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EXECUTIVE SUMMARY

Very efficient systems which use municipal solid waste (MSW) for the generation of power and district heating have been put in place in the more progressive cities in the northern hemisphere. Particularly in Northern Europe, these Energy from Waste (EfW) technologies are widespread and state of the art. However, in countries south of the Mediterranean as well as on the Arabian Peninsula, waste is landfilled and the energy supply relies predominantly on fossil fuels. This paper presents concepts which demonstrate the benefits of combining Energy from Waste systems with Concentrated Solar Power (CSP). These kinds of hybrid power plants achieve two goals: dumping of waste is avoided and sustainable electricity is generated.

INTRODUCTION

In times of global warming and shortages of resources, the importance of renewable energies is on the rise. Especially solar power, which is a free, unlimited and clean source of energy, is a promising technology. The combination of Energy from Waste systems with Concentrated Solar Power is of interest with respect to:

- **Technical features**: Similar water-steam cycles with relatively low steam parameters. The combination of EfW and CSP on one site is economical as both systems make use of the same power-producing equipment.
- **Flexibility**: The lack of solar power at night can be compensated with energy generated from waste.
- **Financial viability**: Relatively high investment is required for both EfW and CSP, but free fuel will be available for several decades.
- **Sustainability**: A viable solution for waste disposal at the location of the plant is guaranteed, even if the electricity is exported.
**State of the art of CSP**

Concentrated Solar Power (CSP) technologies use the sun's heat to produce electricity. Radiation is concentrated by mirrors on an absorber containing water or a heat transfer medium (HTF) like gas or thermo oil, which is heated up. The heat can be fed into the water-steam-cycle of a power plant.

Many factors must be taken into consideration in the planning of a solar thermal power plant. The location plays an important role with respect to the economic efficiency, because the required radiation can only be achieved in high solar resource regions like the Mediterranean, North Africa, California or the Arabian Peninsula. Furthermore, infrastructure and political issues such as feed-in tariff are important criteria. The sun is only available during the day and its radiation intensity is heavily dependent on the time of day and the seasons. Continuous operation of a solar thermal power plant necessitates thermal storage to guarantee the heat supply at night or when it is overcast. The combination of a solar thermal plant with a conventional power plant constitutes a reasonable alternative to thermal storage. Additional energy can be provided by the combustion of gas, coal, biomass or other alternative fuels in such a hybrid power plant.

Combining a solar thermal power plant with a waste to energy facility (EfW) can contribute to environmental protection by providing clean electricity and solving waste problems simultaneously.

**Parabolic Trough Power Plants**

This purpose of this work is not to compare or to analyse the potential of the latest technologies. The main focus of this research is to study the possibilities of supported solar and/or combination EfW plants: only established technologies with a history of long operation times will be considered. Of all the available technologies, parabolic trough power plants are at the forefront with the largest number of installed commercial plants. Some of these plants have been operating since the 80’s.

![Figure 1: Parabolic trough collector in Spain (Thomé-Kozmiensky 2009, p. 403)](image)

In parabolic trough power plants, solar radiation is concentrated on an absorber pipe (containing an HTF) by rows of parabolic trough collectors. The pipe is installed along the focal line of the mirrors (Figure 1). The mirrors are always oriented towards the sun by a uniaxial hydraulic tracking system. Thermo oil is a common HTF, though it can only be heated up to temperatures around 400°C because of its temperature resistance. The HTF is heated up in a primary loop by the parabolic trough collectors. The hot thermo oil passes through the heat exchanger where the water of the secondary loop, which is the water-steam-cycle of the power plant, is preheated, evaporated and overheated. Steam parameters are limited to circa 370°C and 100 bar by the thermo oil temperature (Tzscheutschler 2005, p. 9).
As is the case in a conventional power plant, the steam is expanded in a turbine to produce electricity (Thomé-Kozmiensky 2009, p. 414ff).

Higher steam temperatures up to 500 °C can be reached by direct evaporation of water in the parabolic trough collector field. Water is heated directly, evaporated and overheated by the sun, no HTF loop is necessary, thus simplifying the power plant design. Due to instationary conditions in the solar field depending on weather and time of day, difficulties are posed by heat transfer and density changes in the two-phase-flow in the absorber pipe. Although direct evaporation is a promising technology, it is not state of the art as yet (Pitz-Paal 2008).

Parabolic trough power plants reach capacities ranging between 10 and 1000 MW. The first commercial parabolic trough power plants were built in the Mojave Desert in California (USA) between 1984 and 1991 by LUZ International. Altogether 9 power plants called SEGS I-IX (Solar Electric Generating Systems I-IX) with capacities from 14 to 80 MW were constructed. All plants are still operating economically with a total capacity of 354 MW (Mohr 1999, p. 44ff).

**Further CSP Technologies**

Fresnel collectors are a low-tech alternative to parabolic trough collectors. Rows of uniaxial tracking mirrors focus solar radiation (by a secondary concentrator) on an absorber pipe which is installed centrally above the collector field (Figure 2). Water is heated and evaporated directly in the absorber pipe; the saturated steam with temperatures up to 270°C is fed to the turbine. Notwithstanding the higher optical and heat losses which reduce the efficiency of Fresnel collectors, they are a reasonable alternative to parabolic troughs since they require less technical expertise and consume less water (Thomé-Kozmiensky 2009, p. 404f). Further developments aim at increasing steam temperatures to over 400°C.

![Figure 2: Fresnel reflector system, secondary concentrator with absorber pipe (Thomé-Kozmiensky 2009, p. 404)](image)

The first commercial Fresnel power plant Puerto Errado 1 (PE1) was designed by NOVAL BIOTECH in southern Spain and went online in March 2009. A second plant (PE2) is still under construction. PE1 is a demonstration plant with only 1.4 MW capacity, PE2 achieves 30 MW with a collector surface of 302 000 m² (NOVAL BIOTECH 2010).

Another CSP technology is the solar tower power plant which is based on a point focus system rather than a line focus system. Biaxial tracking mirror planes concentrate the radiation on a receiver which is installed on top of a tower (Figure 3). Depending on geographical location of the plant, the mirrors are arranged in a circle (equatorial regions) or in a semi circle around the tower.
The radiation energy is absorbed by an HTF (molten salt or air) in the receiver and transferred to the water-steam cycle of the power plant via a heat exchanger. Water can also be directly evaporated in the receiver. Because all the energy is focused in one point, high temperatures between 300°C and 1000°C can be reached. Electricity is generated by a steam turbine. A solar tower combined with either a gas turbine or a combined-cycle plant is currently being tested to increase efficiency up to 20-23% (Thomé-Kozmiensky 2009, p. 406).

In addition to several research facilities there are two commercial solar tower power plants in operation worldwide: PS10 and PS20. The demonstration plant PS10 went online with a capacity of 10 MW in March 2007 in southern Spain. PS20 (located next to PS10) which is the biggest solar tower power plant in the world started operation in April 2010 with a capacity of 20MW. Both plants were designed by Abengoa Solar (Abengoa Solar 2009).

**METHODS**

The hybrid power plants were modelled with IPSEpro (registered trademark of SimTech GmbH) version 4.0 software. In order to simulate the different load states caused by varying intensity of solar radiation, the solar-generated steam mass flow was increased from zero to a maximum value in even-paced intervals. The ensuing process parameters and electric power were recorded. Since the focus of this study is solar-supported EfW plants and not vice versa, continuous, full-load operation of the EfW plant over the whole year was assumed. The maximum solar-generated steam mass flow was fixed to equal the steam flow generated by waste combustion. This boundary condition was defined in order to avoid extreme part-load operation of the turbine during non-daylight hours. The resulting electric power for any solar heat input can be interpolated with these data.

A programme was developed for site selection and the dimensioning of the solar field. This programme is able to calculate the heat output of the solar field depending on geographic coordinates, solar altitude and weather. The underlying calculations are based on those of the SOKRATES-Project of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) (Trieb 2004). The measured values of direct normal irradiation (DNI) for optimal siting of concentrated solar power in the USA were taken from the National Renewable Energy Laboratory of the U.S. Department of Energy internet database ([http://www.nrel.gov/rredc/](http://www.nrel.gov/rredc/)). The DNI of Barstow (California, USA) from 1980 was used for the calculations presented here.
Depending on the maximal required solar heat, the programme calculates the size of the collector field surface and the heat output of the solar field (available in the thermo oil) over one year. The resulting load curve of the hybrid power plant can be interpolated with the data from IPSEpro.

Plants are investigated using varying solar field sizes. In this paper the extra amount of electricity generated and the plant efficiency is discussed.

The plant efficiency is calculated using the energy in the waste and the amount of heat supplied by the solar field and not the solar irradiation on the solar field.

\[
\eta_{\text{el,net}} = \frac{W_{\text{el,net}}}{Q_{\text{waste}} + Q_{\text{inputsolar}}}
\]

All known effects such as changes in the sun’s position, reflection, absorption and convective losses of the collector have been taken into consideration in calculation the field size.

The amount of electricity generated is expressed in terms of electrical yield, defined as electrical energy per ton of waste.

For this calculation a lower heating value of 10 MJ/kg of the waste has been considered.

\[
\phi = \frac{W_{\text{el,net}}}{m_{\text{waste}}} \left[ \frac{kWh_{\text{el}}}{t_{\text{waste}}} \right]
\]

**CASES STUDIES**

**Solar-supported air and water preheating**

In standard EfW plants the feed water is preheated to temperatures around 130 °C before entering the boiler. This is done by means of steam extraction. Steam is extracted from various stages of the turbine and condensed in the so-called regenerative feed water preheater where the feed water is preheated. Although the steam flow through the turbine and thus the electrical output is reduced, the cycle efficiency increases. The thermodynamic fundamentals behind this efficiency increase are described elsewhere (Strauß 2006; Knizia 1966).

Additionally steam extraction can be used to preheat the combustion air (preheating temperatures ~ 130 °C). In order to avoid corrosion, combustion air is preheated using steam instead of direct flue gas for temperature ranges below the flue gas dew point.

This first case study considers the possibility of saving the steam extracted during the day by means of solar feed water and air preheating. In this case the power output of the turbine could be increased without efficiency losses. Standard solar flat plate or vacuum tube collectors can be used for this temperature range (up to 130°C). The cycle considered is shown in Figure 4. The most relevant parameters are included in Table 1.

Live steam parameters are 380 °C and 40 bar and gross electrical output is 15 MW. Gross electrical efficiency of such plants is around 24 %. The EfW plant cycle considered has three turbine steam extractions: 10, 4.5 and 1 bar. The steam extracted at 4.5 bar preheats the combustion air to a temperature of around 120 °C. The second extraction (10 bar) is used for air preheating to around 150 °C. Steam extracted at 4.5 bar is also used for feed water preheating up to 130 °C and degassing. The 1 bar extraction preheats the feed water to 100 °C.
Solar collectors have been connected alongside existing preheaters. These collectors preheat the air and feed water and consequently the steam extraction valves can be closed partially during the day and when there is sufficient solar heat input. Short-term variations of the solar radiation can be regulated by means of the steam extraction valves. At night there are no steam extraction savings due to the lack of solar power.

Table 1: Air and water preheating parameters for the case of study

<table>
<thead>
<tr>
<th>Preheating Type</th>
<th>Steam Pressure [bar]</th>
<th>Steam Temperature °C</th>
<th>Steam Flow [kg/s]</th>
<th>Air Input Temperature °C</th>
<th>Air Output Temperature °C</th>
<th>Air Flow [Nm³/h]</th>
<th>Feed Water Temperature °C</th>
<th>Feed Water Flow [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT Preheating</td>
<td>10</td>
<td>220</td>
<td>0.3</td>
<td>40</td>
<td>100</td>
<td>61560</td>
<td>0.6</td>
<td>100</td>
</tr>
<tr>
<td>MT Preheating</td>
<td>4.5</td>
<td>150</td>
<td>0.6</td>
<td>100</td>
<td>130</td>
<td>61560</td>
<td>1.2</td>
<td>100</td>
</tr>
<tr>
<td>LT Preheating</td>
<td>1</td>
<td>100</td>
<td>1.5</td>
<td>100</td>
<td>130</td>
<td>50</td>
<td></td>
<td>17.7</td>
</tr>
</tbody>
</table>

Solar-supported live steam temperature increase

Cycle efficiency can also be increased by increasing the live steam parameters. The higher the pressure and the temperature is, the higher the efficiency. In EfW plants live steam pressure and temperature are limited by high-temperature corrosion. HT corrosion is the main factor responsible for the low efficiency of these plants compared to coal power plants (EfW ~ 21%; Coal ~ 46%). Nowadays standard live steam parameters in EfW plants are 380 °C and 40 bar. Results from this case study will be presented in further publications.

Waste-solar combined cycle

Standard parabolic trough power plants have water-steam cycles with relatively low steam parameters similar to those of EfW plants (370 °C, 100 bar). In this case study the combination of EfW and a parabolic trough power plant will be considered. SEGS VI; one of the nine solar plants in California’s Mojave Desert will be used as reference. The selection of
this plant was based on the large amount of operational data available. Its thermodynamic cycle is shown in Figure 5.

![Figure 5: SEGS VI parabolic trough power plant used as reference](image)

The steam cycle is similar to that of standard fossil fuel plants. Steam of 100 bar and 371 °C is produced in the boiler and expanded in a high pressure (HP) turbine. The expanded steam is reheated to 371 °C and expanded in the second turbine stage. The gross electrical output is 30 MW. Steam is condensed in a hybrid cooling tower and feed water is preheated to 230 °C before entering the boiler. The boiler consists of heat exchangers where the thermo-oil heated in the solar field (temperature 391 °C) is used to produce superheated steam of 371 °C. At night or in the absence of solar radiation, gas burners are used.

**Combination with standard EfW plant**

In this first approach the SEGS VI cycle will be combined with a standard EfW plant (Zella Mehlis). The cycle of this EfW plant has already been described above, see Figure 4. The combination of both cycles proposed in this paper is shown in Figure 6.

The lower part of the figure shows a standard EfW. The solar plant is represented in the upper part. The low pressure (LP) turbine, condenser, preheating to 130 °C and feed water tank are common to both cycles. The air-cooling technology from the EfW plant has been substituted by the hybrid cooling tower technology from the solar plant in the condenser. The feed water tank supplies water for both cycles. The waste boiler is fed directly with water from the feed water tank. This boiler produces steam at 40 bar and 380 °C which is expanded in the LP turbine.

In the case of the solar plant, the feed water is additionally preheated to 250 °C, like in SEGS VI. The solar cycle produces steam at 100 bar and 380 °C that is expanded in a HP turbine. The combination of solar energy and energy from waste as the energy input renders storage unnecessary. Consequently, the produced steam can have temperatures close to the working temperature of the HTF. The final pressure of the high pressure stage has been increased from 17 to 40 bar in order to adapt it to the EfW plant live steam parameters. The expanded steam is reheated to 380 °C in the solar cycle and conveyed into the LP Turbine. The additional preheating in this cycle is carried out by means of extracting steam from the HP turbine.
Due to insufficient information about the partial load behaviour of this kind of turbine, it was assumed that the HP turbine only operates if the produced steam flow exceeds 40% of the full load. In times of low radiation intensity (in the morning/evening or in winter) the HP turbine is shut down. The solar-generated steam is supplied directly to the LP turbine. At night or in overcast conditions when there is no solar heat input, power is generated by the combustion of waste only.

Combination with “newest generation” EfW plant

The second study will combine SEGS VI with a “newest generation” EfW plant (Amsterdam), with live steam parameters of 440 °C and 130 bar and intermediate reheating at 14 bar, see Figure 7. This energy concept was developed by AEB-Afvalenergiebedrijf Amsterdam and is used in the 2 newest EfW units with a waste processing capacity of 2 times 300,000 t per year. The combustion system and boiler were supplied by a consortium comprising MARTIN GmbH and NEM and were started up successfully in the spring of 2007. The gross electricity output of this plant is 66 MW and its gross electrical efficiency more than 30% (City of Amsterdam, Waste and Energy Company 2006).

Figure 7 shows the combination of both systems proposed in this paper. In this case the EfW plant itself has an intermediate reheater heated with saturated steam from the drum at 14 bar. The steam cycle is very similar to that of SEGS VI and thus both cycles can be connected in parallel. It must be considered that a live steam temperature of 440 °C in CSP plants is not state-of-the-art yet. However, research on increased live steam temperatures above 500 °C is in progress. Depending on the solar radiation available, more or less live steam is produced and reheating can be taken over by the solar field.
RESULTS AND DISCUSSION

Solar-supported air and water preheating

Figure 8 shows the annual electrical energy producible in a state-of-the-art EfW plant with solar-supported feed water and air preheating. The additional amount of electricity produced increases linearly with the size of the collector field and is in the range of 2000 MWh/a for a solar field of 10000 m² (1 ha). Compared to the electricity produced by the waste input, the energy produced by the solar input is rather low (<3 %). The changes in the plant scheme only affect the low-pressure turbine since the solar heat helps to reduce the amount of steam extracted at the various stages.

The net electrical efficiency presented in Figure 8 decreases as expected with bigger solar fields. Thermodynamically speaking, the substitution of regenerative feed water heat by imported heat reduces the efficiency of the process. The reason for this is that the heat from the solar collectors is supplied at a very low temperature: the exergy content is thus low, which implies that the heat added to the steam cycle increases faster than the additional electricity produced.

On the other hand, the electrical yield of the plant defined in the Methods, increases with the solar field surface. The solar support increases the electrical yield of the plant from 740
to 755 kWh$_{el}$/t$_{waste}$. The use of solar heat for preheating air and feed water could therefore be used as a retrofit option for EfW plants in sunny locations.

Figure 8: Produced electricity vs. solar collector area for an EfW plant with supported feed water and air preheating

Waste-solar combined cycle

Combination with standard EfW plant

The combination of a high concentrated solar field for producing high-pressure and high-temperature steam with an EfW plant supplies up to 33 % more electricity over the year, which is about 40000 MWh/a (see Figure 9). However, compared to the previous case, the solar field for this case ranges between approximately 50000 to 100000 m$^2$ (5 to 10 ha). This solar field size already corresponds to a small concentrated solar power plant. The additional power output increases linearly with the collector area up to a size of 80000 m$^2$. At that point the steam generation limit is reached (see Methods). Increasing the solar field further leads to a limitation of steam generation for more hours of the year. On the other hand, the turbine operates more hours at full load given bigger solar fields.

Figure 9: Produced electricity vs. solar collector area (left), net electrical efficiency vs. solar collector area (right) for a combination of a state-of-the-art EfW-plant

The combined efficiency increases with increased solar input since the turbine produces high-pressure steam which is used in an additional high-pressure turbine and then reheated to enter the middle-pressure turbine with the steam from the EfW plant. The diagram shows that electrical efficiency gains in the order of magnitude of 1-2 % are possible for solar fields of 50000 to 100000 m$^2$ (5 to 10 ha). The efficiency starts to decrease again from a solar field size of approximately 80000 m$^2$ (8 ha) since a solar field of this size produces heat in excess of plant consumption which is wasted. According to this diagram,
there is an optimal solar field size for each EfW plant conditioned mainly by the operation limits of the steam turbine(s). The electricity yield per ton of waste rises from about 780 to nearly 1000 kWh\textsubscript{el}/t\textsubscript{waste}.

**Combination with “newest generation” EfW plant**

Using a more sophisticated EfW plant already leads to greater electricity generation throughout the year, see Figure 10. Efficient use of solar heat becomes simpler since the steam produced by the solar field can be used directly in the high pressure turbine of the EfW plant. The additional electrical energy ranges are similar to the state-of-the-art EfW plant amounting to 40000 MWh/a. The solar field size required to achieve this energy is also approximately 80000 m\textsuperscript{2}.

The increase in efficiency is not as steep as the other case since the EfW plant is already quite efficient on its own and the solar part of the plant has no extra HP turbine. The decrease is again caused by the unused solar energy. The electricity yield increases from less than 900 to up to 1100 kWh\textsubscript{el}/t\textsubscript{waste}.

![Figure 10: Produced electricity vs. solar collector area for a combination of a “newest generation” EfW plant](image)

**CONCLUSION**

Two different methods for combining concentrated solar power with an EfW plant are discussed in this paper. The use of solar energy increases the production of sustainable electricity by an EfW plant. Using solar heat for preheating feed water and air leads to additional electricity generation requiring only small changes of the plants steam cycle and a small solar field. Therefore this option can be used as a plant retrofit in a sunny location. However, for a solar field of 0.5 to 1 ha the additional electrical yield is approx. 1 %. The second option is to combine a full-scale concentrated solar power plant with an EfW plant. State-of-the-art CSP plants operate at similar temperatures to EfW plants but use higher pressures with an intermediate reheat. For this reason some adjustments to the steam cycle would be necessary for a combination of the two types of plants. The amount of electricity produced by a combined plant in a favourable site increases by approximately one third, depending on the size of the solar field, which results in an additional electricity yield of about 200 kWh\textsubscript{el}/t\textsubscript{waste}.

From a technical point of view, it would be easier to combine a solar field with the steam cycle of an EfW plant which uses a high-pressure steam cycle such as the new block of the Amsterdam EfW plant. The additional electricity in this case would be the same as is the case in standard plants.
The combination of concentrated solar power with energy from waste plants facilitated a sustainable increase in electricity production using local resources. The case studies presented here show the benefit of a hybrid plant using both technologies, since they work on similar process parameters resulting in reduced investment costs. Solar waste hybrid plants should be considered by consultants and decision makers as an option for locations with high solar yields.

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