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INDUSTRIAL SOLAR PROCESS HEAT YIELD AND FEASIBILITY

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ABSTRACT

South Africa is situated in one of the highest solar irradiance regions in the world giving industries access to a substantial amount of alternative energy for their industrial process heat requirements. Industries often receive more solar energy on their premises than they need in their processes. With fuel and electricity prices increasing it means more and more industries are looking towards alternative energy solutions. The challenge is to design a system with the appropriate technologies and integration strategies to effectively access the available energy and apply it to the existing industrial process in a financially feasible manner.

In this study a solar thermal system yield and financial feasibility is applied to two case study industries which have different locations and energy demands. The objective was not to compare various technologies but rather to design a system for each application using appropriate technologies and to determine the solar yield, collector area, solar fraction, component cost breakdowns and payback period.

The results showed that it is possible to replace up to 60% of the energy demands through boiler preheating. For all cases the payback period was determined to be less than 8 years. Keeping in mind a typical 20 year life expectancy of a solar system and significantly lower cost of energy for solar energy makes these systems a viable alternative for industries seeking to reduce their fuel expenses, preserve their existing boiler equipment and reduce their carbon emissions.

NOMENCLATURE

a_1	[Km^2/W]	Linear heat loss coefficient
a_2	[K^{2}m^2/W]	Quadratic heat loss coefficient
C_a	[m^2]	Collector aperture area
C_p	[kWh/(m^{3}K)]	Specific heat
C_y	[kWh/m^2]	Collector yield
DNI	[kWh/m^2]	Direct normal irradiance
η_0	[-]	Maximum collector efficiency
η_c	[-]	Collector efficiency
η_s	[-]	System efficiency
G	[W/m^2]	Solar power
GHI	[kWh/m^2]	Global horizontal irradiance
GII	[kWh/m^2]	Global in-plane irradiance
IRR	[%]	Internal rate of return
$LCOE$	[R/kWh]	Levelised cost of energy
Q	[kWh]	Heat energy
SF	[%]	Solar fraction
S_r	[kWh/m^2]	Solar resource
SWH	[-]	Solar water heating
T_m	[°C]	Mean collector temperature
T_{atm}	[°C]	Atmospheric temperature
T_{st}	[°C]	Storage temperature
V	[m^3]	Water volume

INTRODUCTION

The number solar technologies are vast and have a wide range of applications. In this study solar thermal technologies are considered in the industrial context for replacing fuel demands with the aim of finding appropriate technologies and determining its feasibility. But why is solar thermal technology important for the South African industry?

The South African economy is highly energy dependent consuming 122.4 million tons of oil equivalent fuels every year [1]. The industrial sector uses approximately 40% of the country's total energy of which 66% is needed for process heat [2]. A large part of this heat is needed for processes under 300 °C where existing solar technologies can effectively and affordably be applied as alternatives. South Africa, therefore, has a great energy need in the temperature ranges appropriate for common solar thermal technologies.

The advantage of South African industries over the rest of the world is the abundance of solar resource and favorable climate for solar thermal applications. South Africa falls within one of the top five regions in the world for highest solar irradiance. This is highlighted when comparing global horizontal irradiance (GHI) of various cities around the world (see **Figure 1**). This comparison shows that Johannesburg receives more solar irradiance than many of the major cities of the world.

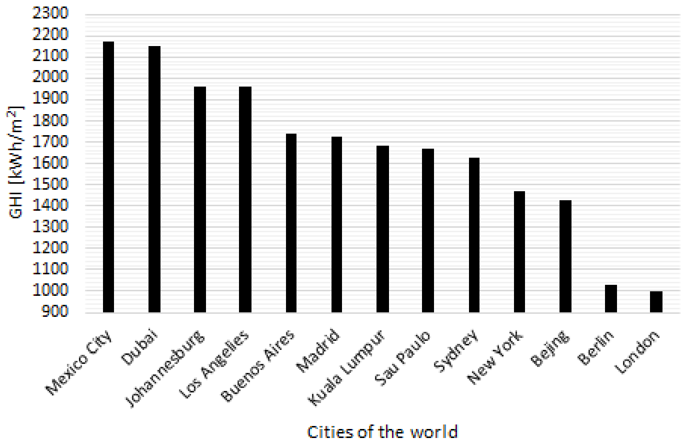


Figure 1 GHI comparison of major cities of the world (data from [3])

The warm climate and high solar resource in South Africa makes it possible for collectors to operate at greater efficiencies. Companies will, therefore, receive more income (savings boiler fuel) for the cost of the system. This in turn results in better payback periods and greater investment potential. Furthermore, an abundant solar resource makes it possible for companies to obtain larger solar fractions (SF) reducing their dependency on fossil fuels, carbon footprint and boiler loading. The advantage of solar thermal technology is its relatively high efficiency, especially at low temperatures, and that the energy can be stored effectively for short periods. For all these reasons solar thermal technology is an attractive alternative for industries in South Africa.

Even so the application of solar thermal technology in the South African industrial sector is still in its infancy. One contributing factor may be the country's abundant coal reserves which effectively makes the income through saving from the solar alternative insignificant and, therefore, not feasible. But not all industries make use of coal fired boilers. This is especially true for smaller industries who often avoid the large initial investment associated with coal fired boilers and instead resort to cheaper boiler but more expensive fuels that can benefit from solar energy.

But how can existing technology be applied to real industries and what is the predicted yield and feasibility of such as system? These are the main questions in this investigation. This paper presents the methodology followed to determine appropriate technology, the yield and financial feasibility of solar thermal systems for two industries.

SOLAR SYSTEMS

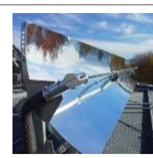
For the purposes of industrial process heat generation typical solar collector technologies can be seen in **Table 1**. The collectors can be divided into low temperature collectors, operating typically between 20 - 80°C, and medium temperature collectors, operating between 80 - 400°C.

Typically, the low temperature collectors are mostly flat plate collectors and evacuated tube collectors which are used for solar water heating (SWH) applications. These collectors make use of global in-plane irradiance (GII) which consists of direct and diffuse components. These collectors are considered mature technology, relatively affordable, robust and well known.

Medium temperature process heat collectors, on the other hand, can be used for steam generation. The higher temperatures are reached using concentrating collectors such as parabolic troughs and linear Fresnel collectors and, therefore, make use of tracking systems and direct normal irradiance (DNI). These systems are less common due to their complexity, associated costs and required open ground space.

The two industries investigated do not have nearby open ground space for free-standing collector fields and tracking mechanisms. Instead a roof mounted collector array is preferred making use of a split- or pumped system (unlike thermosiphon systems) where the storage is located below the collector array situated in or around the factory.

Table 1 Process heat collectors

Collectors	Description	Temperatures	Ref
	Flat plate collectors	20 - 80°C	[4]
	CPC	80 - 120°C	[5]
	High vacuum flat-plate	100 - 200°C	[6]
	Parabolic trough	150 - 250°C	[7]
	Linear Fresnel	100 - 400°C	[8]

A basic system diagram can be seen in **Figure 2**. It consists of a solar loop, charge loop and discharge loop. The solar loop absorbs solar energy through the collector array and transfers it to the storage tank using the charge loop. The discharge loop transfers the stored solar energy to existing systems and processes.

SYSTEMS SIZING

The dimensions of a SWH system depends on the water volume and temperature needed.

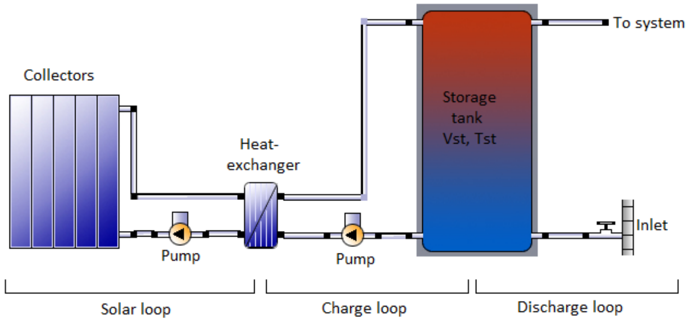


Figure 2 Solar system diagram.

If the volume of water is known, the amount of energy needed to heat the water can be calculated as:

$$Q = VC_p\Delta T = VC_p(T_{st} - T_{atm}) \quad (1)$$

In equation 1, Q is the required heating energy, V is the volume of water heated, C_p is the specific heat capacity of water (1.16 kWh/(m^{3}K)), T_{st} is the storage or hot water temperature needed and T_{atm} is the cold water temperature which in the two case studies was assumed to be equal to the average daily atmospheric temperature.

To determine the collector area required to supply the energy it is necessary to determine the collector yield, C_y, by considering the solar irradiance, S_r, the collector efficiency, η_c, and system efficiency, η_s as:

$$C_y = S_r\eta_c\eta_s \quad (2)$$

The system efficiency, η_s, refers to losses occurring in the proposed solar system between the collector outlet and the supply point. These losses are usually in the form of heat loss through the piping and storage tanks. Since these losses are unknown before the final design and installation the system efficiency is assumed to be 85% (15% losses through piping and storage).

The collector efficiency is dependent on the collector materials, solar power, incidence angle, water temperature inside the collector and atmospheric temperature. This can be seen in **Figure 3**. Optical losses occur due to reflection and absorption into the glass which determines the maximum efficiency, η_0. For this reason unglazed collectors will have a greater maximum efficiency than grazed collectors since there are fewer optical losses.

Other losses are attributed to heat loss to the atmosphere or mounting structure. As the water in the collector heats up more and more energy is lost to the atmosphere through radiation and convection. The lowest efficiency occurs when the collector reaches stagnation in which case all the absorbed energy is lost to the atmosphere. These losses are effectively countered using better insulation (reduce conduction losses), selective coatings (reduce reflection losses) and glazing (reduce convection losses) which effectively increases the efficiency of collectors at higher water temperatures.

The efficiency curve is determined by testing collectors at various inlet water temperatures and comparing the incident solar energy to the absorbed energy. From these tests the linear heat loss coefficient, a_1, and quadratic heat loss coefficient, a_2, can be determined which along with the maximum efficiency, η_0, characterises the performance of a collector.

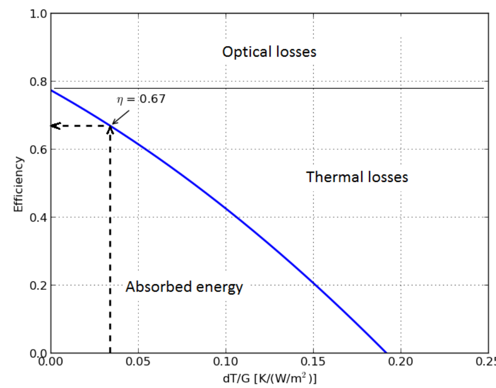


Figure 3 Collector efficiency curve

$$\eta_c = \eta_0 - a_1\frac{(T_m - T_{atm})}{G} - a_2\frac{(T_m - T_{atm})^2}{G} \quad (3)$$

With the heat requirements, Q, and collector yield, C_y, known the collector aperture area, C_a, can be determined as:

$$C_a = Q/C_y \quad (4)$$

FEASIBILITY INDICATORS

When dimensioning a system for industry it is equally important to consider the financial feasibility of a system. A high yield or SF system will not necessarily be economical and so not attractive to investors. Companies are highly cost and income motivated and often reluctant go through the effort to switch to new unfamiliar technologies if a there is no clear financial benefit.

To determine the most attractive solar system for the investor the designer needs to minimize the expenses and maximize the income from the system. Income from a solar thermal system is viewed as the money saved on boiler fuel. This means that the income from the solar system will increase with higher fuel prices and solar yield as well as lower boiler efficiencies. The expenses of the solar system is dependent on the initial investment, loan rates, maintenance and insurance premiums.

There are a number of financial indicators that play an important role in judging how good the investment in the solar system is. The first indicator is the internal rate of return (IRR) which gives an indication of what any investment could earn taking into account the time value of money. The IRR makes it possible to compare the investment to other completely different investments. Typically IRR values should be more than the loan rate. This means that systems with IRR values of 10% or higher are considered good investments worth investigating further.

Another indicator that is important to consider is the payback period indicating the time when the initial expense or loan has been reduced to zero from which point the system earns money over and above the initial investment. In Europe payback periods of less than 10 years for SWH systems with storage are very difficult to achieve without subsidies. In South Africa, with the abundance of solar energy, conservative estimates indicate payback periods of less than 8 years are possible for SWH systems with storage and less than 6 years without storage.

A good way to compare energy systems is with the levelized cost of energy (LCOE). LCOE is the sum of all expenses incurred over the lifetime of the system over the sum of all produced energy over the system life as:

$$LCOE = \frac{\sum(All\ expenses)}{\sum(Produced\ energy)} \quad (5)$$

LCOE makes it possible to compare the cost of various energy sources such as coal, paraffin, solar, etc. LCOE gives the investor the average cost of energy over the life of the system including increases in fuel prices and makes it possible to see if a technology will produce cheaper energy than the existing system without detailed investigations. Preliminary investigation have shown that the LCOE (including the investment cost of the system) of SWH systems is between R 0.52/kWh – R 0.60/kWh with storage and approximately R 0.35/kWh without storage.

Since most industries already have boiler systems in place which, in most cases, will not be replaced by the solar system, it does not make sense to include this cost in the LCOE of the existing boiler system. Instead, the LCOE of the solar system is compared to the LCOE of the fuel only. In other words, the LCOE of the solar system is compared to the average operating cost (for energy) of the existing system during the life of the solar system. The boiler efficiency also needs to be taken into account since it increases the price of the delivered energy. This LCOE of fuel serves as the income in the calculations.

Table 2 Simulation assumptions

Description	Value
System life	20 years
System efficiency	85%
Boiler efficiency	80%
Heat exchanger temperature drop	7.5°C
Annual maintenance cost	0.35% of initial cost
Annual insurance cost	0.18% of initial cost
Fuel price increase rate	6% (inflation) per year
Disassembly costs	Salvage value
Performance degradation over life	Negligible
Financing	No subsidies and initial capital is self-funded

In comparison the approximate current cost of common fuels such as coal is R0.19/kWh, paraffin is R1.19/kWh, diesel is R 1.22/kWh and low-sulphur oil is R 0.75/kWh (based on 90% boiler efficiency). The LCOE of these fuels can be calculated by including the fuel price increases over time which can be very difficult to predict. If we assume a 6% (equal to inflation) increase in paraffin it results in a LCOE of R2.3/kWh. This means that solar systems will struggle to compete with low cost fuels such as coal and low-sulphur oil but become highly attractive investments when more expensive fuels such as paraffin or diesel are used.

Simulations were done on a monthly basis using the listed assumptions in **Table 2** and an in-house developed code. The assumed values presented in **Table 2** were determined through personal communication with various industries in the field and confirmed to be reasonable. Hourly simulations were also done using a commercial software.

NORTHERN CAPE CASE STUDY

In the Northern Cape a company was interested in using a SWH system for reducing boiler fuel expenses. The existing boiler operates on paraffin and creates steam which is used to cure products in an oven over a short period.

The GHI at the factory is 2 100 kWh/m^2 per year which is some of the best solar irradiance in the world (see **Figure 1**). The factory roof is orientated north-west at a 15° tilt consequently receiving 2 243 kWh/m^2 per year of global in-plane solar irradiance (GII). The daily global in-plane irradiance is shown in **Figure 4** with the atmospheric temperature.

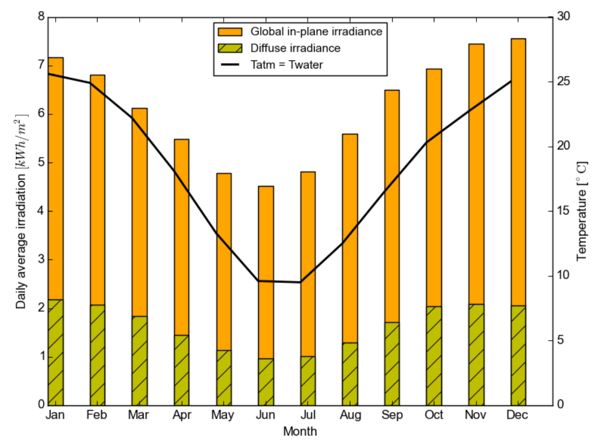


Figure 4: Global daily in-plane irradiance and water temperatures over the year for factory in the Northern Cape (data from [3])

With an annual boiler energy demand of 1.17 MWh this means that the 740 m^2 of roof space receives 142% of the total process energy demand in the form of solar energy. Although there is sufficient energy available the challenge lies fitting the need with the resource availability as well as harnessing this energy in a cost effective and reliable way.

In this factory only 20% of the total steam energy is used for water heating up to the point of boiling and the remaining 80% is used for the phase change of water. This means that the maximum SF achievable using a SWH system is 20% of the total needed process heat. This motivated the investigation of using advanced collectors for combined water heating and steam generation in order to achieve higher SF. Although it was possible to potentially achieve a 35% SF, these systems were found too expensive and introduced higher risk and was, therefore, not considered further.

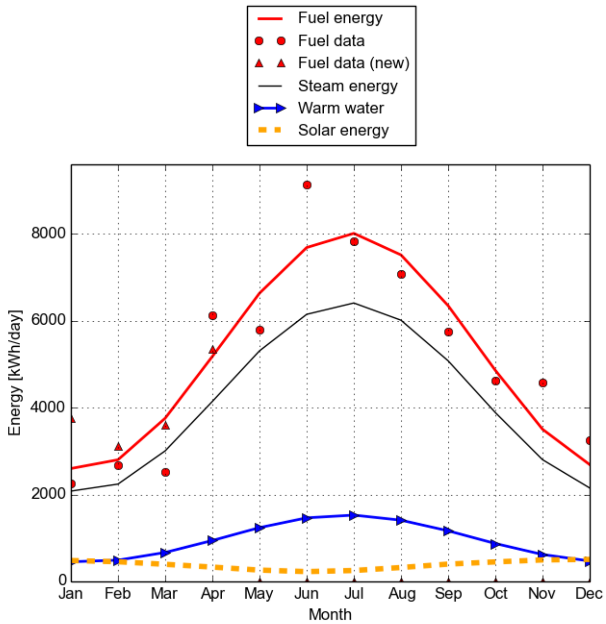


Figure 5 Energy balance for factory in the Northern Cape

With the fuel consumption data provided by the client it is possible to determine the boiler energy that is transferred to the water to produce steam. A least squares sinusoidal curve fit is used to estimate the long term average usage from the available data of one year (see **Figure 5**). The fuel data is significantly more in winter than summer because of the lower raw material and water temperatures. The steam energy refers to the total energy need of factory, the warm water energy is the energy needed to heat the water before phase change (that is replaceable by a SWH system) and the solar energy is the energy provided by the proposed system.

The proposed SWH system is characterised in **Table 3**. The system is dimensioned to provide all hot water needs in summer without oversizing the system. It is estimated that, with the proposed system, it possible to replace 50% of the hot water needs but only 10% of the total needed energy.

The total system cost is calculated to be R 880 000 of which the largest contributors are the storage (32.7%) and collectors (27.6%). The system will save approximately 10 800 litres of paraffin annually equivalent to an income between R 100 000 - R 340 000 over the course of the system life assuming fuel price increases equal to inflation.

Through these savings it is possible to pay back the system in 7 years. The system IRR is 16.5% showing that it is a good investment. Lastly the LCOE of the solar system is determined to be R 0.52/kWh compared to the operating cost of the boiler which is R 1.19/kWh in the first year and R 2.25/kWh on average over the course of the system life (taking into account fuel price increases).

Table 3 Northern Cape system specification

Parameters	Details
Type	Boiler preheat
Collector type	Selective coating flat-plate collector
SF (hot water)	50%
SF (total)	10%
Collector aperture area	124m^2
Collector quantity	43
Storage volume	8 000 litres
Storage temp	80°C

The storage tank makes a significant contribution to the overall cost of the system. Therefore, if a solar system can be integrated into a factory which has an existing hot water tank, then the SWH system becomes a significantly more attractive investment with the LCOE dropping to R 0.35/kWh and the IRR increasing to more than 20%.

WESTERN CAPE CASE STUDY

A company in the Western Cape considered the use of solar water heating for reducing boiler load and fuel cost. In this case the boiler does not produce steam but rather hot water that is circulated to various processes. This boiler also operates on paraffin but very little data was available to determine the energy need of entire factory.

One of the easiest integration points in this case is at an existing hot storage tank which uses boiler energy to heat approximately 7000 litres of water to 85°C daily. The solar system is, therefore, dimensioned to meet this hot water need.

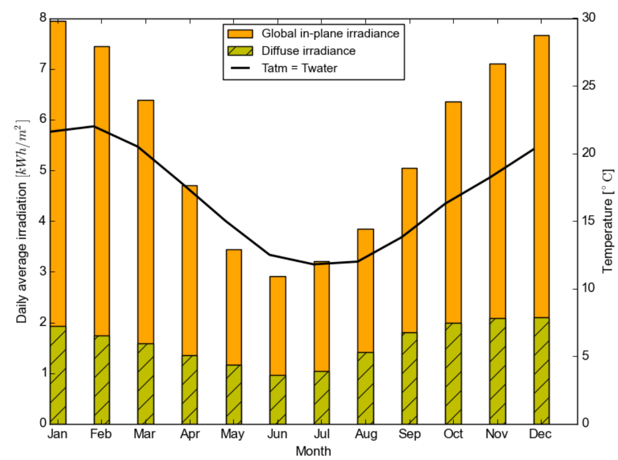


Figure 6 Global daily in-plane irradiance and water temperatures over the year for factory in the Western Cape (data from [3])

The factory roof is approximately 188 m^2 in size, orientated north-east and has a slope of 15°. The global in-plane irradiance can be seen in **Figure 6** which shows a significant difference between the summer and winter irradiance due the winter rainfall in this area. The GII is 2005 kWh/m^2 which means that this roof receives 200% of the energy needed to heat 7000 litres of water from 15 - 85°C daily.

In **Figure 7** the energy balance is shown. The needed energy of the hot storage is shown to vary over the year due to slight variations in the inlet water temperature. The fuel energy in this case is determined using a boiler efficiency of 80%.

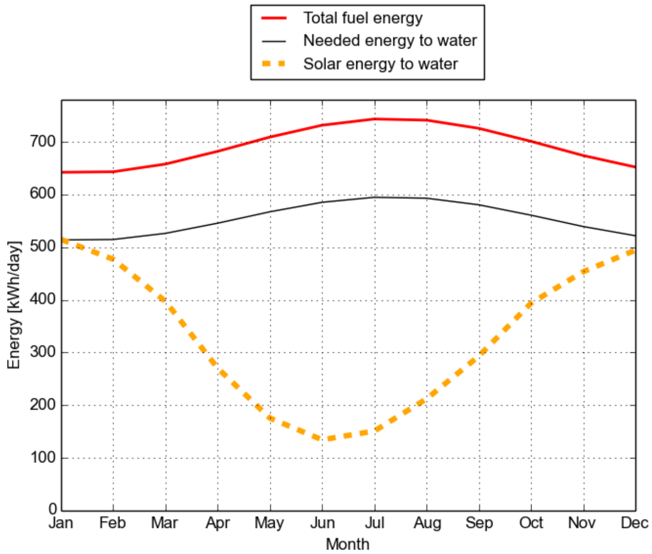


Figure 7 Energy balance for factory in the Western Cape

The solar system is characterised in **Table 4**. It can be seen that the system turns out to be very similar to the one for the factory in the Northern Cape which is allows for effective comparison. The system is dimensioned to match the hot water demand in summer but drops significantly in winter due to the winter rainfall (see **Figure 6**). Any increases in the system size would incur losses in summer and reduce the investment potential since expensive collectors will be underutilised.

Table 4 Western Cape system specification

Parameters	Details
Type	Boiler preheat
Collector type	Selective coating flat-plate collector
SF (hot water)	60%
SF (total)	unknown
Collector aperture area	125m^2
Collector quantity	44
Storage volume	8 000 litres
Storage temp	85°C

The proposed solar system can replace 60% of the hot water energy demand and in so doing save approximately 9 600 litres of paraffin per year. Over the system life net savings is estimated to be between R 98 000 and R 314 000 (due to fuel increases equal to inflation). This results in a payback period of 7 years and 3 months or an IRR of 15.3%. In this case the cost of operating the boiler is R1.22/kWh in year 1 and R 2.37/kWh average over the system life compared to a LCOE of R 0.59/kWh for the solar system.

SUMMARY AND CONCLUSIONS

In this report the motivation for SWH systems for industries in South Africa is presented along with the methodology for evaluating the performance and feasibility of these systems.

Two case studies are presented for systems with storage tanks. The systems cost approximately R 7000/m^2 with the major components being the collectors and storage tank.

It was found that solar systems of more than 100 m^2 are attractive investments with IRR of more than 15% (> 20% for no storage) when replacing expensive fuels such as paraffin or diesel. However, for inexpensive fuels, such as coal, it is not yet feasible to implement SWH systems from a financial viewpoint. When no storage tank is required the solar system LCOE reduces from R 0.65/kWh to R0.35/kWh becoming even competitive with some of the least expensive fuels.

Due to the variability of solar resource SWH systems will usually not be implemented without a backup heating source but present an attractive solution for reducing fuel costs when the energy is available.

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