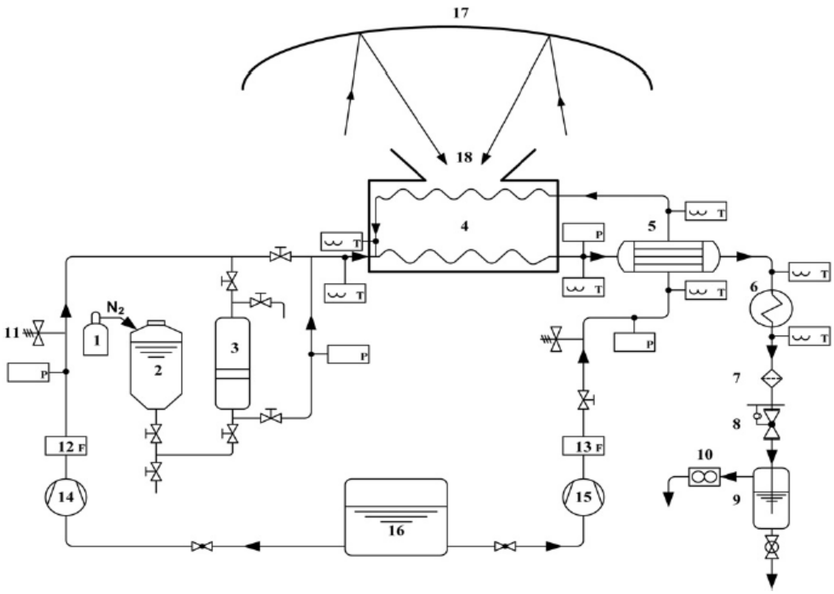


Fig. 24. Schematic diagram of SCWG using concentrated solar energy system [Chen et al., 2010]. (1: nitrogen bottle; 2: feedstock tank; 3: feeder; 4: solar receiver/reactor; 5: heat exchanger; 6: cooler; 7: filter; 8: back-pressure regulator; 9: liquid-gas separator; 10: wet test meter; 11: relief valve; 12, 13: mass flow meter; 14, 15: high pressure metering pump; 16: water tank; 17: toroidal surface heliostat with the two axis spinning-elevation sun tracking; 18: secondary cone surface concentrator).

The maximal gasification efficiency (the mass of product gas/the mass of feedstock) in excess of 110% was reached, hydrogen fraction in the gas product approached 50%.

Big Belly System (Fig. 25) is an interesting initiative for small scale application of PV power for compression of city wastes. It reduces collection frequency by up to 80%, freeing up resources, slashing fuel costs and increasing recycling opportunities. Innovative container allows accommodating 8 times more trashes than traditional one and will bring about 12 mln USD savings in 10 years period in Philadelphia city.

Fig. 25. Big Belly System.

5. Prototype installation of air, water and soil treatment suppliedd from PV panels

Autonomous water treatment installation supplied 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 (Pawlat et al., 2011; Stryczewska, 2011; Komarzyniec et al., 2010; Pawłat et al, 2011a; Pawłat et al, 2011b; Ebihara et al., 2011; Takayama et al., 2006; Komarzyniec et al., 2010).

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.26 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.

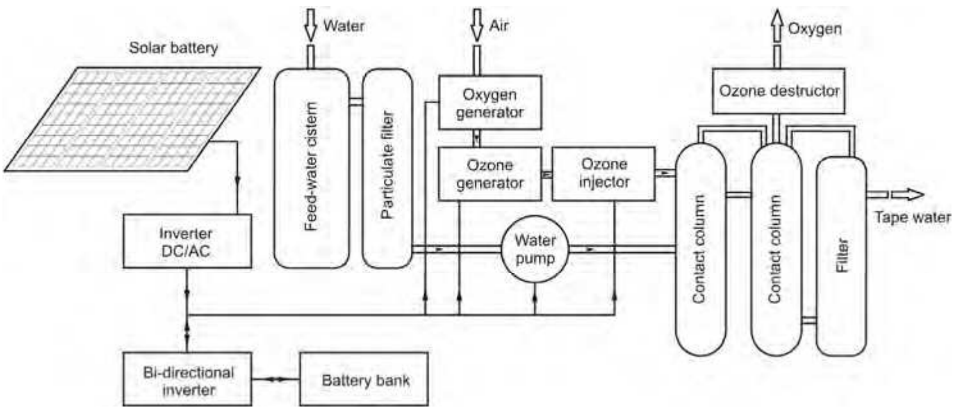


Fig. 26. Water ozonation system

Ozone based techniques in the case of soil contamination are good alternative to the traditional techniques like heating, flushing with chemical additives, landfilling, incineration, etc. Benefits of ozone applications in agriculture might be summarized as follows:

- use of ozone in soil treatment will not result in the build-up of any environmentally persistent or toxic compounds as O_3 is immediately consumed in the soil treatment process.
- ozone is manufactured on site so it cannot be stored and its sudden release to the atmosphere is not possible like it could occur with compressed methyl bromide or other persistent toxic gases or chemicals used for soil sterilization.
- minimum human toxicity.

Integrated system for ozonation of soil was presented in Fig. 27.

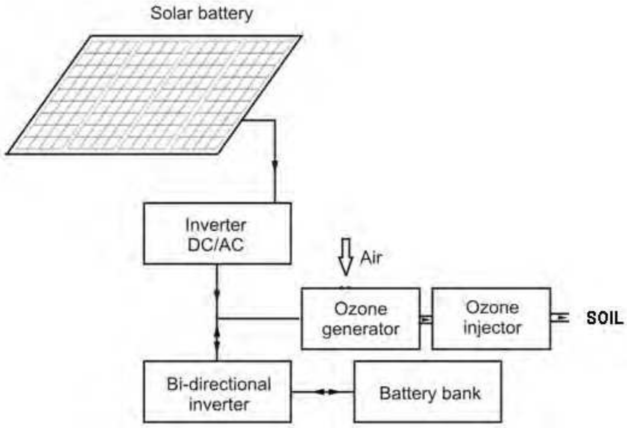


Fig. 27. Soil ozonation system

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. Tab. 4 collects photovoltaic cell parameters, used to supply water ozonation system with electrical energy.

Maximum Power	Maximum System Voltage	Maximum Power Voltage	Maximum Power Current	Open Circuit Voltage	Short Circuit Current
210 W	600 V	26.6 V	7.9 A	33.2 V	8.58 A

Table 4. Photovoltaic cell parameters

5.1 Production of ozone

The ozone generation took place with the usage of corona discharge. The ozonizer was powered with high frequency supplier with pulse control and amplitude modulation. It was possible to control ozone concentration. The basic parts of ozone generator were titanium electrodes (one covered with ceramic dielectric material). In order to lower the ozonier's consumption of electric energy, the complex system of radiators was used, so electrodes were efficiently cooled with atmospheric air (Fig. 28).

The utilized ozone generator operated with both: pure oxygen and atmospheric air as substrate gases, 1.5 g/h and 6 g/h of O_3 were generated, respectively. Gas flow ranged 3,3-4,7 l/min with 180 W of power consumption.

Ozone production chart and voltage characteristics are depicted in Fig. 29 and 30, respectively.

Through an increase of frequency not only the increase of efficiency, but also reduction of electric energy consumption was achieved.

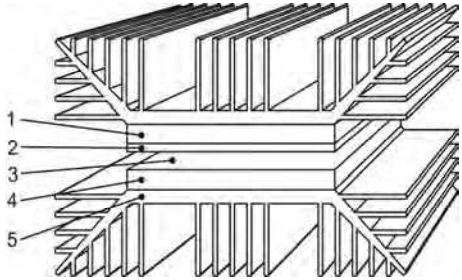


Fig. 28. Ozone generator: 1, 4 – titanium electrode, 2 – ceramic layer, 3 – discharge gap, 4 – radiator

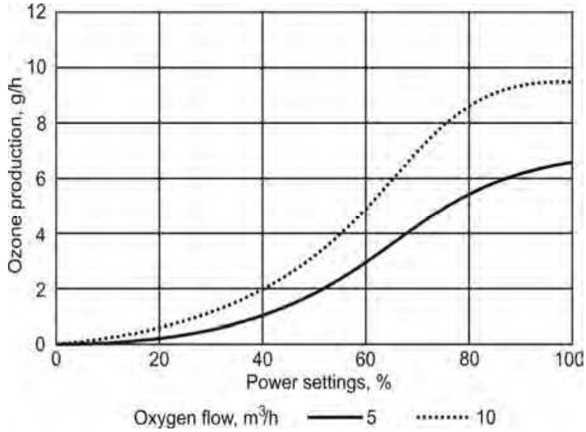


Fig. 29. Ozone generation chart.

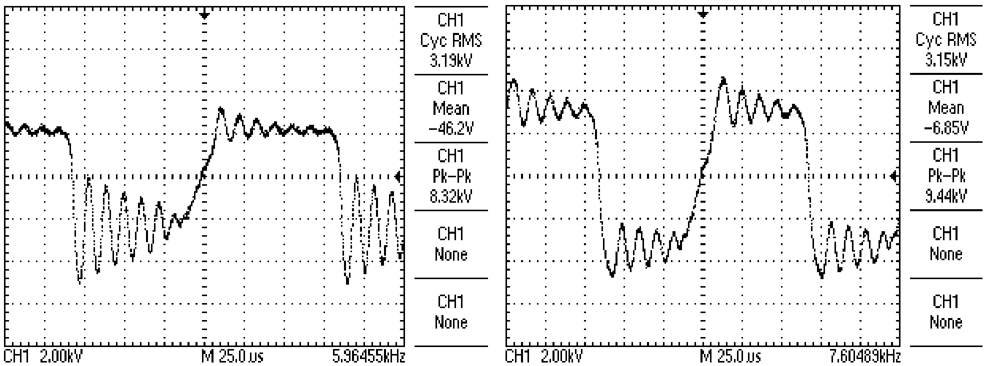


Fig. 30. The voltage characteristics for various frequencies.

5.2 Water ozonation system

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. 31.

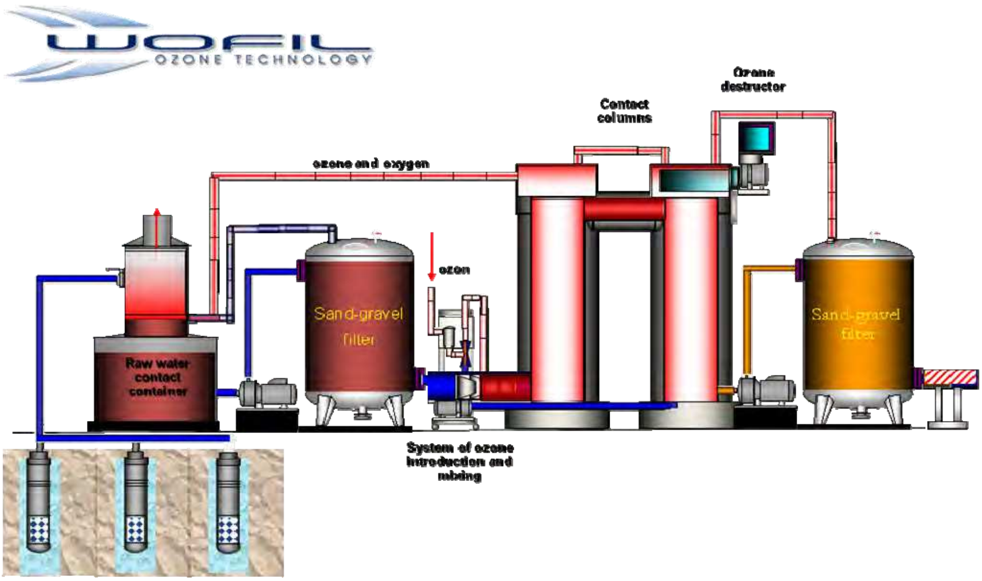


Fig. 31. WOFIL water ozonation system

5.3 Power supply

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. Fig. 32 depicts a flow chart of electric grid which cooperates with water ozonation system.

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.

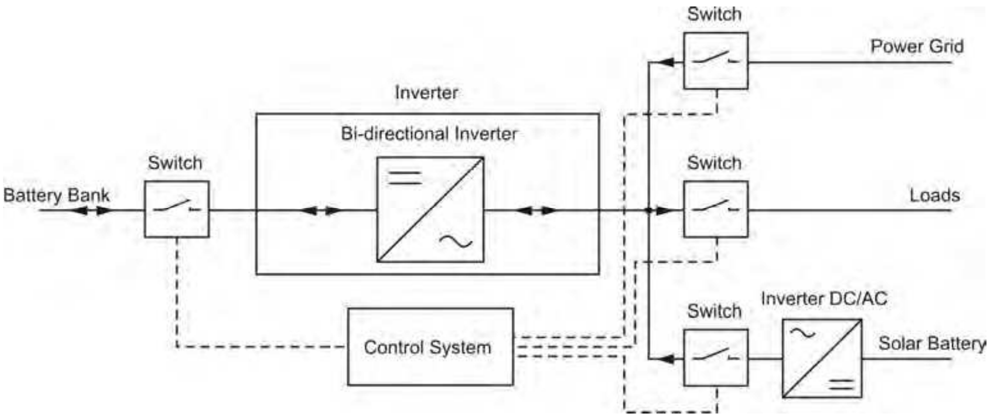


Fig. 32. Grid supplying water ozonation system with electric energy.

5.4 Energy distribution

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.33.

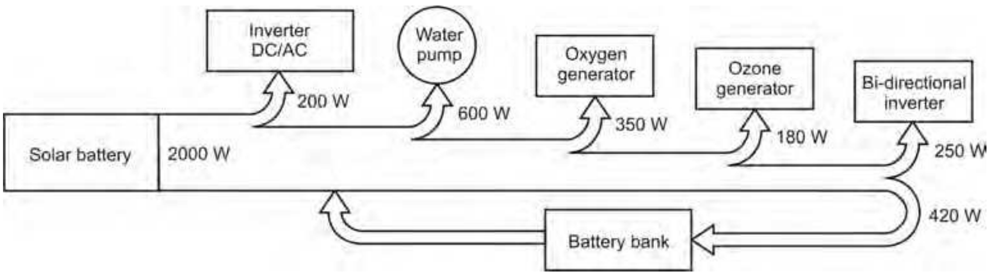


Fig. 33. Electric energy consumption in the system.

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.

6. Conclusions

Usage of solar power via thermal collectors or photovoltaic panels to the water, air, waste and soil treatment is an environmental-friendly and cost-effective solution, especially on areas with yearly uniform and high insolation.

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.

Efficiency of ozone application and AOP methods for water is already well known. Ozone usage in the case of soil allowed to achieve 99.9% sterilization efficiency in the case of Fusarium oxysporum at the ozone dosage over 20 gO_3/m^3.

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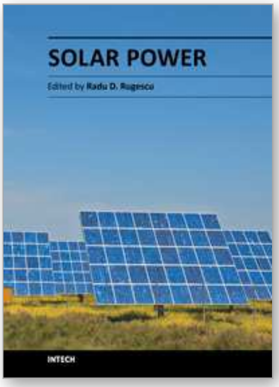

Solar Power

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A wide variety of detail regarding genuine and proprietary research from distinguished authors is presented, ranging from new means of evaluation of the local solar irradiance to the manufacturing technology of photovoltaic cells. Also included is the topic of biotechnology based on solar energy and electricity generation onboard space vehicles in an optimised manner with possible transfer to the Earth. The graphical material supports the presentation, transforming the reading into a pleasant and instructive labor for any interested specialist or student.

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