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A new hybrid ocean thermal energy conversion–Offshore solar pond (OTEC–OSP) design: A cost optimization approach

Paul J.T. Straatman, Wilfried G.J.H.M. van Sark *,[1]

Department of Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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Abstract

Solar thermal electricity (STE) generation offers an excellent opportunity to supply electricity with a non-CO_2 emitting technology. However, present costs hamper widespread deployment and therefore research and development efforts are concentrated on accelerated cost reductions and efficiency improvements. Many focus on the latter, but in this paper we rather focus on attaining very low levelised electricity costs (LEC) by designing a system with very low material cost, while maintaining appreciable conversion efficiency and achieving low maintenance cost. All investigated designs were dimensioned at a 50 MW scale production. Calculated LECs show that a new proposed hybrid of ocean thermal energy conversion with an offshore solar pond (OTEC–OSP) may have the lowest LEC of 0.04 €/kWh. Addition of a floating offshore solar pond (OSP) to an OTEC system increases the temperature difference in the Rankine cycle, which leads to an improved efficiency of 12%, while typical OTEC efficiencies are 3%. This higher efficiency leads to much lower investments needed for power blocks, while the OSP is fabricated using very low-cost plastic foils. The new OTEC–OSP design can be located in many sunny coastal areas in the world.

Keywords: Ocean thermal energy conversion; Solar pond; Solar thermal electricity; Cost optimization

1. Introduction

Solar thermal electricity (STE) is considered one of many options to supply energy to mankind in a sustainable and renewable way (Mills, 2000; WEC, 2004; Johansson and Turkenburg, 2004; Şen, 2004). Future scenarios on the renewable energy portfolio always include STE, albeit in a small role, for example contributing 1% to global energy supply in 2040 (EREC, 2004). This in part is due to present and future costs, which are hampering larger deployment of STE than currently envisaged. Therefore, as with all renewable energy technologies, research and development efforts are concentrated on accelerated cost reductions and efficiency improvements.

Conventional solar thermal electricity (STE) plant types collect solar radiation and convert emerged heat via a power cycle, like the Rankine cycle and a generator, to electricity, not being essentially different from a steam engine. The power cycle energy conversion is based on thermal expansion. A working fluid, or medium, is heated by solar irradiation and expands due to the existing temperature difference. This expansion results in an increase in pressure of a working fluid when it reaches its boiling point. This increase in pressure, if significant enough, is able to drive a turbine. After driving the turbine, the working fluid has lost a part of its total energy, but in order to condense into its original state it needs to be cooled down.

Many designs and types of STE plants are possible. The layouts differ in the methods of collecting solar radiation,

* Corresponding author. Tel.: +31 30 2537611; fax: +31 30 2537601.
E-mail address: w.g.j.h.m.vansark@chem.uu.nl (W.G.J.H.M. van Sark).
[1] ISES member.

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storing the heat, and the type of power cycle. Fig. 1 displays a general scheme of a solar thermal energy conversion plant. An STE plant consists generally out of three parts: (1) a solar ray collecting surface; (2) thermal storage; and (3) power cycle or thermal engine. The collector should be oversized to produce enough heat for night operation. To have a working process, a temperature difference over the cycle is needed. Mostly the collector provides elevated temperatures in comparison with the surroundings. Some designs have a coolant or cold source (i.e., seawater) to increase the temperature difference when the value of the provided temperature is not sufficient.

STE is a group of technologies that is inherently safe, as opposed to nuclear fission technology. Increase in safety, for instance, is an important indicator for environmental sustainability. Energy efficiency is considered a measure for economic appropriateness (Pitz-Paal et al., 2004). Reaching high efficiencies is essential for (fossil) fuel consuming power plants but not necessarily for STE plants. This is because in using these technologies, up to a certain level, one does not have to be sparing with solar energy ("fuel"); instead one should focus on the method of collecting the solar rays. In other words, efficiency may be less important than production costs of electricity. Therefore, it could be more interesting for renewable energy technologies such as STE and investors in these technologies to search for opportunities to lower levelised electricity cost (LEC, €/kWh) rather than to search for opportunities to increase efficiency.

Opportunities for lowering LEC may indefinitely add to the attractiveness of sustainable energy technologies for potential investors. In this paper, the key issue will be to search for a design of an STE plant such that it has an *economically optimal* efficiency instead of a *technologically optimal* efficiency. With an economically optimal efficiency we refer to a design that is optimized for the lowest production costs while having a certain thermal efficiency. This efficiency is most probably lower than the efficiency that can be reached with current state-of-the-art mirror collector systems; however, it is probably higher than efficiencies reached with ocean thermal energy conversion (OTEC) systems. A hybrid concept will be described that we found to evolve from optimizing systems in terms of their lowest electricity production costs: an OTEC-solar pond hybrid, where the solar pond (SP) is located offshore and has become a flexible floating structure of synthetic materials.

In the following we first will describe current STE technologies, OTEC plants, and solar ponds, in brief. This is followed by a conceptual description of a hybrid OTEC–offshore solar pond (OTEC–OSP) system and an estimated cost comparison between current STE systems and the hybrid system as we propose. Finally, conclusions are drawn, and recommendations for future work will be made.

2. Present STE systems

2.1. Concentrating solar power systems

Concentrating solar power (CSP) is a term for a group of STE technologies that use a reflective surface for concentrating solar irradiation on an absorber. The working principle is similar to that of a magnifying glass (Cavanagh et al., 1993). The absorber contains a medium which is heated to high temperatures between 600 and 1200 °C, depending on the technology. Thermodynamical energy conversion efficiencies are therefore high. Carnot efficiencies are theoretically about 66% and 80% for these two temperatures. For thermodynamic conversion a Rankine cycle with organic or water based liquid as working fluid in the primary closed circuit is often used (Straatman, 2006). The process fluid in the secondary closed system (which runs through the solar receiver tubes and transfers the heat to the primary circuit of the thermal engine) has to be liquid at the high operating temperatures, because thermal storage is often desirable. Molten salts and thermal oils meet with these conditions. As a heat sink, the surrounding air is used in a cooling tower. Much research on improvement of LEC for CSP technology already has been performed, see, e.g., (Pitz-Paal et al., 2004; Sargent and Lundy LLC Consulting Group, 2003; Cohen et al., 1999; Trieb, 2000).

Although many variants exist, CSP technology can be divided in the following main types, to show the variety in technologies that have been proposed and tested nowadays:

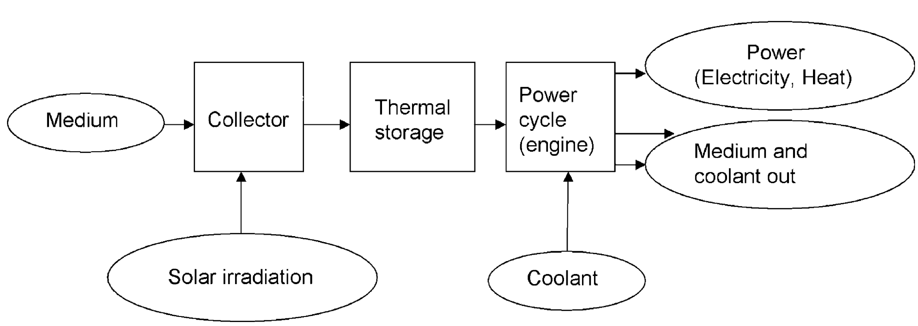

Fig. 1. General characteristics of a solar thermal plant.

(1) Parabolic trough technology's lay out is dominated by the use of parabolic mirrors that focus the solar rays on a tube (Mills, 2000; WEC, 2004; Wenslawski, 2003). Typical generated temperatures are about 400 °C with thermal oil as working fluid (Pitz-Paal et al., 2004).
(2) In parabolic dish technology the concentrator has the shape of a parabolic dish. Typical temperatures in the receiver are about 800 °C, with molten salts or thermal oils as working media (Pitz-Paal et al., 2004).
(3) Central receiver technology deploys a tank (receiver) wherein the medium is heated. Many flat mirrors (heliostats) reflect solar rays on the receiver. Typical temperatures in the receiver are 600–1200 °C, with molten salts as working media (Pitz-Paal et al., 2004; Wenslawski, 2003).

2.2. Ocean thermal energy conversion

OTEC plants (Takahashi and Trenka, 1992) are in fact solar energy plants, because they exist of a solar heat collecting surface (the upper layer of the ocean), thermal storage (the upper layer of the ocean) and a thermal power cycle that runs on a temperature difference. The heat sink, or coolant, consists of the lower, colder layers of the ocean. OTEC technology uses small temperature differences (about 10–30 °C), which makes it a relatively inefficient technology due to the second law of thermodynamics. Carnot efficiency would be 11% at a temperature difference of 30 °C. This low heat to electricity conversion efficiency is a disadvantage for OTEC deployment. However, electricity is not OTEC's only possible application. Other products that can be sold besides electricity are for instance: desalinated water, cold water supply for air-conditioning, refrigeration, and mariculture (Takahashi and Trenka, 1992; Daniel, 1993). The benefits of multiple products from an OTEC plant may thus well justify its presently high electricity costs.

2.3. Solar ponds

The working principle of solar ponds is based on the capture of solar radiation in a salt solution (Duffie and Beckmann, 1991). A solar pond is a pond filled with water that consists of three different layers of salt concentration solution. The bottom water layer is a concentrated (saturated) salt solution; the middle layer has a salt concentration gradient with decreasing salt concentration upwards. The top layer is fresh water. The bottom of the pond is a black solar ray absorbing foil surface. In a normal pond, solar heat will rise to the surface because warmer water has a lower density than its surroundings. In a solar pond, the density of the bottom salt water layer compensates for this effect and therefore there will be no (or very limited) upward convection of warm water. The result is that the solar pond will only be hot at the bottom and the heat is "trapped" in the bottom saturated salt water layer (Duffie and Beckmann, 1991).

There are some advantages and disadvantages of using such solar ponds or lakes as collector. As there are not many natural salt lakes on earth, widespread use is not possible. Also, most natural ponds, e.g., the solar lake at Sinai (Grant, 2007) or El Paso (UTEP, 2007) do not have a heat sink such as a cold-water OTEC pipe nearby, instead only the atmosphere could be used as coolant for the condenser. As advantage, however, there are no digging costs to create the lake shape. Also, no foil is needed at the top surface to contain water; hence material costs and foil welding issues are absent. Finally, a natural solar lake is part of nature already, so environmental impacts are no issue in this sense.

3. Ocean thermal energy conversion–offshore solar pond hybrid

3.1. Conceptual system description

The STE design presented here is denoted OTEC–offshore solar pond hybrid (OTEC–OSP) and is the result of our search for lowest possible costs designs for a STE plant. The plant design consists of the following process units (and cost parts):

(1) Power block for thermal conversion.
(2) Floating salt gradient solar collector of new proposed design to increase temperature difference and therewith reduce power block costs.
(3) Protective embankment of (probably artificial) shore for the floating collector.
(4) Cold water pipe to about 1000 m below sea-surface, to increase temperature difference and reduce power block costs.
(5) Sand filter to reduce overall collector maintenance costs.

The design can be visualized schematically as in Fig. 2. This plant might be situated in sunny coastal areas. The solar collector, embankment and cold water pipe are situated offshore and are connected to the power block and sand filter by means of pipelines. A schematic cross-section is shown in Fig. 3; the water flow is indicated from the left (cold) via the solar pond structure, where the water is heated, to the right (hot), where it is used for electricity generation. The power block and sand filter may be built on the mainland (or island). The generated electricity can be connected to the grid on the mainland. Assumptions of performance in this hybrid system are slightly dependent on local conditions and are based on measured performances of process units of which local conditions are known. For instance, the general performance of a solar pond is known, but depends on solar intensity. For other locations, the performance can easily be corrected for differing solar irradiation conditions, using for instance NASA's solar irradiation database (NASA, 2007;

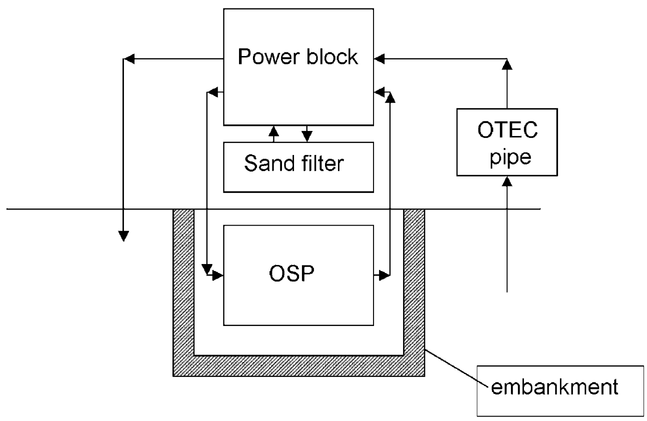

Fig. 2. Schematic top-view visualization of OTEC–OSP plant layout. Around the OSP, an embankment is situated. The power block and the sand filter are situated onshore.

Chandler et al., 2004). On the other hand, a difference in annual solar irradiation may have little effect on LEC, as long as the plant is built in tropical and desert coastal areas.

The OTEC–OSP plant outline is designed for construction at coasts in desert areas and tropical areas because of ample available solar intensity. It is a uniform outline, and the purpose of its design is that it can be built everywhere as it is, without much modifications. Therefore, no extra costs should have to be made to adapt for local circumstances. Interestingly, the costs could be reduced even further at locations where natural solar lakes exist and if at such locations electricity demand would warrant building of (new) generation capacity.

Conceptually, this design is a hybrid between an OTEC electricity plant and an offshore solar pond electricity plant. The principles and working conditions of the process units themselves therefore are not new and can be considered "proven" technologies, except for the floating solar pond. This has the advantage that working conditions, process conditions and production of the units are well known from existing literature and practical experiences. One exception is of course the layout of the solar pond, which is not constructed on the mainland, but is slightly adapted for floating on sea (surface) water. The advantages of such a collector construction (Figs. 2 and 3) are:

(1) Marginal land costs.
(2) No digging and soil preparation costs.
(3) Collector design allows for construction on many locations.
(4) Leakage risk reduced due to the design, which ensures that welds or attachments are above water surface.
(5) Water surface disturbances reduced by the construction as the collector shape adapts to water surface, because of its inherent flexibility.
(6) No dependence on local salt delivery and related costs because the pond is designed to be self-sustaining in concentrated salt by means of natural evaporation of seawater.
(7) Leakage of concentrated salt water to the sea is undesirable, but if it occurs, it is firstly isolated from the environment by a first containment: the embankment. Secondly, concentrated salt-water leakage on small scale into the ocean is not expected to be an environmental problem, however this may be subject of further research.

In some cases it might be necessary to protect the construction from waves and ocean currents, because the collector floats on water. Therefore a protective embankment is included in the design. One way of constructing a low-cost embankment is by means of coastal recovery or land gaining. Coastal recovery has been tested in areas where coastal erosion occurs. Beaches are restored by pumping up sand from the bottom of the sea to the desired location for coastal recovery. There is an extra argument in favour of coastal recovery in areas where people (and their homes) and infrastructure suffer from coastal erosion and where it is too expensive to perform coastal recovery. When an embankment is created for protection of a collector, it also protects the shoreline from erosion.

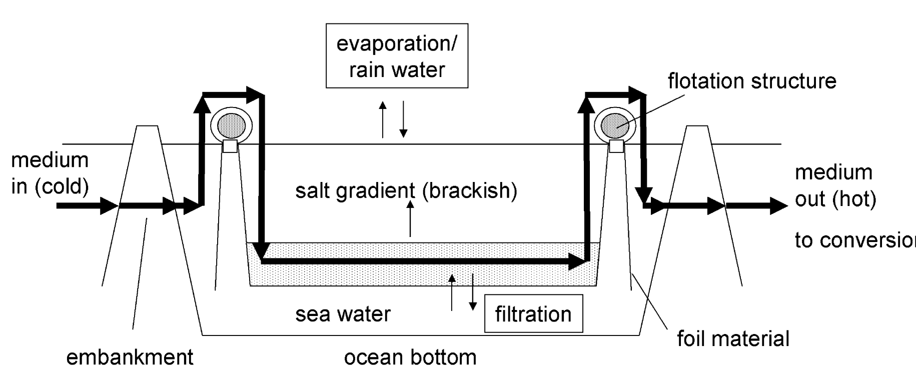

Fig. 3. Schematic cross-section showing the water flow from the left (cold) via the solar pond structure, where the water is heated, to the right (hot), where it is used for electricity conversion.

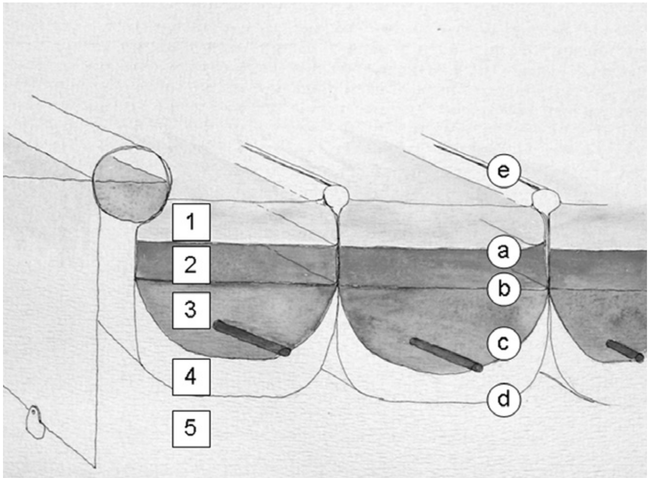

Fig. 4. Artist impression of a cross section of the proposed floating solar pond. Marks 1–5 refer to water layers of different salt concentration; marks a–e refer to different foil layers, see text for further explanation.

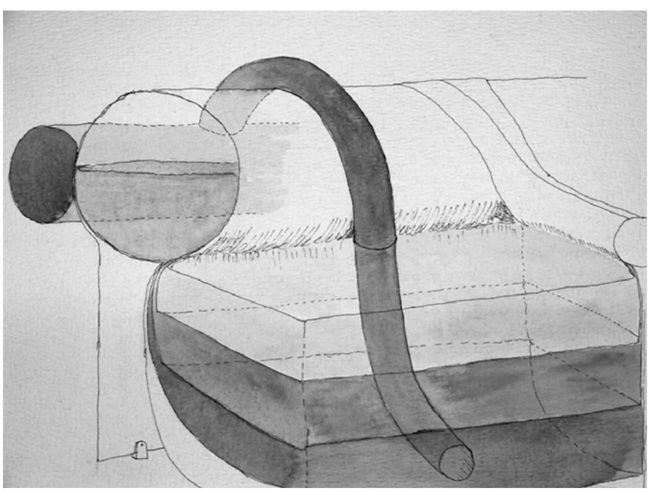

Fig. 5. Artist impression of a side-view of the proposed floating solar pond.

3.2. Floating solar pond

An impression of a detailed cross section of the proposed floating solar pond is shown in Fig. 4; a side view is shown in Fig. 5. The solar pond is designed for flotation on water. It therefore floats on tunnel-shaped plastic foil floating devices (mark e in Fig 4). These floating pipes support a structure of plastic foils (a–d), which are attached together above the water surface by means of for instance rope or thermal welding (e). The pond consists of four foil layers (a–d). The foil layers separate layers of water with different salt concentration and temperature. The uppermost plastic foil (a) is transparent and secures the concentration difference between the middle (dark grey coloured) brackish water layer (2) and the upper (light grey coloured layer (1)). The upper layer (1) functions as a salt concentrator if maintenance of salinity gradient is needed. During periods of drought and sun, the upper water layer (1) may therefore consist of seawater that evaporates into air. When a storm or rain is expected, concentrated salt water (1) is transported to the lower concentrated salt layer (3) to sustain the salt gradient. When it rains, the upper layer (1) will consist of sweet or brackish water. The second transparent plastic foil from above (b) separates the middle water layer (2) from the lower water layer (3). The concentrated salt solution has a higher density than its surroundings and therefore exerts a small downwards pressure on the foil. The density gradient induces heat accumulation in the lowest water layers (3 and 4), preventing heat to rise to the surface by means of convection. Because in a downward salt gradient the convection will not be upward but will be downward (2). Now the only mechanism of upward heat transport is conduction. The water underneath the hot concentrated salt-water layer (4) is of uniform salt concentration. This has upward convection. Upward convection and downward convection meet at the border-layer between the concentrated salt layer and the underlying water (b). This way sunlight is trapped in the salt-water layer (3) and the water underneath. This water layer (4) is heated and due to that expands in volume depending on solar intensity; this layer functions as hot water storage. Heat leakage downward causes seawater to rise in temperature; it therefore decreases in density in proportion to the surrounding water and attempts to rise. It forms an isolating hot blanket under the collector. The hottest zone consists of the concentrated salt water layer and the isolating hot blanket under the collector (5). The hot blanket (4 and 5) is prevented to rise to the water surface at the edges, by means of plastic foil walls. Ocean current under the collector should be reduced, which can be established by the embankment (see Fig. 2).

An ideal situation is reached in terms of low LEC when a solar collector and a thermal storage (solar pond) are of low costs and have a high and stable heat output. The use of plastic foils ensures low equipment cost. Preferably the pond should be located in a sunny area for optimal production. Also frost damage should therewith be avoided. Welds should be above water level to reduce leakage risk (see mark 'e' in Fig. 4). The floating pond is constructed mainly from heat resistant plastic foils, which are able to withstand a long-term load of 100 °C. The plastic construction materials are protected from ultraviolet radiation by coating the parts above water level (e) with a UV coating, which is resistant to corrosion. UV light does not penetrate deep in water, therefore mostly parts above water are coated with either UV blocking foil or aluminium foil, which is resistant to the corrosive environment and low priced.

4. Cost comparison of OTEC–OSP hybrid with existing STE approaches

4.1. Cost calculation method

The levelised electricity cost is defined as the sum of all costs that an investor makes in a particular electricity generating technology to produce one kWh. The gross profit per kWh of an investor is his selling price minus LEC. To calculate the electricity production price, the following equation was used, in line with Pitz-Paal et al. (2004):

$$LEC = \frac{crf * C_{\text{invest}} + C_{\text{OM}} + C_{\text{fuel}}}{E_{\text{net}}} \quad (1)$$

in which LEC is the levelised electricity cost (€/kWh), C_{invest} the total investment costs (€), $C_{\text{O\&M}}$ the operation and maintenance cost per year (€/year), C_{fuel} the fuel cost per year if natural gas is used for cogeneration (equals zero for the OTEC–OSP), E_{net} the net produced electricity per year to the grid (kWh/yr), and "crf" is the annual capital recovery factor, which is calculated as follows (Pitz-Paal et al., 2004):

$$crf = \frac{k_{\text{d}}(1+k_{\text{d}})^n}{(1+k_{\text{d}})^n - 1} + k_{\text{insurance}} \quad (2)$$

in which k_{d} is the annual real debt interest rate (8–10%), $k_{\text{insurance}}$ the annual insurance rate (1%), n the depreciation period in years (30 years).

4.2. STE system description and assumptions

In this study a comparison is made between several STE options and thermal power plant construction scenarios. To estimate kWh prices, certain assumptions have to be made. Each scenario was assumed to have a power block with a capacity of 50 MW. The year load or capacity factor is 90% of the time. Grid losses are assumed to be 5%. The annual capital recovery factor is 11.6%, using an interest rate of 10%. Other assumptions are detailed in Table 1. The total investments are displayed in Table 2. For further details, see Straatman (2006).

In this study the power block investment was strikingly diverse per construction scenario, as is apparent from Table 1. This investment depends on many factors that relate to the specific working conditions that answer to the needs of the plant design. The power block costs depend on the temperature difference (dT) over the power block and the size of the power block in MW (Rafferty, 2000; Vega, 2002/2003): the larger dT the lower the specific investment and the larger the size the lower the specific investment.

The power scale is set to 50 MW for each scenario, and only the dT has the most influence on the investment of the power block, besides pumping losses. Because dT has the most effect on the specific investment of the power block in the lower temperature difference range due to a logarithmic descending in cost versus dT (Rafferty, 2000; Vega, 2002/2003), an enormous cost advantage can emerge from improving STE plants by increasing dT with 50–80° from the low temperature range (dT = 20 °C) to a lower middle temperature range (dT = 70–100 °C).

It was estimated (Straatman, 2006), using the method described above and following Pitz-Paal et al., 2004] that 7.5 million € for fuel per year is needed for a 50 MW coal plant. As operation and maintenance cost for the power block 2 million € per year is estimated. The total annual expense thus is 9.5 million €. Note that this is higher than the annual expenses of the other scenarios, which consists only of operation and maintenance costs.

The estimation of the costs of artificial shoreline for protection of the floating solar pond structure in the new OTEC–OSP scenario is based on a report of the foundation LWI (LWI-TNLI, 1998). In this report, a multipurpose assessment is made for (among others) the costs of the construction of an artificial island. Due to the size of the collector in the OTEC–OSP scenario, the total length of this embankment has to be 12 km with an estimated investment per meter of 1250 €. This investment is added to the investment of this scenario.

The uncertainties are derived according to error propagation theory. The uncertainty of the kWh price of the OTEC–OSP hybrid is low compared to the other scenarios because the level of detail of the estimation of the kWh price in this scenario is much elaborated. For further details we refer to Straatman (2006).

Table 1
Summary of scenario assumptions for thermal plant scenarios with 50 MW power block

	CSP	OTEC	Land pond	OTEC–OSP	Coal plant
OTEC pipe vertical length (m)	0	1000	0	1000	0
Estimated price of OTEC pipe (€/m)	0	500	0	500	0
Price per installed kW of Rankine cycle (€/kW)	800	8000	4000	1060	800
Estimated collector investment (million €)	91	0	38	24	0
Installed power after estimation of pumping losses (MW)	50	52	52	52	50

Table 2
Summary of results of **kWh** price estimations

	CSP	OTEC	Land pond	OTEC–OSP	Coal plant
Investment (million €)	176	500	294	110	48
Production (million kWh/year)	125	375	375	375	375
$C_{\text{O\&M}}$ (million €/year)	4	7	5	3	2
C_{fuel} (million €/year)	0	0	0	0	7.5
Collector area (km^2)	0.5	Sea surface	25	10	0
Estimated temperature difference over Rankine cycle (°C)	400	20	40	76	400
Theoretical thermal efficiency (%)	33	3	7	12	33
Estimated kWh price (€cent/kWh)	19	17	10	4	4
Uncertainty (€cent/kWh)	6	8	3	1	2

4.3. Results

Technical and economical characteristics of existing STE plants are compared with the characteristics of the new OTEC–OSP scenario in Table 1, and as a reference also with a fossil fuel fired thermal power plant. Therefore characteristics of a typical coal plant are also given (Straatman, 2006). Table 2 shows a summary of results of kWh price estimations. It can be clearly observed that the OTEC–OSP scenario has the lowest investment between all STE scenarios. Due to the increased thermal efficiency compared to OTEC by the low cost OSP collector, the power block costs are reduced enormously. Power block costs dominate the total investment.

The OTEC–OSP design has also the lowest operation and maintenance cost. This is due to the fact that operation and maintenance are mainly determined by maintenance cost of the power block and collector maintenance. The larger and/or more expensive the power block, the more related maintenance should be allocated to the power block. The OSP collector is maintained by the sand filter, which costs are part of the (low) total investment. The annual electricity production is high because unlike the CSP scenario, the OTEC–OSP scenario produces electricity both day and night. The low investment, low operation and maintenance costs and a high annual electricity production lead to low electricity costs of the OTEC–OSP design. The new OTEC–OSP design has the lowest kWh price of all STE scenarios.

Generally, one could say that the fuel costs of the coal plant are replaced by the collector investment of the OTEC–OSP scenario, because the collector is relatively low priced. Therefore, after estimating the electricity prices of the coal plant and the OTEC–OSP plant we conclude based on these kWh prices the OTEC–OSP is cost-competitive with the conventional coal-fired power plant.

5. Conclusion

In focusing on the reduction of LEC instead of increasing conversion efficiency we have proposed a new hybrid design of an OTEC system with an offshore solar pond: OTEC–OSP. We do not claim that the proposed design in this paper is the one and only possibility for generating low priced solar electricity. Nevertheless, the following aspects were found to be of considerable influence on the LEC.

(1) The designer should avoid maintenance costs as much as possible. Therefore the collector should be designed as is shown here (sand filter for cleaning the solar pond instead of manual glass washing labour as is the case with mirror collectors).
(2) A collector should be constructed in such a way that it consists out of natural substances as much as possible. For example, the collector in this design consists mainly out of seawater; the foils are only used to separate the different functional layers.
(3) Frictional losses in the system need to be as low as possible. Investments needed for the reduction of friction losses are often much lower (with elevated OTEC–OSP temperatures) than the benefits lost due to the loss of electricity over the years. As an example, expanding the diameter of the cold water pipe and over dimensioning of the sand filter are measures to reduce the pumping losses enormously for a relatively low investment.
(4) When designing these plants, the first step should be an evaluation of a site on suitability for construction.

Based on the results, we deem it possible that a solar thermal electricity plant can be designed, which at present is able to compete with fossil fuel fired thermal electricity plants in terms of LEC. To be able to come to a successful working plant, several steps have to be taken. Firstly, the design has to be tested on a small scale in a pilot plant. The conceptual design is also very general with regard to location of construction. Probably, the design must be altered somewhat to deal with local conditions. Finally, potential designers should be aware of the relatively large collector surface compared to collector surfaces of concentrating solar power of the same scale. This may lead to local environmental problems that have to be assessed before construction of the OTEC–OSP hybrid.

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