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A techno-economic feasibility study on the use of distributed concentrating solar power generation in Johannesburg

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Abstract

The technical and financial feasibility of small-scale distributed Concentrating Solar Thermal Power (CSP) systems for urban areas in Johannesburg, South Africa, is investigated. The University of the Witwatersrand (Wits), located in central Johannesburg, is used as the basis of a case study for the implementation of these systems. A number of proven CSP technologies were identified and a technology screening was performed to identify suitable technologies for possible implementation, for a reference output of 120 kW(e). From these, a number of systems were chosen for more detailed evaluation and the hourly energy production of these systems was analysed, using local weather data. The Compound Linear Fresnel Reflector system (CLFR) proved to be most suitable because of the space and cost benefits it offers. Systems that integrate organic Rankine cycles (ORC) as well as thermal storage and hybridisation were also investigated. The levelised cost of electricity (LEC) was predicted to be between R4.31 and R3.18 per kWh. Currently these technologies cannot compete financially with the price of local, fossil produced electricity, but with the increase in electricity tariffs and demand for clean reliable power CSP technologies, may become competitive in distributed generation systems in urban areas.

Keywords: concentrating solar power, distributed generation

Introduction

The South African government is currently encouraging the development of renewable energy technologies to provide energy security as well as tackling climate change. After the electricity crisis in 2008, the University of the Witwatersrand (Wits) has reconfirmed its interest in pursuing research into energy efficiency and alternative electricity generation methods. Because of the high solar energy resource available in most of South Africa, a feasibility study of distributed CSP generation in urban areas of Johannesburg is investigated, using Wits as a case study.

CSP technologies

Of the concentrating solar thermal technologies, several were evaluated in this study. Most can be classified into the following categories:

- line focussing systems
    - trough technology
    - compound linear fresnel reflectors.
- point focussing systems
    - central receiver technology
    - dish-stirling.

Trough technology

Parabolic-trough power plants are line-focusing thermal electric power plants. Trough systems use the mirrored surface of a linear parabolic concentrator to focus direct solar radiation on to an absorber pipe running along the focal line of the parabola. The heat transfer fluid (HTF) inside the absorber pipe is heated and pumped to the steam generator, which in turn, is connected to a steam turbine. A natural gas burner can be used to produce steam at times of insufficient insolation (STI, 2005).

Compound linear fresnel reflectors

The CLFR configuration is similar to the trough technology but instead large fields thin mirror strips are used to concentrate beam radiation to a stationary receiver several metres high. This receiver contains a second stage reflector that directs all incoming rays to a tubular absorber (Häberle *et al.*, 2002).

Central receiver technology

A circular array of heliostats (large individually tracking mirrors) is used to concentrate sunlight on to a central receiver mounted at the top of a tower. A heat-transfer medium in this central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy to be used for the subsequent generation of electricity in a Rankine or Brayton cycle turbine. To date, the heat transfer media demonstrated include water/steam, molten salts, liquid sodium and air. If pressurised gas or air is used at very high temperatures of about 1 000 °C or more as the heat transfer medium, it can even be used to directly replace natural gas burning in a gas turbine, thus making use of the excellent cycle efficiency (60% and more) of modern gas and steam combined cycles (STI, 2005).

Dish Stirling systems

A parabolic dish-shaped reflector is used to concentrate sunlight on to a receiver located at the focal point of the dish. The concentrated beam radiation is absorbed into the receiver to heat a fluid or gas to approximately 750 °C. This fluid or gas is then used to generate electricity in a small piston or Stirling engine or a micro turbine, attached to the receiver (Beerbauma, 2005).

Data sources

The European Concentrated Solar Thermal Road Mapping document (Ecostar, 2005), as well as a study undertaken by Eskom (2001), South Africa's public electricity utility, were used as the main data sources for cost and performance data of the several technologies considered in this study. These previous studies provide a very convenient means of comparison between various technologies already in operation.

Absolute cost data for each of the reference systems in the studies are hard to estimate because the systems are all on different levels of maturity. However, the relative variations of the different cost items are considered to be well estimated by the approach. Data for modular trough power plants (MTPP) were taken from a study performed by Hassani *et al.* (2001) which outlined the development of a parabolic trough collector system that incorporates an organic Rankine cycle (ORC) as the electric generation system. Häberle *et al.* (2003) outline the prototyping of the Belgian Solarmundo CLFR system. In their paper, Häberle *et al.* present optical and thermal properties of the Solarmundo collector. These properties, as well as design details from Mills' CLFR system (2000) have been utilised.

Analysis procedure

The following is a brief guide to the basic method followed in this study:

- Verification of data– data and methodology from the multiple data sources were verified. This included the technical aspects of the systems under comparison. The absolute cost data for each of the reference systems in the studies were not verified but just compared to cost data used in the other studies.
- A basic model comparing the technologies used in the Ecostar Study to those of the Eskom study was produced. This model incorporated basic assumptions to compare the technologies under common conditions in South Africa. The conclusions from this comparison enabled technology screening.
- A technology screening was performed by identifying several functional criteria relevant to distributed urban generation.
- An analysis of the chosen technologies was carried out with respect to their installation at Wits University. This was performed by analysing Wits University's electricity profile, usage trends and other local conditions such as the appropriate direct normal radiation (DNI) data and space constraints.
- The conclusions from the above analysis resulted in separate design configurations being chosen for Wits University. The technical performance of these systems was then analysed, which included thermal energy flow modelling in Matlab. A model was then developed that analyses the impact that these technologies will have on Wits University's power usage on an hourly basis. The affects this has on Wits University's total bill was also calculated and these savings were considered in the calculation of a nominal cost of electricity generated.

The thermal modelling was performed using the method prescribed by the Ecostar study as well as that provided by Broesamle *et al.* (2000).

The comparison of the cost of electricity produced was done using the levelised cost of electricity (LEC) approach (IEA, 1991). The LEC evaluation provides a simple way to compare alternative projects to each other and is broadly used in the utility industry. To compare the plants at a common base, certain adjustments were made to the economic data, such as finding the present day value of the technologies, as well as converting the respective currencies to South African Rands (ZAR). Peters *et al.* (1991) have recommended the Chemical Engineering Plant Cost Index to find the present value of the technologies. Other adjustments to the data included scaling plant capacities through the economies of scale, suggested by Sargent and Lundy (S&L, 2003) as well as the adjustment of the DNI data to match Johannesburg conditions.

The DNI data used in the analysis were in Energy Plus Weather (EPW) format in SI units. The format is simple text-based data, based on the TMY2 (typical meteorological year) obtained from the NREL (1995). The total yearly DNI used for Johannesburg was 1781 kWh/m^2a.

Technology screening

The study involved the screening of the following technologies in order to select systems best suited for small-scale production in urban areas in Johannesburg. The following technologies were chosen, with data originating from the references mentioned above:

1. Standard parabolic trough (SEGS).
2. Parabolic trough with storage (SEGS with storage).
3. Parabolic trough with direct steam generation (SEGS DSG).
4. Compound Linear Fresnel (CLFR).
5. Central receiver with heliostat field and Salt as HTF (Molten Salt).
6. Central receiver with heliostat field with atmospheric receiver – air as heat transfer fluid (Central receiver atmospheric air).
7. Central receiver with heliostat field with pressurized volumetric receiver (Central receiver Brayton).
8. Integrated Solar Combined Cycle– (Fossil-fired Brayton topping cycle and solar-assisted Rankine bottoming cycle) (ISCCS).
9. Dish-Stirling engines (Stirling Cycle).
10. Solar Chimney.
11. Modular Thermal Power Plant (MTPP).

Functional criteria

The following criteria were identified and used to analyse the different technologies.

Produce electricity
This is the primary function of the power plant and because all plants (including fossil-fired plants) produce electricity, it is important to define this function more specifically in terms of the capacity factor.

Minimise costs
The cost referred to here is solely the cost of producing electricity. The Levelised Cost of Electricity (LEC) takes into account initial capital costs, maintenance and operation and fuel costs.

Simplify integration
Because urban areas are usually quite space constrained, this was one of the most important evaluation criteria. The first criterion evaluated is the required floor size of the solar field and power plant (Power/Area ratio [kW/m^2]). The second is the vertical height of the structures. For example, building a central receiver on the roof of an existing building may oppose the aesthetic appeal of the building. The disjointed nature of the space found in urban areas was also taken into consideration.

Reduce emissions
This function refers to the reduction of greenhouse gas emissions typically produced by fossil fuel power generation facilities. It was deemed less important because all of the solar technologies reduce emissions to some extent. This criterion is usually used to evaluate renewable energy in general, as compared to fossils. South Africa, as a developing country, is still more concerned with energy security and economic growth than it is with emission reduction.

Maturity of technology
Here the maturity of the technology refers to its reliability through the use of demonstrated performance.

Promote local industry
Technologies that can be produced using local industries are preferred to those that need to be imported.

Chosen technologies

By ranking the proven systems using the above criteria, the following systems were chosen to be further examined:

1. Parabolic Trough with normal Steam Cycle using no storage or hybridisation
2. Parabolic Trough with normal Steam Cycle, with storage
3. Parabolic Trough with normal Steam Cycle, with hybridisation
4. Parabolic Trough with Organic Rankine Cycle using no storage or hybridisation
5. Parabolic Trough with Organic Rankine Cycle, with storage
6. Parabolic Trough with Organic Rankine Cycle, with hybridisation
7. CLFR with normal Steam Cycle using no storage or hybridisation
8. CLFR with normal Steam Cycle, with storage
9. CLFR with normal Steam Cycle, with hybridisation
10. CLFR with Organic Rankine Cycle using no storage or hybridisation
11. CLFR with Organic Rankine Cycle, with storage
12. CLFR with Organic Rankine Cycle, with hybridisation.

Energy modelling was performed using Matlab© software, for each of the technologies at a reference capacity of 120 kW(e). The base case reference plants (no storage or hybridisation) were sized for a design capacity of 20%. The technologies that make use of storage were sized using a design capacity factor of 30% (solar field multiple of 1.5). As Kolb (1998) describes, the hybrid systems make use of the '*fuel saver*' configuration, where the fuel usage is reduced when solar energy is available and electricity output is held constant. The hybrid technologies make use of a natural gas boiler with a capacity factor of 54% (electricity production between 07:00 and 20:00 daily). Egoli Gas is the local natural gas supplier that is located next to the University supplying gas at R128.57/GJ.

Results

Figure 1 shows the initial economic comparison between the various technologies. This was used as the base case to compare data from the Ecostar study (solid points) and the Eskom study (empty points). The MTPP data was taken from the study performed by Hassani (2001). To compare the technologies, the financial data was adjusted to assume the following assumptions, common to the data provided by Eskom:

- DNI radiation 2900 kWh/m^{2}a (Upington, South Africa)
- Plant capacity 100 MW(*e*).

The results from Figure 1 contributed to the technology screening, leading to certain systems being chosen for further evaluation. The chosen technologies were then adjusted for local, Johannesburg conditions.

Design efficiencies of these 12 chosen systems are given in Table 1. The plant areas are given in Figure 2.

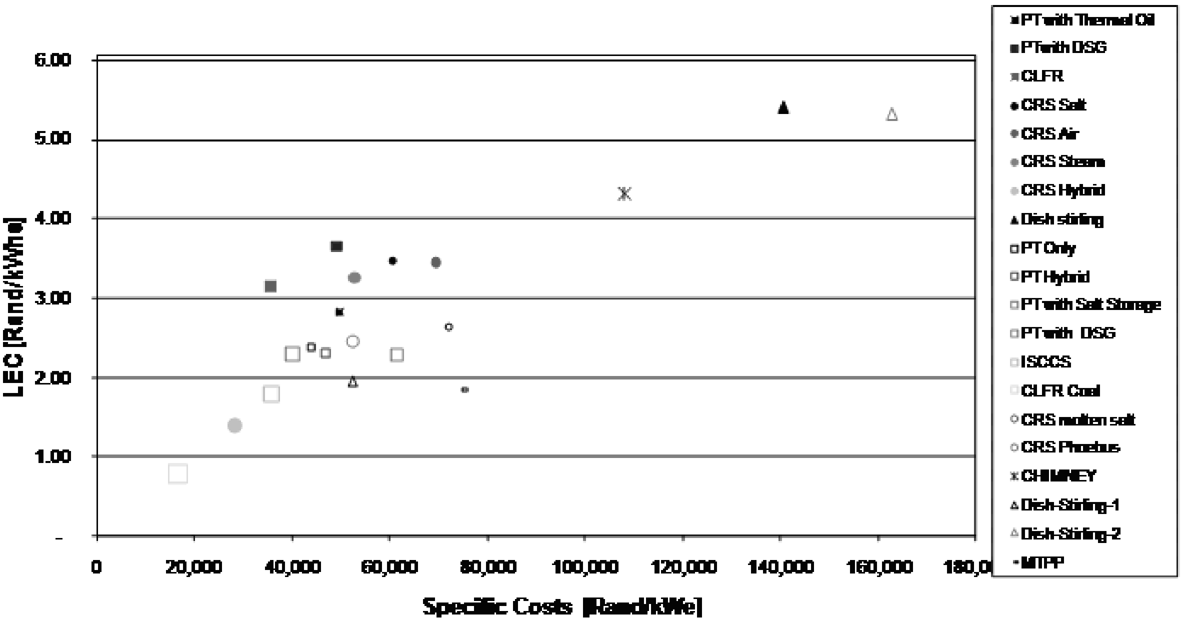

Figure 1: Financial comparison for base case 100 MW(e) Eskom-Ecostar (Upington)

Table 1: Design efficiencies for chosen 120 kW(e) Reference plants (Johannesburg)

#	*Collector type*	*Power cycle*	*Optical eff'cy [%]*	*Geometric eff'cy [%]*	*Collector eff'cy [%]*	*Convection losses [%]*	*Radiation losses [%]*	*Solar field eff'cy [%]*	*Eff'cy – parasitic losses [%]*	*Eff'cy – piping losses [%]*	*Storage eff'cy [%]*	*Power block eff'cy [net %]*	*Solar to electric eff'cy [%]*
1&3	Parabolic trough	Steam cycle	75.7	89.0	67.4	3.5	12.6	51.2	90.8	85.1	100.0	35.5	14.1
2	Parabolic trough	Steam cycle	75.7	89.0	67.4	3.5	12.6	51.2	90.8	85.1	94.7	35.5	13.3
4&6	Parabolic trough	ORC	75.7	89.0	67.4	3.5	12.6	51.2	90.8	85.1	100.0	23.0	9.1
5	Parabolic trough	ORC	75.7	89.0	67.4	3.5	12.6	51.2	90.8	85.1	94.7	23.0	8.6
7&9	CLFR	Steam cycle	68.2	80.0	54.6	5.9	8.5	40.1	90.8	85.1	100.0	35.5	11.0
8	CLFR	Steam cycle	68.2	80.0	54.6	5.9	8.5	40.1	90.8	85.1	94.7	35.5	10.4
10&12	CLFR	ORC	68.2	80.0	54.6	5.9	8.5	40.1	90.8	85.1	100.0	23.0	7.1
11	CLFR	ORC	68.2	80.0	54.6	5.9	8.5	40.1	90.8	85.1	94.7	23.0	6.8

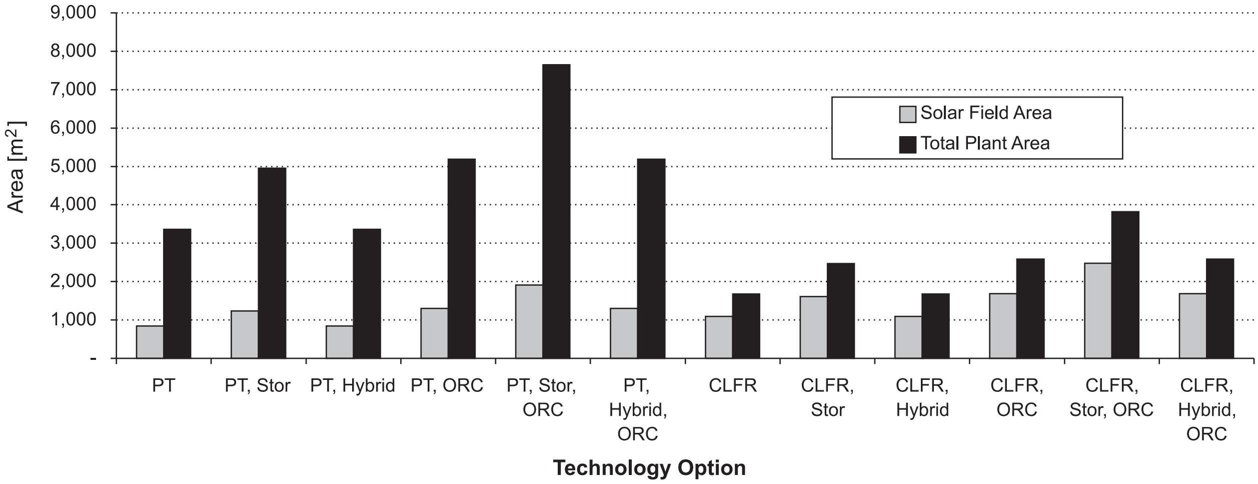

Figure 2: Resulting reference plant areas – 120 kW(e) (Johannesburg)

To find the relevant LEC's, the total costs of the systems needed to be determined. To find the total investment, financial data and specific costs of technologies from several studies were averaged. Financial assumptions are given in Table 2 and the results of the analysis are given in Table 3 and depicted in Figure 3. Fuel costs are based on the natural gas price from Egoli Gas (2008) in Johannesburg.

Table 2: Economic assumptions

FCR (fixed charge rate)	11.6%
Annual insurance rate	1.0%
Interest rate	10.0%
Depreciation life	30
Contingencies	30%
O&M costs [steam] (as %of total)	2.8%
O&M costs [ORC] (as %of total)	2.0%
Euro dollar exchange (XE, 2008)	0.78
Rand euro exchange (XE, 2008)	13.01
Fuel costs (natural Gas– Nov 2008) Yearly service charge [R]	2908.32
2,400 to 4,799 GJ/a [R/GJ]	128.57
Energy content of the fuel [MJ/m^3]	36.1

Energy modelling was performed on the chosen systems. The effects on Wits University's West Campus bill were also investigated. The savings on the bill resulted in a second LEC being determined– the Wits LEC. A third scenario was also investigated, the effects of a renewable energy feed-in tariff (REFIT). Because the electricity is not 'grid connected' generation and would be generated for usage at the University, it would not qualify for REFIT but it has been included to show what the market related value of this electricity is.

A REFIT of R2.05/kWh was used in this analysis. At the time of writing, a REFIT of R2.10/kWh was released for CSP generation with storage, which compares favourably. The results of these are shown in Figure 4. The real LEC is the actual cost of generation which doesn't include bill savings. The Wits LEC is based on the bill savings due to decreased demand in grid electricity at the University.

Application at Wits University

The reference size of the chosen systems for further analysis is 480 kW(e). This size was chosen because of the benefits it has in bringing down the day-time peak load experienced at Wits University. The following three options were chosen and recommended for further investigation. Reasons for the choice of solar field and power cycle are also given:

- CLFR with ORC
- CLFR with ORC making use of thermal storage
- CLFR with ORC with hybridisation using natural gas.

Solar field

The chosen solar field is the CLFR configuration. It is the most compact and offers the smallest plant area for a set electric output. The CLFR option also offers large infrastructure savings. The solar field also requires less water for cleaning and considering the sustainability of the water supply in a rapidly growing city such as Johannesburg, this benefit is favoured.

Power cycle

In terms of the potential power cycle, only the ORC options that are recommended for further investigation. ORC plants are noted to have less demanding operating requirements because they are capable of automatic start-up, safe shutdown, and regulation with varying solar conditions. Because the ORC systems can operates at lower temperatures, the efficiency of the solar field is less important.

Table 3: Economic results (120 kW(e) reference plants – Johannesburg)

System #	*PT*	*PT, Stor*	*PT, Hybrid*	*PT, ORC*	*PT, Stor, ORC*	*PT, Hybrid, ORC*	*CLFR*	*CLFR, Stor*	*CLFR, Hybrid*	*CLFR, ORC*	*CLFR, Stor, ORC*	*CLFR, Hybrid, ORC*
Size of field [m^2]	841	1,239	841	1,297	1,912	1,297	1,090	1,607	1,090	1,682	2,481	1,682
Total area	3,362	4,954	3,362	5,189	7,647	5,189	1,676	2,473	1,676	2,587	3,817	2,587
Investment solar field [R]	3,495,459	5,150,559	3,495,459	5,395,165	7,949,776	5,395,165	2,189,055	3,228,857	2,189,055	3,378,759	4,983,670	3,378,759
Investment power block, balance of plant [R]	1,901,368	1,901,368	1,901,368	1,744,356	1,744,356	1,744,356	1,901,368	1,901,368	1,901,368	1,744,356	1,744,356	1,744,356
Investment storage [R]	0	656,199	0	0	1,012,829	0	0	656,199	0	0	1,012,829	0
Investment land [R]	0	0	0	0	0	0	0	0	0	0	0	0
Contingencies [R]	1,619,048	2,312,438	1,619,048	2,141,856	3,212,088	2,141,856	1,227,127	1,735,927	1,227,127	1,536,934	2,322,256	1,536,934
Sum total equipment costs [R]	5,396,827	7,708,126	5,396,827	7,139,521	10,706,961	7,139,521	4,090,423	5,786,423	4,090,423	5,123,115	7,740,855	5,123,115
Total including contingencies [R]	7,015,875	10,020,564	7,015,875	9,281,377	13,919,049	9,281,377	5,317,550	7,522,350	5,317,550	6,660,049	10,063,111	6,660,049
Actual O&M Costs [R]	201,706	288,091	201,706	185,628	278,381	185,628	152,880	216,268	152,880	133,201	201,262	133,201
Annual financing & insurance costs (=FCR*Total inc. contingencies) [R]	814,397	1,163,179	814,397	1,077,375	1,615,713	1,077,375	617,257	873,189	617,257	773,094	1,168,118	773,094
Annual fuel costs [R]			587,111			904,612			587,111			904,612
Total net electricity [kWh]	210,240	315,360	568,699	210,240	315,360	568,699	210,240	315,360	568,699	210,240	315,360	568,699
Solar net electricity (Jo'burg)	210,240	315,360	210,240	210,240	315,360	210,240	210,240	315,360	210,240	210,240	315,360	210,240
Fossil net electricity [kWh]	-	-	358,459	-	-	358,459	-	-	358,459	-	-	358,459
Fossil thermal energy required [kWh_{th}]	-	-	1,009,744	-	-	1,558,518	-	-	1,009,744	-	-	1,558,518
Fossil thermal energy input [GJ]	-	-	4,544	-	-	7,013	-	-	4,544	-	-	7,013
Total costs [R]	7,015,875	10,020,564	7,015,875	9,281,377	13,919,049	9,281,377	5,317,550	7,522,350	5,317,550	6,660,049	10,063,111	6,660,049
Specific investment (R/kW)	58,466	83,505	58,466	77,345	115,992	77,345	44,313	62,686	44,313	55,500	83,859	55,500
LEC - Real (based on total net elec.) (R/kWh)	4.83	4.60	2.82	6.01	6.01	3.81	3.66	3.45	2.39	4.31	4.34	3.18

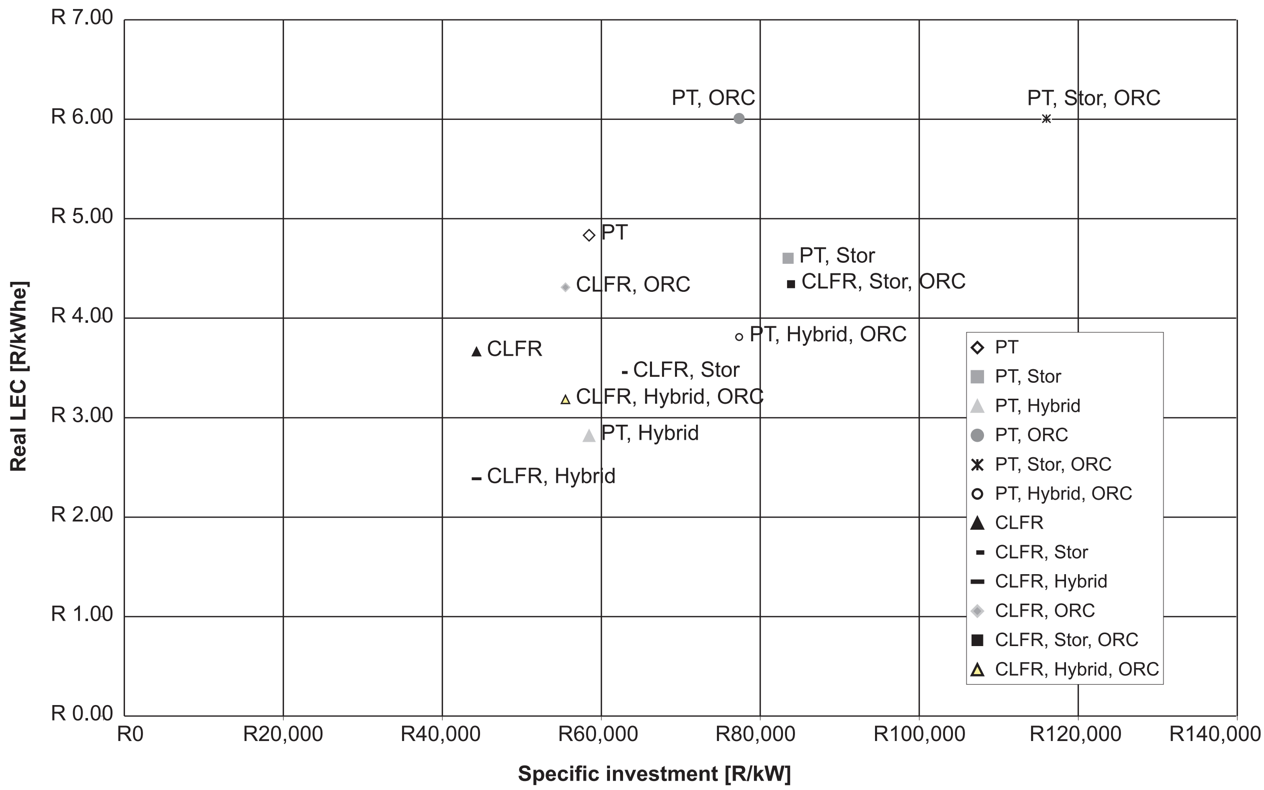

Figure 3: Economic results for 120 kW(e) reference plants (Johannesburg)

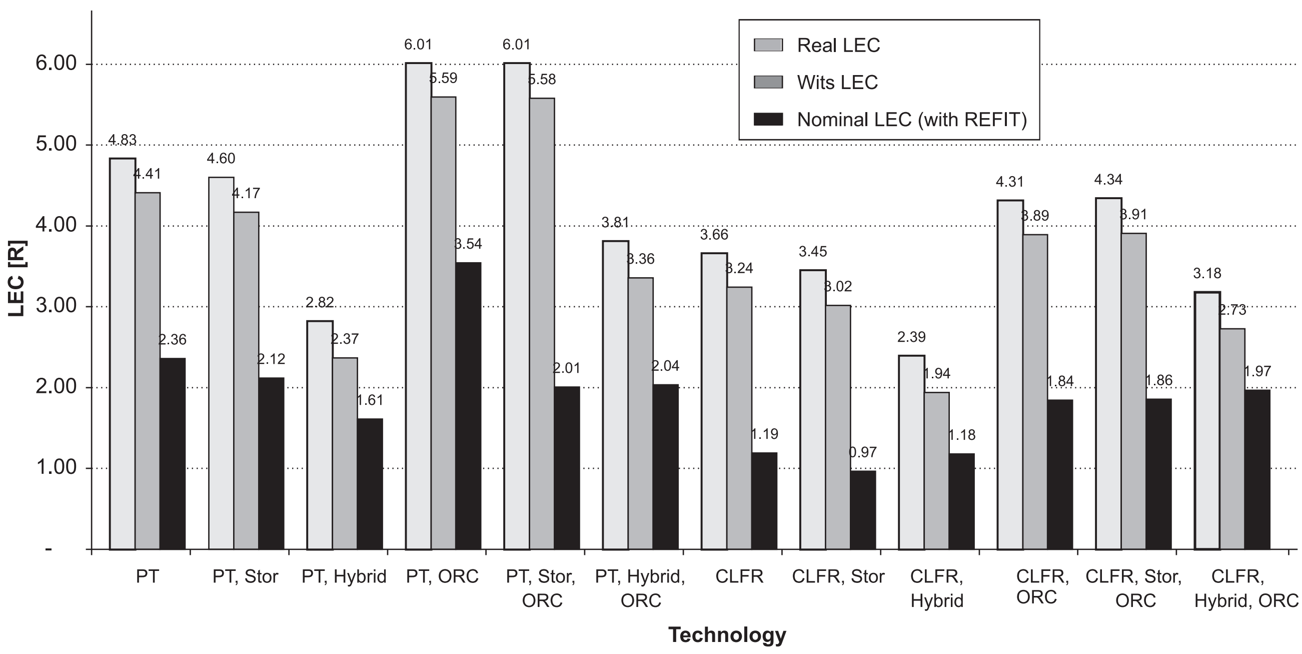

Figure 4: LEC for 120 kW(e) reference plants (Johannesburg)

Modelling

The hourly electricity usage has been tracked and represented in Figures 6-8. The graphs respectively represent the hourly electricity used (and generated) for the CLFR plants using ORC without storage or hybridisation, with storage, and with hybridisation. These graphs each represent a random weekday in the winter during term (17 June 2008) where the electricity demand is high.

Figure 7 shows the effects of the storage system coming on line at 18:00. The electricity generated using hybridisation can be clearly seen as a constant input between the hours 07:00 and 20:00 in Figure 8. Figures 8-10 show the average hourly

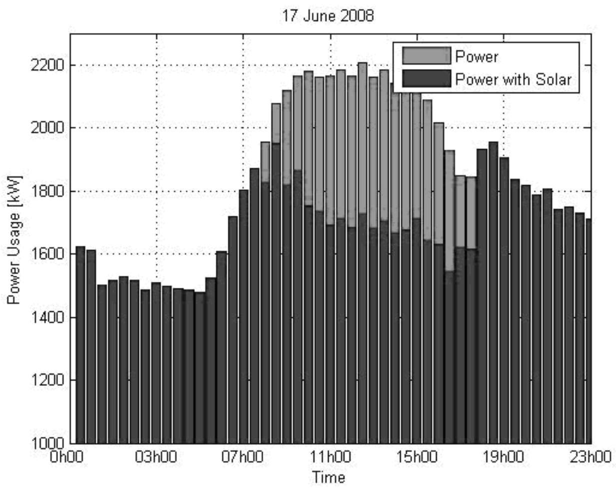

Figure 5: West Campus power usage – CLFR, ORC (480 kW(e))

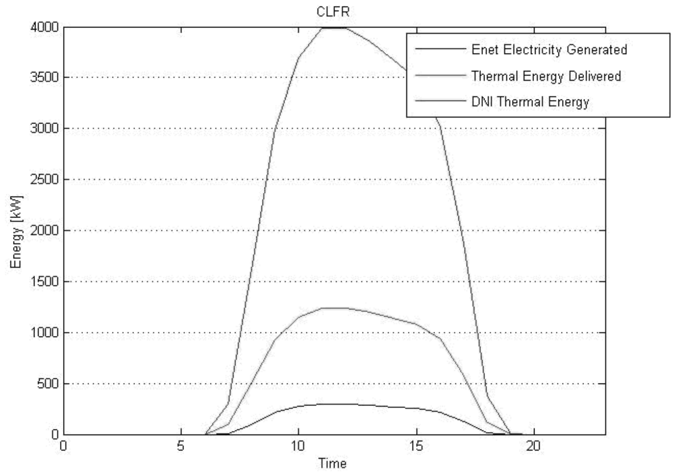

Figure 6: Average energy flow for CLFR, ORC (480 kW(e))

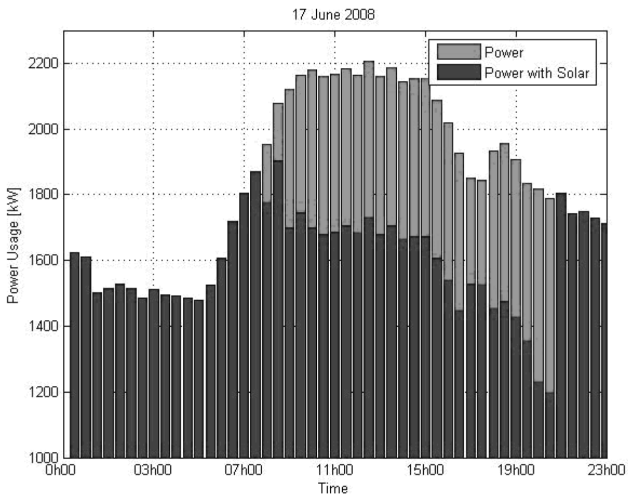

Figure 7: West Campus power usage– CLFR, ORC, with storage (480 kW(e))

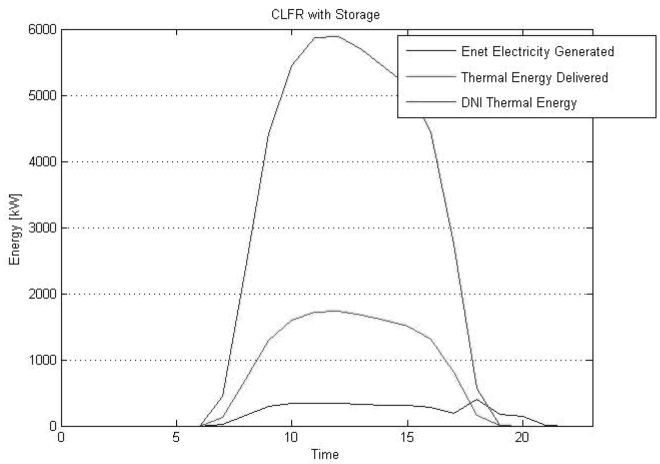

Figure 8: Average energy flow for CLFR, ORC, with storage (480 kW(e))

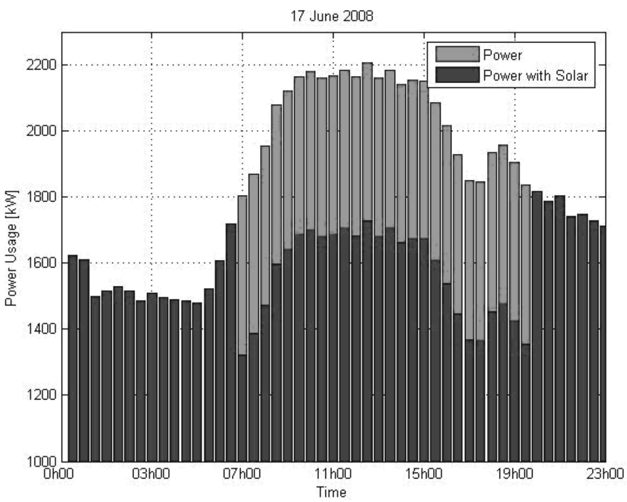

Figure 9: West Campus power usage – CLFR, ORC, with hybridisation (480 kW(e))

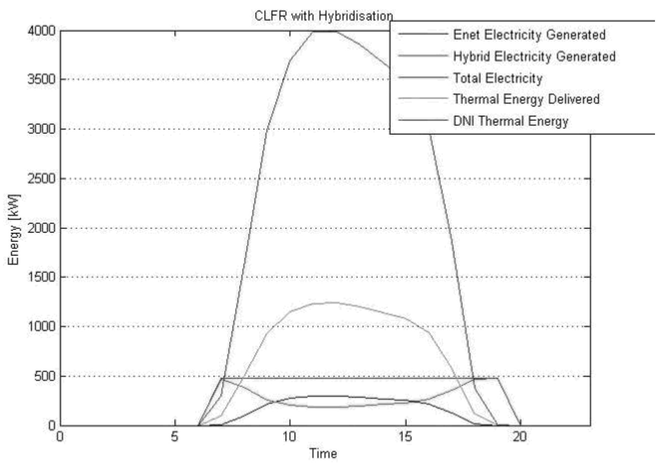

Figure 10: Average energy flow for CLFR, ORC, with hybridisation (480 kW(e))

Table 4: Summary for CLFR, ORC technologies at 480kW(e)

	CLFR, ORC	*CLFR, Storage, ORC*	*CLFR, Hybrid, ORC*
Total electricity consumption [kWh]	12,922,073	12,922,073	12,922,073
Total solar electricity generated [kWh]	858,856	1,341,094	2,277,600
Yearly bill [R]	7,291,654	7,291,654	7,291,654
Total bill [R] (incl. cost of Solar)	10,647,589	12,559,262	13,452,154
Extra cost for solar [R/year]	3,355,935	5,267,608	6,160,499
Cost saved on bill [R/year]	345,735	552,740	1,082,269
Real LEC [R/kWh]	4.31	4.34	3.18
Wits LEC [R/kWh]	3.98	4.00	2.77
Average capacity factor	0.21	0.32	0.55
Total Investment [R]	26,640,198	40,252,445	26,640,198
Payback [years]	77	73	25
	-	-	-
Nominal LEC [R/kWh] (with REFIT)	1.93	1.95	2.01
Payback [years] (with REFIT)	12.7	12.2	9.5

energy flow from the initial *DNI* collected by the solar field to the electric generation for the three alternatives discussed above.

Table 4 shows a summary of the analysis. The fourth column represents the total bill after adding on the yearly capital costs for a solar installation. The sixth column is the amount of savings experienced with the alternative generation.

Discussion and conclusions

The data comparison of existing technologies is satisfactory and the relative distribution of the different cost items is considered to be well estimated by the approach followed. The economies-of-scale method was used and is suitable for utility scale plant sizes but discrepancies may arise when scaling down below 1 MW(e). However, data was used as comparative analysis and thus sufficiently fulfils the scope of work. A full life-cycle cost analysis is recommended for future application. It is also recommended that different financing and tax incentives be investigated in full in order to find the optimal implementation strategy.

South Africa has one of the greatest solar resources in the world and we should therefore be technology leaders and pioneers. With greater emphasis being placed on the need for renewable energy systems, it is imperative that South Africa develops its skills and a knowledge base that will work at making the implementation of renewable energy, and in particular CSP generation, a reality. There are countless institutional benefits that will be gained by the implementation of CSP technology at the University. This can be expanded to also include the commercial advantages gained from research at the University. Research, development and demonstration practices aim at alleviating technical barriers and reducing costs altogether and in improving materials, components and system design for installers and users. To further bring down the cost of electricity it would be possible to use the waste heat from the power cycle and integrate it into Wits University's heating and cooling requirements.

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