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Solar energy and cork: A binomial of the future?

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Abstract

In this article, several solar energy application possibilities in forestry and industrial processes are foreseen and discussed, focused on the case of cork harvesting and processing, in world areas where solar radiation is high. Cork processing to obtain several cork-based products has several and different operational steps in which electricity, heat and thermal fluids are necessary. Different types of existing solar technologies are considered, for the specific forestry and industrial steps of cork transformation. Most of these technologies are not yet being used in the cork sector. Besides this, the use of different cork derived products in several solar energy technologies and applications is also assessed and discussed. Cork is a sector where solar energy may be used in various ways and cork material could be a component in various solar energy systems/devices, increasing its domain of applications.

Keywords: Solar energy; Cork; Cork processing; Solar heat for industrial processes; Cork agglomerates; Solar drying

1. Introduction

Solar energy can meet several industrial and forestry energy demands in several ways, *e.g.* electricity, steam, direct heat, hot air, hot water, etc. In addition to photovoltaic technology for electricity production, there are three groups of interest in the field of solar thermal technologies: solar water systems, solar air collectors and solar concentrators [1]. In water systems, for temperatures up to 250 °C, flat-plate collectors (FPC) or evacuated tube collectors (ETC) can be used [1]. The main systems for thermal concentrators, usually for temperatures up to 400 °C are the parabolic trough collectors, linear Fresnel collectors and parabolic dish collectors [1]. Solar dryers use natural-circulation or forced-convection equipment [1].

Solar heating technology collects the sun's thermal energy and transfers it into a heat transfer fluid. In indirect systems, the heat transfer fluid passes through a heat exchanger and warms the process fluid [1]. For continuous processes, energy storage has to be considered as well as adequate control systems. Costs are changing every day with a trend for a sharp decrease in several technology fields. Two important references on solar heat are [2,3].

This paper aims to foresee several possibilities of solar energy technologies utilization in the cork sector. As cork is produced and processed in regions where solar radiation is high, this sector can be a good example of solar energy application in forest based systems. Besides this, the objective is also to discuss the possible uses of cork products in solar energy equipment and technologies.

Until now only water thermal solar heating for cork boiling has being used as an auxiliary heating method in very few cork processing units. Following, this cork processing is described together with several solar based technologies that can be foreseen for the different forest and industrial processes.

Cork products were not also being used, until now an at an industrial level, in solar energy systems, but some studies were carried out and are going to be described as well as some other applications.

Although there were some studies on a few aspects dealing with solar energy and cork, a global approach like this was not done before. So, this paper intends to contribute to this discussion and to explore ways of using solar energy in cork processing as well as of using cork materials in solar equipment and systems.

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Fig. 1. Cork oak forest (by Jean-Pol GRANDMONT [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY 3.0 (https://creativecommons.org/licenses/by/3.0)], from Wikimedia Commons).

Fig. 2. Cork boiling steel tanks.

2. Cork: current production, processing and applications

Cork is a versatile raw material – the bark of a tree (*Quercus suber* L.) and one of the most important non-timber forest products – which adopts different technological transformation processes in order to be able to be used in different applications. Different cork raw materials (*e.g.* cork from forest and cork processing wastes) are used for different cork products. Cork processing to obtain the multitude of cork-derived products has several and different operational steps in which heating and thermal fluids are necessary (Fig. 1).

In the case of cork processing where heating must be carried out, the main steps are cork boiling in water (100 °C), cork stoppers drying (40–60 °C), agglomerates curing and agglomerated cork stoppers extrusion (120–150 °C) and also superheated steam (>300 °C) generation for insulation corkboard production. Other operations may also be envisaged, e.g. granulates drying, extruders heating, hot plates press heating. Besides this, electrical energy is also needed for powering all kind of electric equipment for cork processing. An integrated overall cork processing scheme can be seen in [4].

After harvesting (using axes or special debarking machines) and stabilization cork is taken to the factory where some defects are withdrawn and the first operation of boiling takes place. Cork industrial processing is usually divided in four main activities [5,6]:

1. *Preparation*: activity where the reproduction cork is selected and prepared through boiling, marking, cutting, selection and, sometimes, packing.
2. *Transformation*: activity to produce by carving or simply cutting a plank, a varied range of natural cork products (cork stoppers, disks, cork paper, handicrafts, etc.). This activity involves several different processes, namely separation of cork planks by thickness and quality, cutting, pre-drying, rectification, further washing and drying, selection, marking, finishing treatment, commercialization and dispatch. The wastes resulting from the cutting processes are feed to the granulation process.
3. *Granulation*: activity based on using the parings that result from the activity of producing natural cork stoppers and cork waste of an inferior quality. The production process is based on grinding and milling of cork wastes, which are then classified according to their volumetric mass and granulometric characteristics.
4. *Agglomeration*: activity which consists of agglutinating granulates and other kinds of inferior quality cork that through heat and pressure, are pressed or agglomerated in autoclaves with superheated steam.

More specifically [5] the process is as follows.

The boiling consists of immersing the cork, for approximately 1 h, in boiling water, in big metal tanks. The aim of this operation is to remove dirt, insects etc., to extract contaminating products, to decrease porosity and to render the planks flat, softer and more flexible, and thus easier to work. The boiling water is regularly changed (Fig. 2).

After boiling the cork, it is left to ripen in warehouses for days or weeks. Finally, the edges are cut to make the planks rectangular and a supervisor inspects and selects them according to thickness and quality (i.e. flexibility, homogeneity, color, evenness and natural defects). The best cork goes to stopper production and the remainder is used for agglomerates or other uses.

The rectangular planks are cut into strips with a thickness bigger than the diameter of the cork stopper and a width corresponding approximately to the height of the stopper. The corks are manually or automatically punched with a cutting rotating tube. After this, dimensional rectification of the obtained cylinders, such as ends trimming and control of height and diameter, is carried out.

The corks are classified in 4–6 categories (defined by the factories or the clients). The selection is made by visual inspection by qualified workers or by classifying machines (electronic optical reading or automated optical scanners programmed to select corks on the basis of pattern recognition).

Corks stoppers are treated by several means. The pores or lenticels are filled with a mixture of cork powder and glue (clogging process), to improve the surface appearance. Corks are usually washed (in tanks or automatic rotating machines), nowadays usually by a peroxide method. After washing the cork stoppers, these are centrifuged and dried in special stoves to a 6–8% moisture content. When the moisture level is lowered, the stopper performance is maximized and the microbial contamination is minimized. They can also be lubricated, *i.e.* being covered by a fine film of paraffin (solid, oil emulsion) or silicone, to facilitate cork stopper extraction and improve their sealing capacity. The surface of the cork stoppers can be marked with ink or fire before coating with paraffin or silicone.

In the case of cork disks, these are produced using the thinnest good quality cork. The planks are cut in small slabs from which the belly and the rasp are cut to obtain a clean slab of cork from which disks are punched and then dimensionally finished.

Waste cork from the stopper industry and low quality cork (refuse) and eventually virgin cork are used to produce cork granulates by grinding. These are separated and classified according to density and dimensions. These cork granulates can be used as a final product in several applications or used as raw material for the production of composition cork.

Floor and wall coverings made of cork are usually produced in the form of tiles, with different thickness and linear dimensions, densities and surface finishing. These are simply polished, waxed and varnished or coated with a vinyl layer. This last group may use a decorative sheet (cork or other material, *e.g.* wood) between the PVC and the agglomerate underneath. A cork layer associated *e.g.* to a MDF basis constitute floating floor coverings.

Composition cork is made of granules, which are joined together using different synthetic or natural binding agents. By using various binding agents and chemical additives it is possible to obtain materials for different requirements and purposes. The agglutination is usually made with rubber, urethane, melamine and phenolic resins etc. These products are usually produced in sheets, rolls or blocks, or even extruded or moulded.

To produce these products a mixture of cork granules and glue and/or other additives are put into a mold which is then closed and heated; heating is performed usually in a heating chamber at more than 120 °C and for some hours, in order to produce a block. This, even still hot or after cooling is then sliced into sheets, which are then dimensionally finished.

The granulation of cork for the production of agglomerated cork stoppers uses cork waste from the natural cork stopper production or material rejected at the stopper sorting stage.

Agglomerated cork stoppers consist of small pieces of natural cork bound together into a single stopper. There are simple agglomerated corks and two types of composite stoppers: the stopper for champagne and sparkling wine (head in agglomerate and two or more disks in the bottom); the "1 + 1″ stopper for the other wines (body in agglomerate and one disk at each end). The body or head of this type of corks is produced by techniques such as individual molding and extrusion. Simple agglomerate cork stoppers and champagne stoppers are usually edge finished. In the case of simple agglomerated corks, these may be cleaned and lubricated.

The production of corkrubber is similar to the rubber like products' production. The mixture of rubber and cork granules is done in mixing rolls and the mats obtained are introduced into a mold. The mold filled with the material is heated for binding. The molds are usually parallelepipedic (blocks) or cylindrical (cylinders). The blocks are sliced and the cylinders are cut to produce rolls. The duration of the heating process depends on the technique. It may take from several hours (in a typical oven) to some minutes (in microwave systems).

Fig. 3. Composition corkboard (by Elke Wetzig (elya) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons).

Insulation corkboard (ICB) is a product made of granules of cork (mainly winter virgin cork and other lowest quality types of cork) which is expanded (steam baked) in autoclaves and agglomerated together by pressure and temperature without any exogenous glue. The granules are placed into an autoclave, undergo light compression and then steaming occurs at more than 300 °C and about 50 kPa. Heat expansion represents an increase in cell volume of about 100% and so the granules are compressed against each other and in the boundaries the cells collapse and bind. The blocks formed are then cut into planks which are then finished (usually by sanding) as required.

Most of the other cork products are made by a similar process to the floor and wall covering cork products but include specific conditions or components (Fig. 3).

Cork fabric and paper, also known as cork leather or cork skin is produced from very fine laminated sheets of natural cork or agglomerated cork (usually with a thickness of 50–500 μm), which is glued on a textile or paper base. The grade of the backing varies depending on the use of the cork fabric.

Thus, cork is a natural material whose applications have been exploited since antiquity but has had a massive expansion, particularly due to the development of several cork based agglomerates [6]. Cork, worldwide known as the material of excellence for the sealing of alcoholic beverage bottles, is a natural cellular material that has also many other interesting applications [7]. Among these, new applications in solar energy equipment/systems are foreseen.

So, in these different steps several existing technologies using solar energy can be used due to the fact that cork production and processing are located in the southern western Mediterranean countries (Southwest of Europe and Northwest of Africa) where solar radiation is strong. Solar energy can also be integrated as auxiliary in traditional heating processes or be considered for integration with other renewable energies, as foreseen hereinafter (Fig. 4).

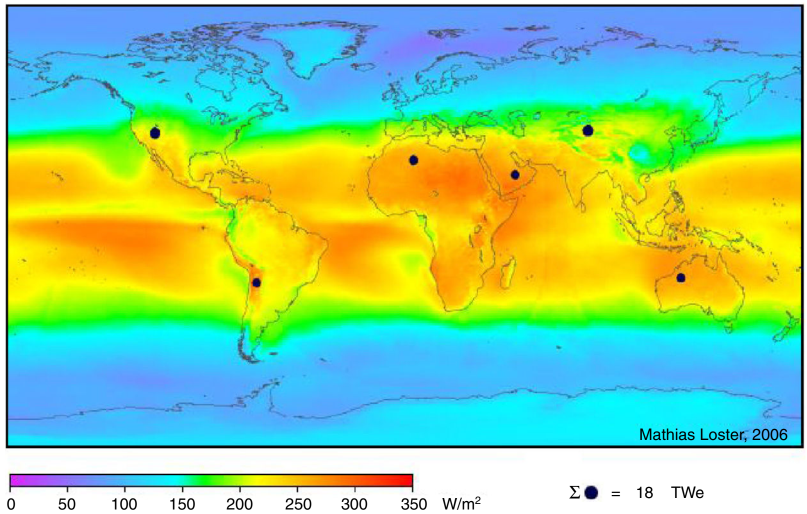

Fig. 4. Total primary energy supply from sunlight (by Mlino76 (http://www.ez2c.de/ml/solar_land_area/) [GFDL (http://www.gnu.org/copyleft/fdl.html), CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/) or CC BY 2.5 (https://creativecommons.org/licenses/by/2.5)], via Wikimedia Commons).

3. Solar energy in cork processing

In cork harvesting new mechanized tools have been developed for cork debarking [8]. These electric tools perform cutting operations and must have a power supply, *e.g.* through a decentralized electricity generation installation or batteries, since the work is carried out in open field away from grid electric power systems. In order to overcome this necessity, a PV portable system can be envisaged for battery charge or energy supply. This can also be used for other machinery as it is the case of chainsaws used in pruning or sanitary tree felling (Fig. 5).

As referred above, one of the first cork processing operations is cork boiling. One can consider, for example, a current cork boiling system based on a stainless steel rectangular tank with a water volume of 6-7 m^3 and working in the conditions mentioned in Table 1 [9,10].

In this case, considering the thermal solar energy as the main energy supply (with a possible secondary backup of different origin: electric power (*e.g.* PV), biomass of 350 kW) the use of solar compound parabolic collectors (CPC) having 120 m^2 of panel area (60 panels), would be sufficient [9,10]. A scheme of this system is shown in Fig. 6 [9].

Fig. 5. Photovoltaic system (by LG전자 (https://www.flickr.com/photos/lge/10845298325/) [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons).

Table 1
Cork boiling conditions (example 1).

Boiling operation	4 days/week (184 days/year)
Number of cork batches	5/day (8 h work)
Weight of cork	2 ton/day (24 500@/year)
Cork batches volume	1.6 m^3
Water replenishment	0.1 m^3/batch
Water temperature	99.5 °C

For the same operation, another example can be given, considering a system based on 70% of solar thermal energy and 30% of biomass secondary energy system (580 kW), for a larger capacity (2 × 21 m^3 tanks) based on Table 2 and Fig. 7 as follows [9].

As mentioned, these water boiling solar systems must have secondary support systems and one of the options could also be a biological process based on the upgrading (biogas) of an anaerobic digested flow. Cork boiling gives rise to an effluent named cork boiling wastewater (CBW) which is an aqueous and complex substrate. CBW contains suspended and dissolved solids and organic materials and has no utility, being a serious environmental hazard [4,11].

Another way of treating the effluent CBW or even the cork stoppers washing waters is based on a combined solar photo-Fenton/biological oxidation treatment [12]. The process uses solar radiation to accelerate the Fenton reaction and can use different types of solar photo-chemical reactors. A CPC pilot was used in this study showing that this is an efficient way for treating simultaneously both effluents. A similar process was previously studied [13] for solar decontamination of CBW reaching a removal greater than 50%, improving biodegradability and allowing the effluent for a final biological treatment in a traditional sewage treatment plant.

Solar kiln drying of cork raw material can also be used, namely cork material with excess of moisture [7] for example

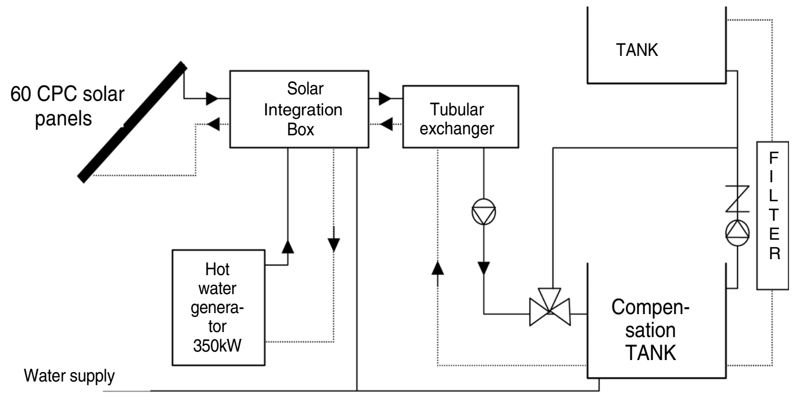

Fig. 6. First scheme of a solar cork boiling system.

Table 2
Cork boiling conditions (example 2).

Boiling operation	268 days/year
Number of cork batches	5/day (8 h work)
Weight of cork	100 000@/year
Cork batches weight	1.3 ton
Water replenishment	0.3 m^3/batch
Water temperature	99.5 °C

the so called “green” cork or even cork stoppers in intermediate or final steps to achieve the adequate moisture content. For these operations a kiln drying system based on direct solar heating, like the ones usually used *e.g.* for fruits drying or wood, can also be used, as cork drying must be slow to achieve the best results. A commercial hybrid system based on this was already developed [14].

For cork drying one can also foresee a kiln heating system with solar support through photovoltaic panels which supply the energy needed for the ventilation and control system of the installation, in order to regulate the temperature and drying speed for optimizing the drying process according to the environmental conditions and initial cork moisture. The idea is to avoid the excessive retraction of cork enabling its utilization for cork stoppers production. A prototype for this was proposed [15].

Another link between cork and solar energy can be the heating of water in order to produce steam (>300 °C) for the agglomeration of cork granules in the insulation corkboard (ICB) production. In this case the use of concentrated solar

Fig. 8. Concentrated solar system for steam production (parabolic trough) (by Masdar Official (Shams 1 Parabolic Trough in Abu Dhabi) [CC BY-SA 2.0 (https://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons).

technology is foreseen [7]. A thesis mentions a concentrated solar system based on a parabolic trough which was considered for pre-heating the feeding water for the boiler (which uses cork powder as fuel). The solar field was projected to produce water at 170 °C and 8 bar. With solar energy supply maximization the solar energy fraction could achieve 41% with a cost of 8.3 c€/kWh (Fig. 8) [16].

As it has been seen, for cork processing as a whole, heat and power are needed. So a combined generation based on, *e.g.* a concentrating solar collector field, considering thermal energy storage for continuous processes, could be considered, and a

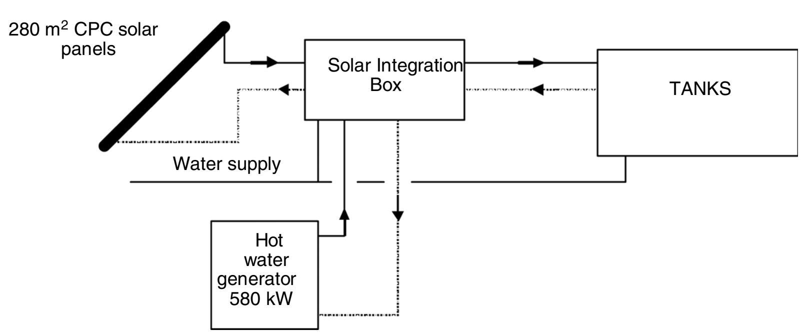

Fig. 7. Second scheme of a solar cork boiling system.

scheme for this could be as follows [1]. The auxiliary fuel is, *e.g.* biomass, like cork powder (the main cork waste). This system, for small industries, could be based on the AORA Solar Tulip [18] which is a modular hybrid concentrated solar system to produce electricity and heat with an output of 100 kW of electricity and 170 kW of thermal energy.

As mentioned before, cork powder is the main cork waste in cork processing, produced at different steps as cork grinding, cork punching, cork stoppers and cork agglomerates dimensional rectification (cutting, abrasion) etc. reaching *e.g.* 24.5–27.7% in weight of all the cork used for natural cork stoppers production [5]. One of the options for the valorization of this waste is its gasification through concentrated thermal solar energy (*e.g.* using a vortex flow, a packed-bed or an entrained-flow reactor) which allows the temperatures (>1200 °C) needed for the process of thermochemical conversion of this biomass in syngas. Liquid fuels can be obtained using the Fischer–Tropsch process with syngas or electricity can be produced using a fuel cell using syngas [17]. Either of these energy vectors can be used in several cork processing operations.

4. Cork in solar energy systems and applications

One of the possibilities of using cork in solar energy systems is the use of this material as a template to produce biomimetic ceramics based on ceria (CeO_2) for the production of hydrogen through water splitting using direct concentrated solar energy [19]. Novel ceramics able to withstand very high temperatures which are needed to split water for sustainable hydrogen generation were produced [20]. When cork is pyrolyzed at 900 °C the resulting carbon skeleton having a honeycomb arrangement is infiltrated with an aqueous ceria precursor and then re-heated at 1000 °C for at least 2 h to produce a ceramic material maintaining the 3D cork cell structure. However, the rear hexagonal walls are pierced (this feature does not occur in cork) and so, gases like hydrogen can permeate well into the structure. With this, the reactive surface available for catalysis is increased [19]. Based on this, a first set of experiments for hydrogen production using a thermochemical process in cycling studies with an experimental concentrated solar device showed a peak of hydrogen release of 0.14 ml H_2/g min (8.4 l/kg h).

A flexible extruded composition cork can be used for pipe insulation *e.g.* in thermal solar energy piping, due to its weather and ageing resistance when in outdoor [21]. In solar thermal collectors for producing hot water, part of the water piping is in the exterior, where the weather factors (UV radiation, rain, frost) or even biotic factors accelerate the pipe thermal insulator's degradation. This cork agglomerate pipe insulation is easy to handle and to apply, and it was also demonstrated as being very resistant to the weather action and decay, with low maintenance costs. This is also true for the piping (<200 °C) of other kind of hot fluids *e.g.* used in renewable energy systems [7,22].

Another product containing cork that can be used in solar applications is the so-called "projected cork" [23]. Composed by cork particles which are mixed with a polymer/binding material, usually *in situ*, this product is projected (spray-gun) directly into the surface to cover (it sticks well to any kind of surface),

Fig. 9. Example of a solar oven (not cork construction) (by Xuaxo [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], from Wikimedia Commons).

and has a work temperature range work of −165 °C to +165 °C. Due to its great elasticity, flexibility and mechanical resistance this material can be used to repair some defective insulating material previously existing. There is also the possibility to use this for insulating the reservoirs and/or piping of solar thermal collectors or other renewable energy systems which need to be impermeabilized and/or thermally and acoustically insulated [7,20].

Also worth to mention, for this type of applications, are the paints including cork particles for better thermal behavior [24].

Cork agglomerate was also tried, in some exploratory experiments, for the production of solar thermal collectors, constituting the collector body with thermal insulation capacities. Using adequate cork composites, it was possible to form, in a single step, the solar thermal collector body, incorporating some rigid and mechanically resistant support systems (*e.g.* metal frames) that allow the assembling of the collector. High diameter metal tubes which work both as water reservoirs and heaters are the foreseen technology for water heating [7,22].

A project also dealing with the binomial cork-solar energy is the SUNTASTE solar oven [25]. The prototype has a full body made of cork agglomerate which as structural strength and works as thermal insulator as an all-in-one. It allows the cooking and drying of food or even yogurt making (Fig. 9).

Another recent project called Slimframe PV & Cork Skin [26] aims at the development of a kit solution for façades consisting of a modular system with multiple functions and settings. The system joins the cork thermal insulator (ICB) with the photovoltaic glass (amorphous silicon), optimizing the thermal and aesthetic performance.

5. Discussion and conclusions

Several possibilities of utilization of renewable solar energy in the cork sector were proposed or described. The use of the existing solar technologies may have to be integrated and adapted to the particular features of cork processing. This is something that has to be studied in the future. For some enterprises rooftop or other spaces and financing aspects may be key barriers to achieve this.

The use of thermal solar heating for the cork boiling process must be widely implemented, opening doors to other uses of solar energy in the cork sector. Cork solar kiln drying should also be easy to implement. The study of ICB production using solar energy should be demonstrated at a pre-industrial scale.

Cork derived products are known as having a wide range of applications, and now some new applications in the solar energy field are being studied, were developed and/or can be foreseen based on the knowledge of their characteristics. Although some foreseen applications are at a laboratorial level (e.g. biomimetic ceramics) and must be scale-up, other can be widely used (e.g. pipe insulation).

Although the cork sector is undoubtedly a recognized sustainable sector, having in mind the cork production, processing and applications, the use of even more environmental friendly energy supply, will allow this sector to be one of the top in sustainability and low carbon energy domains.

So, cork is a sector were solar energy has several ways to be used and cork material can be a component in various solar energy systems/devices.

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