Assessment of the Economic Impact of Full Scale use of Domestic Solar Water Heaters in Zimbabwe in Comparison with other Electrical Management Options

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Abstract: ***This research study investigates the possibility of solar energy replacing other sources of energy such as thermal and hydro electric energy in domestic water heaters. Other than it being a renewable and cheaper alternative source of energy, solar energy has no documented polluting effect on its generation thus contributing positively to cleaner production for sustainable development, reduction in green house gas emission and potential cost savings. Economic comparative work on its use has been dealt with in water heating, and it has been found out that it can be utilized and result in appreciable power savings as well as effectively complementing existing supply sources. A number of energy management strategies have also been outlined to reinforce the solar initiative. Power deficit has been cited a challenge which need to be attended to. This work can be used as a resource for those considering an investment in solar water heating system option.***

Key words: solar, water heating, domestic, savings, energy

1. Introduction

Solar water heating is a form of energy efficiency strategy which reduces the amount of electrical energy. Energy deficit where the demand far outweighs the supply is a major challenge the country faces and often to forced to import power [10].

At the time of this research, the average cost of generating electricity was US$0.0492 per kilowatt-hour. Table 1 shows the generating capacities from PowerCo (2012). Its internal generating capacity is 1292 MW, imports are 100MW, while the forecast demand is 1770 MW in June 2012. Table 2, shows the energy balance sheet and energy deficit [10].

Table 1: PowerCo internal generation (thermal & hydro)

	(MW)
Hwange	529
Kariba	700
Harare P/Stn.2	10
Munyati	23
Bulawayo	30
TOTAL	**1292**

Table 2: PowerCo energy balance sheet [10]

Internal Generation	1292
Imports	100
Exports NamPower	-25
	1367
Power Deficit	403
forecast Demand	1770

The increasing demand for electrical energy as shown in Figure 2 requires cost effective solution to be developed.

The red line represents internal generation capacity. The blue line represents internal generation plus power imports. The black curve is the demand profile. Power demand profile is above the red line [10].

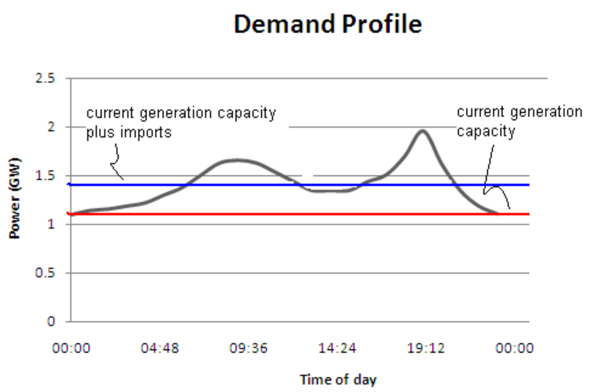

Figure 1: Electrical power demand in a day

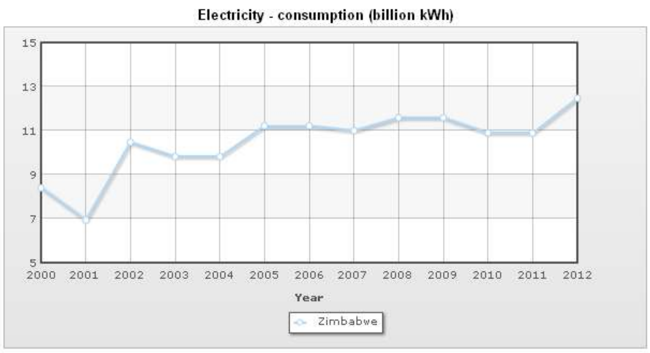

Figure 2: Energy demand profile over years [10]

2. Justification

Use of solar water heaters is a renewable energy intervention to the energy shortfall. Domestic heated water is widely used for showers, baths [5], laundry, dishwashing and general cleaning. Solar water reduces demand for electrical energy. This is effective if done together with energy efficiency to reduce energy [6].

High energy efficiency technologies, infrastructure and processes, alongside demand reduction and retrofit strategies to release additional capacity to meet requirements of all consumers.

The use of hot water for domestic purposes is a major contributor to domestic energy consumption [3]. The use of solar water heaters has a major contribution towards reduction in the demand for electrical energy on the grid.
Both economic and technical evaluations are done to ensure the suitability of the solar option..

The limited budget and increasing energy consumption pattern against a backdrop of dwindling power generation capacity prompted PowerCo to consider energy efficiency and electrical energy management strategies [10].

3. Economic Assessment

This process enumerates potential costs and evaluates the anticipated benefits of solar water heating [6].

3.1 Economic analysis of Solar Energy Systems

3.1.1Present Value Analysis [2]

A cash flow F occurring N years from now can be reduced to its present value PV by:

$$PV = F/(1+d)^N$$

d = market discount rate (%).
With an annual inflation rate i; a purchase cost C at the end of year N will become a future cost F according to:

$$F = C(1+i)^{N-1}$$

The discounted cost (PW) of an investment C at the end of N years, at a discount rate d and inflation rate i, is given by

$$PW = C(1+i)^{N-1}/(1+d)^N$$

The annual energy savings are obtained by subtracting the annual cost of energy of the auxiliary system, C_{aux} (solar plus electricity system), from the annual cost of energy of conventional system (electricity only system)

$$C_{aux} = \int C_a Q_{aux}\, dt$$

$$C_{con} = \int C_c Q_{load}\, dt$$

Were C_a is the auxiliary cost rate and C_c is the conventional energy cost rate.

The cost to be included in determining total solar energy savings are:

- Fuel savings
- Extra mortgage payment
- Extra maintenance cost
- Extra tax savings
- Solar savings
- Parasitic costs

Parasitic costs refer to the auxiliary energy required to power additional equipment such as fans, pumps, controllers and electric heating elements.

Solar savings = - Extra mortgage payment - Extra maintenance cost - Extra parasitic cost + Fuel savings + Extra tax savings

$$\mathbf{NPV = -I_o + \sum_{t=1}^{n} NR_t/(1+d)^t.}$$

The economic analysis of solar energy systems determines the least cost of meeting the energy needs, considering both solar and non-solar alternatives. When choosing among alternatives, it is generally agreed that the same study period should be used when evaluating each of the alternatives.

3.1.2 Total life cycle cost (TLCC) [2]

TLCC = present value of total life-cycle cost

C_n = Costs cash flow in period n, includes investment costs, expected salvage value, nonfuel O & M and repair costs, replacement costs, energy costs

d = discount rate
i = Interest rate
f = Inflation rate
n = Analysis period

PVOM = Present Value of Operations and Maintenance Costs

TLCC = I + PVOM

$$TLCC = I + OM\,[(1 + d)^n - 1] / [d(1 + d)^n]$$

$$d = (1 + i) / (1 + f) - 1$$

3.1.2 Levelized cost of energy (LCOE)

Levelised Cost of Energy(LCOE) is the price at which electricity must be generated from a specific source to break even over the lifetime of the project [1]. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital, and is very useful in calculating the costs of generation from different sources.

The basic formula to determine your LCOE starts with equating your costs and revenues. This can be represented in the simple formula below.

Q_n = energy output or saved in year n
d = discount rate
n = Analysis Period
TLCC = Total life cycle costs
I = Initial Investment

$$LCOE = TLCC / [\Sigma_n Q / (1 + d)^n]$$

Amount of energy saved in the analysis period

$$= [\Sigma_n Q / (1 + d)^n]$$

$$[\Sigma_n Q / (1 + d)^n] = Q \times [(1 + d)^n - 1] / [d(1 + d)^n]$$

The levelized cost of energy (LCOE) allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both exist.

The LCOE is that cost that, if assigned to every unit of energy produced (or saved) by the system over the analysis period, will equal the TLCC when discounted back to the base year.

LCOE is recommended for use when ranking alternatives given a limited budget simply because the measure will provide a proper ordering of the alternatives, which may then be selected until the budget is expended [5].

Solar processes are generally characterized by high initial cost and low operating costs thus, the basic economic problem is of comparing an initial known investment with estimated future operating costs. Life cycle cost (LCC) is the sum of all the costs associated with an energy delivery system over its lifetime in today's money [4], and takes into account the time value of money. The life cycle savings (LCS), for a solar plus auxiliary system, is defined as the difference between the LCC of a conventional fuel-only system and the LCC of the solar plus auxiliary system.

The fossil fuel plant has lower capital costs but higher fuel costs compared to the solar plant which has higher capital costs and no fuel costs. Fuel costs for the fossil fuel plant will be expensed and recovered immediately. However, the solar plant with no fuel cost and higher capital costs will have to wait until capital costs are depreciated to recover costs.

3.1.3 Electrical Energy Management

Energy management methods are grouped into four general categories [10]:

- House keeping measures
- Equipment and process modification
- Better utilization of equipment
- Loss reduction

It entails load management programs that change the load pattern and encourage less demand at peak times and peak rates. Demand side management (DSM) targets reduction of peak demand during periods when energy-supply systems are constrained.

4. Renewable Energy Technologies

Renewable energy technologies (RETs) are attractive and environmentally sound technology options [5]. In addition, most of renewable energy technologies are modularized and are well suited for meeting decentralized rural energy demand. Renewable energy technologies that utilize locally available resources and expertise provide employment opportunities for the locals. Finally, RETs can improve an electrical power supply system by providing energy surplus to the grid system [7].

5. Power factor correction

Power factor is the ratio between the kW and the KVA drawn by an electrical load. It is a measure of how effective the current is being converted into useful work [6]. Whenever loads are connected to an alternate current (AC) supply, there is a possibility that current and voltage will be out of phase. Loads such as induction motors draw current that lags behind voltage, while capacitive loads (e.g. synchronous motors, battery chargers) draw current that leads the voltage. Loads that are predominantly resistive such as heaters and cookers draw current in phase with voltage. The angle between the current and voltage is known as the phase angle ϕ. This can be leading or lagging (or zero) depending on the load. The power factor (PF) is defined as cosine ϕ and is always less than 1. It represents the ratio of active power (or useful power) to the total power supplied by the generating station.

Capacitors are used to correct the power factor. Alternative ways of improving the power factor include:

i. Replacement of over-sized motors with standard or high efficiency motors of the right horsepower.
ii. Shutdown idle running motors.
iii. Avoid operation of equipment above its rated voltage.

6. Energy Efficiency

Energy efficient practices seek to use less energy. An electrical utility may embark on supply side management to [3]:

- Ensure reliable availability of energy at the minimum economic cost ultimately increasing its profits;
- Provide maximum value to its customers by reducing energy prices;
- Meet increasing electricity demand without incurring unnecessary major capital investments in new generating capacity;
- Minimize environmental impact.

7. Hot water systems

Hot water systems typically comprise of a hot water storage tank, a fuel source to heat water, hot water piping to outlet points, and a cold water feed to the storage tank [7]. The efficiency of the complete system includes all losses in heating the water from the cold water inlet to the desired outlet temperature. System efficiencies may range from less than 50 percent to about 85 percent. The system should be capable of meeting peak hot water demand at an acceptable efficiency level.

There are four main strategies to reduce water heating energy:

- Use less hot water
- Turn down the thermostat of the water heater,
- Insulate your water heater and pipes,
- Install a new, more efficient water heater.

Advanced technologies and methods to increase energy savings in domestic water heating systems [8]:

Heat pump water heaters: Heat pumps use mechanical energy to transfer thermal energy from a source at a lower temperature to a sink at a higher temperature. Electrically driven heat pump heating systems have two advantages compared to electric resistance heating or expensive fuels. The heat pump's Coefficient of Performance (COP) is high enough to yield 11 to 15 MJ of heat for each kW h (3.6 MJ) of energy supplied to the compressor , which saves on use of energy. They can be used in conjunction with solar water heaters to bring more energy economy into the system. The heat pump is the same as a refrigeration system which works to transfer heat from a low temperature source to a higher temperature heat sink, but the useful part is the deposition of heat at the higher temperature. Heat pumps transfer energy from the surrounding air to water in a storage tank[7]. These water heaters are much more efficient than electric resistance water heaters and most effective in warm with long cooling seasons.

Manifold plumbing systems: Maniflow saves energy and conserves water by having a dedicated pipeline from a manifold near the hot water cylinder to each tap or fixture in the house. Hot water goes straight where it's needed without sitting around and cooling in the big feeder pipes needed to serve multiple outlets. Less energy and water is wasted as hot water arrives faster at the tap. Flexible and non-metallic pipes result in a quiet and efficient plumbing system that doesn't suffer corrosion, scaling or microbiological build-up. Cross-linked polyethylene (PEX) is a high-temperature, flexible, polymer pipe used for plumbing pipe work. PEX piping offers reduced heat loss and improved thermal characteristics when compared to a metallic pipe. In addition, less energy is used by the water heater because of shorter delivery time for hot water with PEX parallel plumbing systems. The polybutylene manifold construction provides better heat insulation, doesn't support microbiological growth, scale or corrosion even in aggressive water areas.

Instantaneous water heaters: They are also known as on demand hot water heaters. They reduce energy losses due to storage and in the pipes. They have a flow switch which activates the heater only when there is a flow due to instantaneous demand for water. Although, they are an efficient technology, its benefits like any other energy efficient technology can be realised through practicing water conservation and efficiency measures .

Low cost measures to reduce hot water energy consumption include the following:

- Practicing conservation behaviors that lead to reduced hot water use (e.g., turning off faucets while brushing your teeth, while hand cleaning dishes, washing fewer but larger loads of laundry, running the dishwasher only when it's full)
- Installing low-flow showerheads and faucets
- Installing shut-off valves in showerheads and faucets, which dribble when closed so as to maintain water in the pipe at the selected temperature while soaping, shampooing or shaving
- insulating hot water pipes
- Fixing all leaks

Moderate to high-cost measures:

- Installing ENERGY STAR clothes washers and dishwashers
- Installing a drain-water heat recovery system
- Minimizing the piping runs to the kitchen, laundry room and bathrooms when building new or remodeling
- Use of timer switch to switch off power during -Peak Power and at night when hot water is not required.

7.1 Production of hot water using electricity

Figure 3 shows four key steps of hot water production and the various losses associated with each step [7]. The numbers are illustrative and represent typical numbers found in practice, although there could be wide variations from plant to plant. Losses accumulate over the four steps because:

- Handling of the coal results in a loss of 2 per cent (lost to the area around the plant, lost in loading and unloading trucks, etc.);
- The power station is actually operated at about 28 per cent overall efficiency (losses of hot combustion gases from the stack, warm cooling water discharges, mechanical inefficiencies in turbines and generators, etc.);
- The transmission of electricity to the location of the hot water production and distribution within the generator plant itself is only 87 per cent efficient overall (mainly losses in lines and transformers)
- The efficiency of the water heater at the laundry is 80 per cent (heat losses are experienced from the boiler, storage tanks and pipe work).

The cumulative losses over the four stages thus amount to over 80 per cent of the original coal energy content. In terms of efficiency, the overall efficiency is:

0.98 x 0.28 x 0.87 x 0.80 = 0.191 (or 19.1%)

Table 3: Steps of hot water production

Key steps	Energy input (energy units)	Step losses (per cent)	Energy output (energy units)	Corresponding efficiency (of the step per cent)
Step 1: primary energy resource	100	2	98	98
Step 2: power station	98	72	27.4	28
Step 3: electricity trans-mission and distribution	27.4	13	23.3	87
Step 4: water heater	23.9	20	19.1	80
Overall result	**100**	**80.9**	**19.1**	**19**

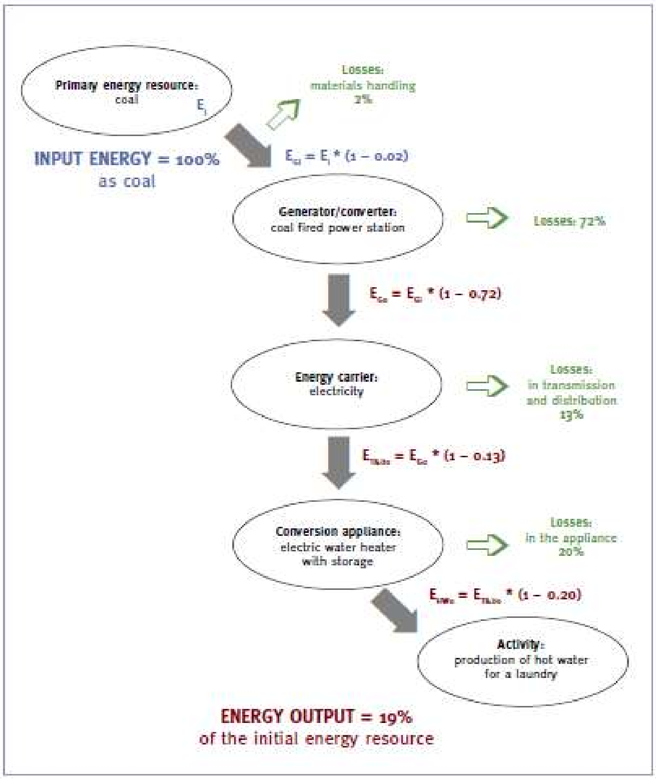

Figure 3: Steps of hot water production[8]

8. Solar water heating (SWH) systems

The main part of a SWH is the solar collector array that absorbs solar radiation and converts it into heat. The heat is absorbed by a heat transfer fluid that passes through the collector. This heat is stored or used directly. In solar water heating systems, water is heated directly in the collector or indirectly by a heat transfer fluid that is heated in the collector, passes through a heat exchanger to transfer its heat to the domestic or service [9]. The heat transfer fluid is transported either naturally or by forced circulation. Natural circulation occurs by natural convection, whereas for the forced circulation systems, pumps are used.

Five types of solar energy systems used to heat domestic and service hot water are:

- Thermosyphon
- Integrated collector storage (ICS)
- Direct circulation
- Indirect
- Air to water

The first two are called passive systems as no pump is employed, whereas the others are called active systems because a pump or fan is employed in order to circulate the fluid.

8.1 Thermosyphon system

Thermosyphon system is shown schematically in Figure 4, heat potable water or heat transfer fluid and use natural convection to transport it from the collector to storage. The water in the collector expands becoming less dense as the sun heats it and rises through the collector into the top of the storage tank. There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector [9]. The circulation is continuous as long as there is sunshine. Since the driving force is only a small density difference larger than normal pipe sizes must be used to minimise pipe friction. Connecting lines must be well insulated to prevent heat losses and sloped to prevent formation of air pockets which would stop circulation [4]. At night, or whenever the collector is cooler than the water in the tank the direction of the thermosyphon flow will reverse, thus cooling the stored water.

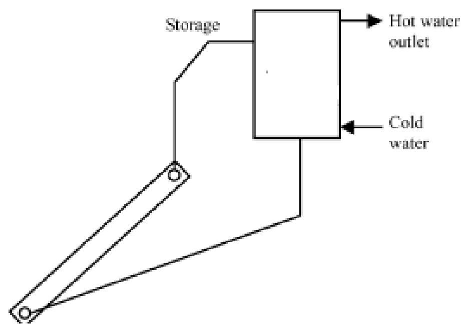

Figure 4: Thermosyphon systems

8.2 Integrated collector storage systems (ICS)

ICS systems use hot water storage as part of the collector. The surface of the storage tank is used also as an absorber. As in all other systems, to improve stratification, the hot water is drawn from the top of the tank and cold make-up water enters to the bottom of the tank on the opposite side. The main disadvantage of the ICS systems is the high thermal losses from the storage tank to the surroundings since most of the surface area of the storage tank cannot be thermally insulated as it is intentionally exposed for the absorption of solar radiation [9].

Advantages:

- Passive solar water heater systems contain no electrical components,
- They are more reliable, easier to maintain
- Have a longer work life than active solar water heater systems.

8.3 Direct circulation system

In direct circulation system in Figure 5, a pump is used to circulate potable water from storage to the collectors when there is enough solar energy to increase its temperature and then return the heated water to the storage tank until it is needed. Since pump circulates the water, the collectors can be mounted either above or below the storage tank. The pump circulates the water from the tank up to the collector and back again. This system has a differential controller that senses temperature differences between water leaving the solar collector and the coldest water in the storage tank. When the water in the collector is about 5°C warmer than the water in the storage tank, the pump is turned on by the controller [5]. When the temperature difference drops to about 1°C, the pump is turned off.

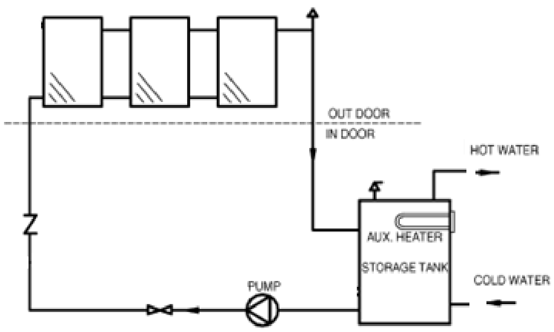

Figure 5: Active and direct system

Direct circulation system is used with water supplied from a cold water storage tank or connected directly to municipal mains. Pressure-reducing valves and pressure relief valves are required however when the city water pressure is greater than the working pressure of the collectors. Direct water heating systems should not be used in areas where the water is extremely hard or acidic because scale deposits may clog or corrode the collectors.

8.4 Indirect water heating systems

Indirect water heating system in Figure 6, circulates a heat transfer fluid through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water. The commonly used heat transfer fluids are water/ethylene glycol solutions; although other heat transfers fluids such as silicone oils and refrigerants can also be used [4].

Pump circulates a non-freezing, heat transfer fluid through the collector(s) and a heat exchanger. This heats the water that then flows into the home. This type of system works well in climates prone to freezing temperatures.

A fail-safe method of ensuring that collectors and collector loop piping never freeze is to remove all the water from the collectors and piping when the system is not collecting heat. This is a major feature of the drain back system. Freeze protection is provided when the system is in the drain mode. Water in the collectors and exposed piping drains into the insulated drain-back reservoir tank each time the circulating pump shuts off [8].

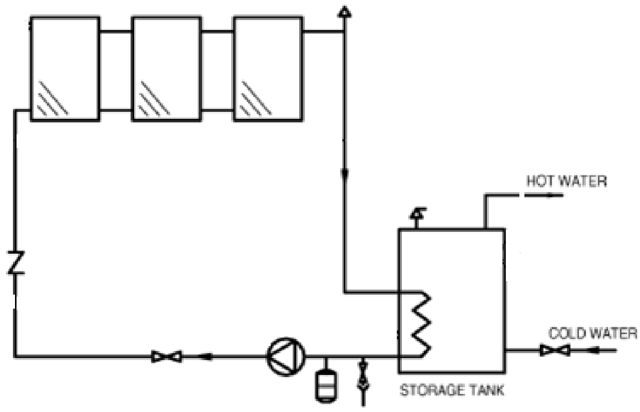

Figure 6: Indirect and Active System

8.5 Air systems

Air systems are an indirect water heating systems that circulate air via ductwork through the collectors to an air-to liquid heat exchanger. In the heat exchanger, heat is transferred to the water, which is also circulated through the heat exchanger and returned to the storage tank as shown in Figure 6. The main advantage of the system is that air does not need to be protected from freezing or boiling, is noncorrosive, and is free. The disadvantages are that air handling equipment (ducts and fans) need more space than piping and pumps, air leaks are difficult to detect, and parasitic power consumption is generally higher than that of liquid systems [7].

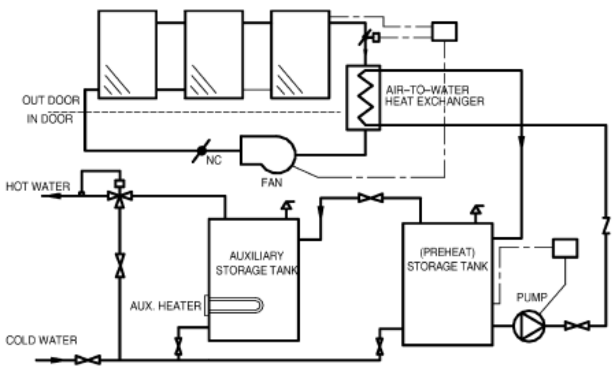

Figure 6: Air system

9. Solar thermal heating technologies

9.1 Stationary collector

Solar collectors are a special kind of heat exchanger that transforms solar radiation energy to internal energy of the transport medium. There are three types of stationary collectors namely [2]:

1. Flat plate collectors (FPC)
2. Stationary compound parabolic collectors (CPC)
3. Evacuated tube collectors (ETC).

9.1.1 Flat plate collectors

An FPC generally consists of the following items as shown in Figure 7

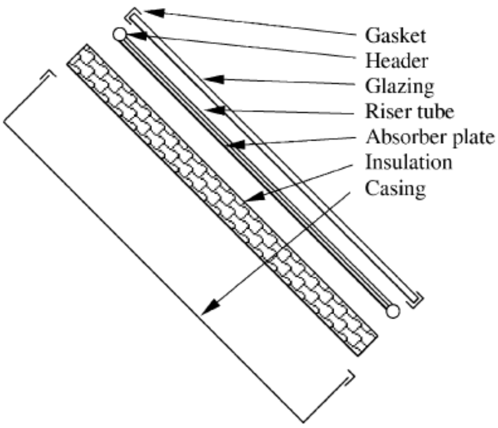

Figure 7: Flat collector

The glazing should be one or more sheets of radiation transmitting material. Glass can transmit as much as 90% of incoming short radiation while it is transparent to long wave radiation emitted by the absorber plate. Glass with low iron content has a relatively high transmittance of 0.85 – 0.90 at normal incidence while it is virtually transparent to long wave radiation (5 – 50 mm). Plastic films and sheets have a high shortwave transmittance but also have significant long wave transmittance of up to 0.40. However transmittance varies with the angle of incidence [1].

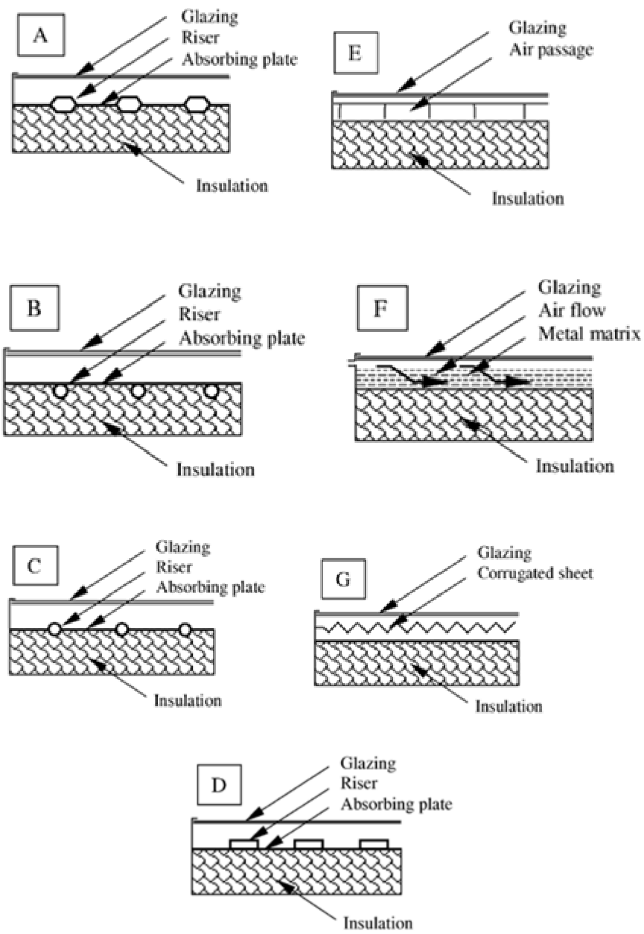

Figure 8: Types of flat plate collector

The absorber plates should be flat, corrugated or grooved plates to which the tubes, fins, or passages are attached. The absorptance of the collector surface for shortwave solar radiation depends on the nature and colour of the coating and the incidence angle. Commercial solar absorbers are made by electroplating, anodization, evaporation, sputtering and by applying solar selective paints [3]. Material most frequently used for absorber plates are copper, aluminium and stainless steel. The tubes should have good contact with the absorbing surface and copper is usually used because of corrosion resistance. In order to achieve a good bond between tubes and absorber plates mechanical pressure, thermal cement or brazing can be used. FPC is usually employed for low temperature applications usually up to 100°C. However, with the use of selective coatings temperatures of up to 200°C have been achieved.

Flat plate collectors are usually permanently fixed in position and require no tracking of the sun. The collectors should be oriented directly towards the equator and the optimum tilt angle is equal to the latitude with angle variations of plus or minus 15°.

9.1.2 Evacuated tube collector

The vacuum envelop employed in ETC reduce convective losses to the environment and hence the collectors can operated at higher temperatures than FPC. Like FPC they collect both direct and diffuse radiation. However, their efficiency is higher at lower incidence angles. ETC use liquid- vapour phase materials to transfer heat at high efficiency. These collectors have a heat pipe which is a sealed copper pipe, attached to a black copper fin that fills the tube forming the absorber plate .The heat pipe contains a liquid usually methanol which evaporates when heated and rises to the heat sink, the water tank where it condenses releasing the absorbed heat [9].

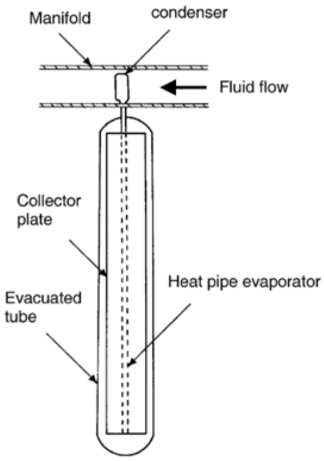

Figure 9: Evacuated Tube Collector

10. Hot water consumption

Owing to Zimbabwe's very mild climate, hot-water heating is the largest user of energy in the domestic sector. It is estimated that as high as 40% to 50% of the monthly electricity use of an average household is used for water heating [9].

The average household size for non poor families Zimbabwe is 3.5

Table 4: Water use by fixture

Category	Per Capita Hot Water Use (litres/day)	Household Hot Water Use (litres/day)	Percent of Total Hot Water Use in Each Category (%)	Percent of Overall Use that is Hot Water (%)
Bath	15.9	41.3	16.7	78.2
Clothes Washer	14.8	38.2	15.5	27.8
Dishwasher	3.4	8.7	3.6	100
Faucet	32.6	84.8	34.3	72.7
Leak	4.5	11.7	4.8	26.8
Shower	23.8	62.1	25.1	73.1
Toilet	0.0	0.0	0	0.0
Other	0.04	0.1	0	35.1
Indoor Total	95.0	247.2	100%	39.6%

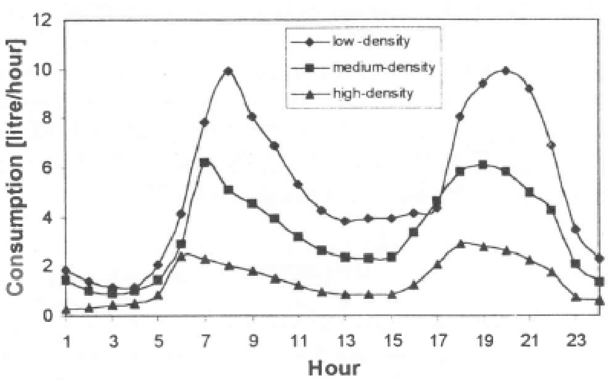

Figure 10: Daily water demand profile [10]

11. Solar water heating option impact assessment

The assessment of the economic impact of the wide scale use of solar water heaters was carried out in comparison with energy efficiency strategies, electrical energy management strategies and various other measures that the power utility PowerCo can to solve energy problem. Solar water heaters are an energy efficiency intervention strategy [6].

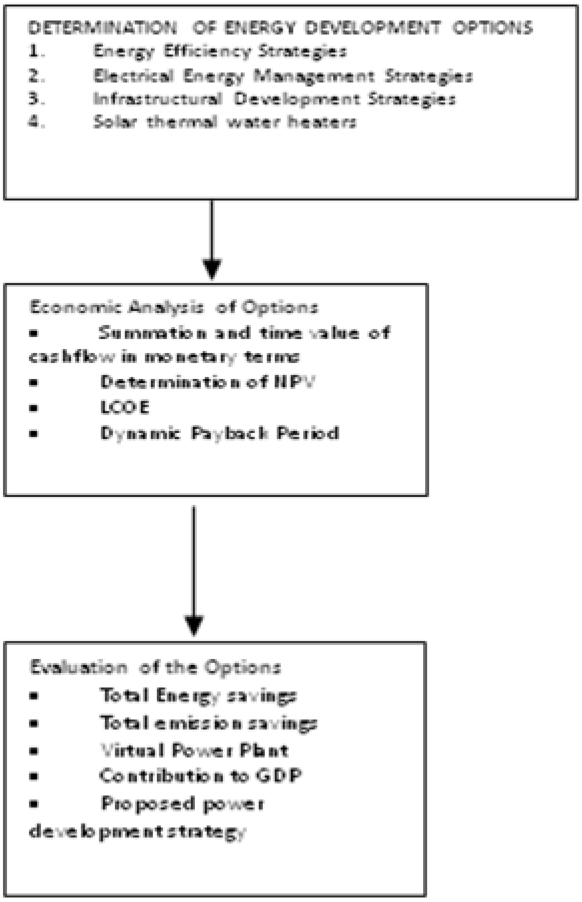

Figure 11: Energy assessment methodology [1]

The average cost of generating electricity was US$0.0492 per kilowatt-hour. PowerCo charges an average tariff of US$0.0983 to domestic customers. PowerCo's break-even tariff rate is US$0.11 per kilowatt-hour. Electricity production from hydro is 57% while electricity production from fossil fuels is 43% [10]. Table 5 shows electrical energy consumption pattern over the past twelve years.

Table 5: Energy consumption over years (MWh per year)

Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Zimbabwe	8.4	6.94	10.48	9.81	9.81	11.22	11.22	11	11.59	11.59	10.89	10.89	12.47

Zimbabwe's energy requirements stood at 12,470,000 MWh. Electrical Energy Management strategies aim to contain all the country's energy demand within its energy generation capacity to avoid electricity imports or major infrastructural developments involving large capital outlay. Energy

Efficiency strategies aim to reduce the amount of energy consumed and infrastructural development strategies aim to increase the supply capacity.

Renewable energy strategies such as solar water heating is to be implemented to mitigate [5]. Power Co's problems. Figure 12 shows a water demand profile. It was established that the shape of the water demand curve is similar in shape to that of the electricity demand curve in Figure 1, which strongly suggests that water heating is key to solving the problems of PowerCo.

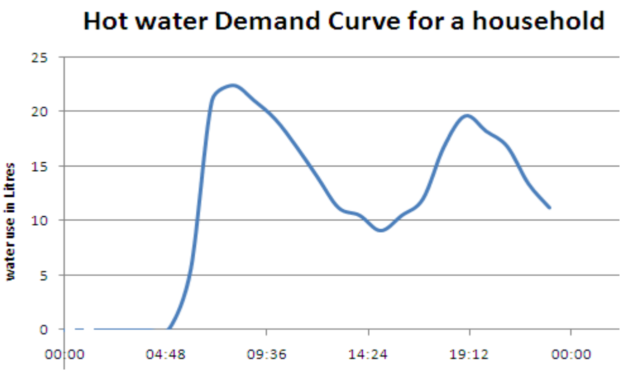

Figure 12: Hot water demand for domestic use [10]

11.1 Infrastructural development option

Feasibility studies for infrastructural development aimed at increasing the domestic generation capacity were considered and are long term solutions and difficult to implement given the financial position of PowerCo [10].

Table 6: Infrastructure development and time frames involved (both thermal & hydro)

Project Title	Estimated Cost (US$)	Implementation Time Frame
Hwange Stage 3: 2 x 300MW	600 million	3 – 4 years
Kariba South Extension 2 x 150 MW	300 million	4 – 5 years
Gokwe North 2 x 350 MW	1400 million	5 – 6 years
Batoka Gorge 4 x 200 MW	1350 million	5 – 6 years
Lupane Gas 2 x 150 MW	300 million	2 – 3 years

11.2 Electrical energy management strategies

11.2.1 Use of a timer

The use of a 24 hour timer is to regulate the operation of the geyser to reduce peak demand and overall energy consumption. The geyser should be operated during off peak periods to reduce peak demand on electricity [3]. This kind of system could work as a substitute to the ripple control system. While it could work for geysers, it could also be extended to air-conditioning systems. Geyser timers are supplied at US$50 per unit and installed at US$20 per unit.

Table 7 shows the variation of energy demand with hour of the day. During the week days from 7 am to 11 am, it is most probable that hot water is used for bathing and laundry. Because of high water usage during this period the geysers are operational. At the same time people want to prepare food for breakfast hence the peak energy demand during this period.

Table 7: Power demand chart [10]

	HOUR																							
Day of week	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Sunday/Holiday	O	O	O	O	O	O	S	S	S	S	S	S	S	S	S	S	S	P	P	P	S	S	O	O
Week-day	O	O	O	O	O	O	O	P	P	P	P	P	S	S	S	S	S	P	P	P	P	S	O	O
Saturday	O	O	O	O	O	O	O	P	P	P	P	S	S	S	S	S	S	P	P	P	S	S	O	O

Key O - Off peak period
P - Peak period
S - Standard period

Number of geysers in use = 227,000
Number of geysers to be temperature adjusted = 227,000
Analysis period = 20 years
Average Cost of generating electricity = $0.0492
Average selling price of electricity = $0.075
Probability that all geysers are ON at the same time during peak hours = 0.85 (PowerCo assumption)

Table 8: Costs table

Operating and Maintenance Costs	
Fixed Operation Disposal *Costs*	
Variable Operating Costs	
Installation costs @$20 per unit	**4,540,000**
Investment Costs **227000 timers @ $50.00 per unit**	**11,350,000**
Energy saved per year	
Energy Savings per annum	
Reduction in Peak Electrical Energy Demand	
227,000 x 1500W x 0.85 = **289,425 MW** Distribution and transmission costs 15.15% Equivalent virtual power plant 289,425/0.845 = **<u>342,515 MW</u>**	

Calculating levelized cost of energy (LCOE)

n = Analysis Period
d = discount rate
TLCC = Total life cycle costs

I = Initial Investment

PVOM = Present Value of Operations and Maintenance Costs

TLCC = I + PVOM

n = 25

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

TLCC = OM $[(1 + d)^n - 1] / [d(1 + d)^n]$

I = **11,350,000.00 + 4,540,000.00**

TLCC = US$ 15,890,000.00

11.2.2 Ripple control system

Calculating levelized cost of energy (LCOE)

n = Analysis Period
d = discount rate
TLCC = Total life cycle costs

I = Initial Investment

PVOM = Present Value of Operations and Maintenance Costs

TLCC = I + PVOM

n = 25

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

TLCC = OM $[(1 + d)^n - 1] / [d(1 + d)^n]$

I = **11,350,000.00 + 4,540,000.00**

TLCC = US$ 15,890,000.00

11.2.2 Ripple control system

The primary use of the ripple control system is to switch off all geysers during peak power demand hours. PowerCo in 2012 estimates water heating constitutes 39% of domestic load. Ripple control systems to control domestic water heaters if installed in two major cities to switch off the geysers during the evening peak, the system has a potential of shedding 270 MW. Then another 270 MW if extended to new houses and other towns. This extension requires about US$13 million [10].

The basic arrangement of the ripple control scheme consists of the following components:

- Main controller located at the National Control Centre
- Modem pairs located at the National Control Centre
- Pilot cable which form the communication channel
- Local controllers located at the substation
- Coupling networks located at the substation and used for blocking signals
- Receivers located in the houses

The communication channel is over the already existing distribution network cables, overhead lines and transformers. A command signal is sent from the NCC to a frequency generator located at the substation. The frequency generator injects a signal called a ripple control code into the distribution network. This signal activates all relay receivers which are wired on the back of the distribution boards in houses where geysers are located. The signal switches the geysers on or off.

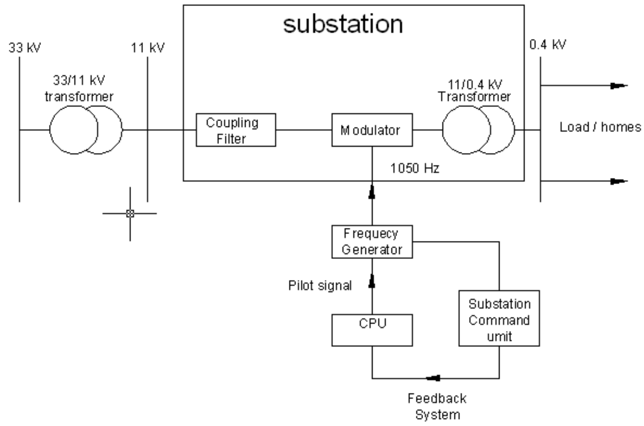

Figure 13: Schematic diagram of ripple control system

11.3 Energy efficiency strategies

11.3.1 Geyser temperature setting

Traditionally thermostats are set at 65°C or even higher, in many instances it is possible to reduce the temperature to 60°C or even 55°C.

Energy policy is to make it mandatory for geyser thermostats to be set between 55°C and 60°C, particularly in a warm climate like Zimbabwe. Temperature should not be set below 55°C due to the possibility of microbial growth in the water. A good water storage tank should lose at most 2% of its heat over 24 hrs. The design of the insulation plays a very important part in this regard. For geysers that are already installed, it is possible to further improve their performance through the use of geyser blankets [7]. Choice of the insulation material and design of the thickness is very important in the design of the geysers to achieve 98% storage efficiency. Table 9 gives a list of recommended insulating materials.

Calculating energy losses in geysers

$q_{losses} = (T_h - T_{ambient}) / (\Delta x / k + 1/h)$
q_{losses} = heat loss in W/m^2
T_h = water temperature inside the HWC in ºC
$T_{ambient}$ = air temperature outside the HWC in ºC
Δx = thickness of insulation layer in m
k = thermal conductivity in W/m.K
h = surface heat transfer coefficient in W/m^2.K
For these calculations all pipe losses were excluded and the following values are assumed:

There are three cases:

1. set temperature T_r = 65˚C
2. Set temperature T_r = 60˚C
3. Set temperature T_r = 55˚C

Table 9: Insulation materials [4]

Generic Insulation Products	Density Kg/m³	Thermal Conductivity W/(m.k.)
Cellulose Fiber Loose-Fill	27.5	0.040
Flexible Fiber Glass Blanket	10-18	0.040
Flexible BOQ Polyester Fiber Blanket	24	0.038
Flexible Polyester Blanket	11.5	0.046
Flexible Mineral / Rock Wool	60-120	0.033
Flexible Ceramic Fiber	84	0.033
Rigid Expanded Polystyrene (EPS)SD	15	*0.035
Rigid Extruded Polystyrene (XPS)	32	*0.028
Rigid Fiber Glass Board	47.5	0.033
Rigid BOQ Polyester Fiber Board	61	0.034
Rigid Polyurethane Board	32	*0.025

$T_{ambient}$ = average ambient air temperature for the whole day outside the HWC is 20 ºC
Δx = thickness of insulation layer is 0.035 m
k = thermal conductivity is 0.055 W/m.K
h = surface heat transfer coefficient in 6.3 $W/m^2.K$
A = surface area of 1.5 m^2 for 150 litre geyser

$R_{Total} = 1/h_o + x_1 / k_1$

$q_{losses} = A \times (T_r - T_m) / (R_{Total})$

Scenario 1:

a) Case of T_r = 65°C

q_{losses} = 1.5 (65 – 20) / (0.035 / 0.055 + 1/6.3)
= 84.9 W

b) Case of T_r = 60°C
q_{losses} = 1.5 (60 – 20) / (0.035 / 0.055 + 1/6.3)
= 74.7 W

c) Case of T_r = 55°C
q_{losses} = 1.5(55 – 20) / (0.035 / 0.055 + 1/6.3)
= 66 W

11.3.1.1 Economic analysis of geyser temperature setting

Number of geysers in use = 227,000
Number of geysers to be temperature adjusted = 227,000
Average number of operating hours per day = 24 hrs
Analysis period = 20 years (Same as solar geyser)
Power saving by adjusting to 60ºC= 9.45 watts
Power saving by adjusting to 55ºC= 18.9 watts
Adjustment costs = $5000
Average Cost of generating electricity= $0.502
Average selling price of electricity = $0.075
Assuming that all geysers are operational

Table 10: Costs analysis

Operating and Maintenance Costs	
Fixed Operation Disposal *Costs*	
Adjustment and inspection costs per	**5,000.00**
Variable Operating Costs	
Electricity generation costs per annum	
Investment Costs	
Energy saved	
227,000 x 18.9 x 24x365 /1000 = ***37,583,028 kWh*** Distribution Losses 15.15 % Equivalent Energy saved ***37,583,028 kWh*** / (1 -15.15) = 44,293,492.04 ***kWh***	
Energy Savings per year 44,293,492.04 ***kWh*** **x** 0.0502	**2,223,533.00**
Reduction in Peak Electrical Energy Demand	

Calculating levelized cost of energy (LCOE)

Energy Savings per annum = US$2,223,533.00

n = Analysis Period
d = discount rate

TLCC = Total life cycle costs

I = Initial Investment

PVOM = Present Value of Operations and Maintenance Costs

TLCC = I + PVOM

n = 25

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

TLCC = OM $[(1 + d)^n - 1] / [d(1 + d)^n]$

TLCC = $5000[(1 + 0.095)^{25} – 1] / [0.095(1 + 0.095)^{25}]$

TLCC = <u>US$ 47,190.00</u>

LCOE = TLCC / $[\Sigma_n Q / (1 + d)^n]$

Q = Energy saved per year

= 44,293,492.04 ***kWh***

Amount of energy saved in the analysis period = $[\Sigma_n Q / (1 + d)^n]$

$[\Sigma_n Q / (1 + d)^n]$ = Q x $[(1 + d)^n - 1] / [d(1 + d)^n]$

= 44,293,492.04 ***kWh*** x $[(1 + 0.095)^{25} – 1] / 0.095$

= 418,041,977.9 ***kWh***

LCOE = US$ 47,190.00 /418,041,977.9 ***kWh***

= US$ 0.00011288

11.4 Power factor correction

Power factor correction reduces demand by 218 MW. The annual capacity is 1910 GWh valued at US$129,000,000 annually for PowerCo.

11.5 Energy Efficient Lighting

Estimated 5,670,000 incandescent lamps are installed in the country amounting to 340MW. The national lighting load could be reduced to 62 MW through the use of energy saving lights [3]. These energy savers used only 20% of the conventional lamp energy for the same light output and lasted up to six times longer. The savings would translate to about US$2million per month on the import bill. The project cost is estimated at US$15 million.

Table 11 shows the different lighting options that are available. Two cases are considered for energy efficient lighting:

- Replacement of all incandescent lamps by compact fluorescent lights (CFL)
- Replacement of all incandescent lamps by LED lights

Table 11: Lighting Options

			
	Light emitting diode	Incandescent light bulb	Compact fluorescent light
Life Span (average)	**50,000 hours**	**1,200 hours**	**8,000 hours**
Watts of electricity used (equivalent to 60 watt bulb).	**6 - 8 watts**	**60 watts**	**13-15 watts**
Kilo-watts of Electricity used			
Contains the TOXIC Mercury	**No**	**No**	**Yes** - Mercury is very toxic to your health and the environment
Carbon Dioxide Emissions (30 bulbs per year) Lower energy consumption decreases: CO2 emissions, sulfur oxide, and high-level nuclear waste.	**451 pounds/year**	**4500 pounds/year**	**1051 pounds/year**
Sensitivity to low temperatures	**None**	**Some**	**Yes - may not work under negative 10 degrees**
Sensitive to humidity	**None**	**Some**	Yes
Quick On/off switching	**No Effect**	**Some**	**Yes - can reduce lifespan drastically**
Durability	**Very Durable. Good impact resistance**	**Not Very Durable - glass or filament is very fragile**	**Not Very Durable - glass or filament is very fragile**
Lumens	Watts	Watts	Watts
450	4 – 5	**40**	9 – 13
800	**6 – 8**	60	13 – 15
1100	9 -13	75	18 – 25
1600	16 -20	100	23 – 30
2600	25 – 28	150	30 -55
Price (75 watt)	$17.20	$0.60	$1.89

11.5.1 Economic Analysis of compact fluorescent light (CFL)

Case 1: CFL

Number of bulbs in use =5,500,000

Number of bulbs to be replaced =5,500,000

Average number of lighting hours per day = 6 hrs

Life span of CFL bulb = 10000 hrs

Number of days = 1667 days

Number of years = 4.6 years ≈ 5 years

Analysis period = 5 years

Average wattage of each bulb = 18.5 watts

Average price of bulb = $1.89

Cost of disposal = $28000

Salvage value = 0

Installation costs = 0

Distribution costs= $5000

Average Cost of generating electricity = $0.0502

Average selling price of electricity =$0.075

Probability that all lights are on at the same = 0.65 (this is what PowerCo uses)

Table 12: Cost analysis for CFL

Operating and Maintenance Costs	
Fixed Operation Costs	
Disposal _ one off payment after 5 years	**US$28,000.00**
Distribution costs _ one off payment	**5,000.00**
Variable Operating Costs	
Electricity generation costs per annum	
5500000 x 6 x 365/1000 x 18.5 x 0.0492	**10,963,359.00**
Investment Costs	
5500000 million bulbs @$1.89 each	**10,395,000.00**
Energy saved	
5,500,000 x 6 x 365 /1000 x (75-18.5) = ***680,542,500 kWh*** **Distribution and transmission efficiency = 0.8485** Equivalent energy saved = ***802,053,624 kWh***	
Energy Savings ***802,053,624 kWh*** x 0,0502	**40,263,091.93**
Reduction in Peak Electrical Energy Demand	
5500000x (75 – 18.5) = **310,75 MW x 0.65 = 201.5 MW**	
equivalent virtual power plant = 201.5/0.8485 = <u>238.5 MW</u>	

Calculating LCOE

Energy Savings per annum = US$40,263,091.93

n = 5

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

TLCC = I + OM $[(1 + d)^n-1]/ [d(1 + d)^n]$

I = 5,000.00 + 10,395,000.00 = 10,400,000.00

TLCC = 10,400,000.00 + **10,963,359.00** $[(1 + 0.095)^5 – 1]/ [0.095(1 + 0.095)^5]$
+ $28000(1 + 0.095)^5$

TLCC = <u>US$ 52,543,377.24</u>

LCOE = TLCC / $[\Sigma_n Q / (1 + d)^n]$

Q = Energy saved per year

= ***802,053,624*** **kWh**

Amount of energy saved in the analysis period = $[\Sigma_n Q / (1 + d)^n]$

$[\Sigma_n Q / (1 + d)^n]$ = Q x $[(1 + d)^n-1]/ [d(1 + d)^n]$

= ***802,053,624*** **kWh** x 3.84

= 3,079,885,916 ***kWh***

LCOE = US$ 52,543,377.24/3,079,885,916 ***kWh***

<u>= US$ 0.017</u>

11.5.2 Economic analysis of LED

Case 2: LED lights

Number of bulbs in use = 5,500,000

Number of bulbs to be replaced = 5,500,000

Average number of lighting hours per day = 6 hrs

Life span of LED bulb = 50000 hrs

Number of days = 8333.3 days

Number of years = 22.8 years ≈ 23 years

Analysis period =23 years

Average wattage of each bulb = 10 watts

Average price of bulb = $17.20

Cost of disposal = $5500 (Land fill)

Salvage value = 0

Installation costs = 0

Distribution costs = $5000

Average Cost of generating electricity= $0.0492

Average selling price of electricity = $0.075

Probability that all lights are on at the same = 0.65 (this is what PowerCo uses)

Table 13: Cost analysis for LED

Operating and Maintenance Costs	
Fixed Operation Costs	
Disposal once off payment after 23 years	**US$5,500.00**
Distribution costs once off payment	**5,000.00**
Variable Operating Costs	
Electricity generation costs per annum	
5500000 x 6 x 365/1000 x 10 x 0.0492	**5,926,140.00**
Investment Costs	
5500000 million bulbs @$17.20 each	**94,600,000.00**
Energy saved	
5,500,000 x 6 x 365 /1000 x (75-10) = ***782,925,000 kWh*** Distribution and transmission efficiency = 0.8485 Equivalent Energy Saved = ***782,925,000 kWh/0.8485*** = ***922,716,558.6 kWh***	
Energy Savings *922,716,558.6* ***kWh*** **x $0.0502**	**46,320,371.24**
Reduction in Peak Electrical Energy Demand	
5500000x (75 – 10) = **357.50 MW x 0.65** **=232.375 MW**	
equivalent virtual power plant 232.375/0.8485 = <u>275 MW</u>	

11.6 Solar water heating

11.6.1 Calculation of daily radiation for Zimbabwe from January to December

Extra terrestrial radiation falling on a horizontal surface is given by [1]

$H_0 = 24/\pi \times 3600 \times 1367\ [1 + 0.033\cos(360n/365)][\ \sin\delta \sin\text{Ø}\ \omega_s + \cos\delta \cos\text{Ø} \sin\omega_s]$
ω_s = Sunset hour angle
Ø = latitude for a particular location
n = day number
δ = declination angle
$\omega_s = \arccos(-\tan\delta \tan\text{Ø})$
$\delta = 23.45 \sin((n-81)\times 360/365)$

H_0 = is the daily total extraterrestrial radiation falling on a horizontal plane at a particular location outside the atmosphere of the earth.

H_h = is the daily total radiation falling on a horizontal plane on the surface of the earth at a particular location. It is experimentally determined.

Table 14 shows the H_o, H_h, H_d and average air temperature for the average month days for Harare.

Table 14: Daily radiation data on a horizontal surface

Day	n	δ	ω_s	H_o (MJ)	H_h (MJ)	K_h	H_d/H_h	H_d (MJ)	Temp
17-Jan	17	-20.9	97	41.4	20.3	0.49	0.47	9.54	22.1
16-Feb	47	-12.95	94.23	39.91	20	0.5	0.46	9.2	21.9
16-Mar	75	-2.42	90.78	36.86	19.37	0.53	0.43	8.33	21.6
15-Apr	105	9.41	86.95	32.16	18.65	0.58	0.368	6.86	20.4
15-May	135	18.8	83.73	27.63	17.24	0.62	0.32	5.52	18.4
11-Jun	162	23.1	82.13	25.34	15.7	0.62	0.32	5.02	16.3
17-Jul	198	21.2	82.85	26.24	16.7	0.64	0.3	5.01	16.2
16-Aug	228	13.45	85.6	29.99	19.55	0.65	0.29	5.67	18.7
15-Sep	258	2.22	89.28	34.5	22.97	0.67	0.27	6.2	22.3
15-Oct	288	-9.6	93.1	38.66	23.36	0.6	0.35	8.18	23.7
14-Nov	318	-18.9	96.3	40.8	22.07	0.54	0.41	9.05	23.5
10-Dec	344	-23	97.8	41.55	20.05	0.48	0.48	9.62	22.2

K_h = is the clearness index, a measure of the clearness of the sky
$K_h = H_h / H_0$

If $K_h < 0.75$
$H_d / H_h = 1.0294 - 1.14(K_h)$

H_d = is the daily diffuse radiation falling on a horizontal plane on the surface of the earth.
I_d = is the hourly diffuse radiation falling on a horizontal plane on the surface of the earth.

$I_d = r_d \times H_d$
$r_d = \pi/24 \times (\cos\omega - \cos\omega_s)/(\sin\omega_s - \omega_s \cos\omega_s)$
$I_h = r_h \times H_h$
$r_h = r_d\ [a + b\cos\omega]$
$a = 0.409 + 0.5016 \sin(\omega - 60)$
$b = 0.6609 - 0.4767\sin(\omega - 60)$

I_h = is the hourly total radiation falling on a horizontal plane on the surface of the earth.

$I_b = I_h - I_d$
$R_b = \cos\theta_{eq} / \cos\theta_z$
$\cos\theta = \sin\delta\sin\text{Ø}\cos\beta + \sin\delta\cos\text{Ø}\sin\beta\cos\gamma + \cos\delta\cos\omega\cos\text{Ø}\cos\beta - \cos\delta\cos\omega\sin\text{Ø}\sin\beta\cos\gamma + \cos\delta\sin\beta\sin\gamma\sin\omega$

γ = solar surface azimuth angle
ω = hour angle
β = angle of collector tilt to the horizontal

to determine $\cos\theta_z$, $\beta = 0$
$\cos\theta_z = \sin\delta \sin\text{Ø} + \cos\delta \cos\omega \cos\text{Ø}$
to determine $\cos\theta_{eq}$, $\gamma = 0$
$\cos\theta_{eq} = \sin\delta\sin\text{Ø}\cos\beta + \sin\delta\cos\text{Ø}\sin\beta + \cos\delta\cos\omega\cos\text{Ø}\cos\beta - \cos\delta\cos\omega\sin\text{Ø}\sin\beta$
$= \sin\delta \sin(\text{Ø} + \beta) + \cos\delta\cos\omega \cos(\text{Ø} + \beta)$

$R_b = (\sin\delta \sin(\text{Ø}+\beta) + \cos\delta \cos(\text{Ø}+\beta) \cos\omega) / (\sin\delta\sin\text{Ø} + \cos\text{Ø}\cos\delta\cos\omega)$

$I_T = I_b R_b + I_d F_d + I_h \rho_g F_g$ (Liu, Jordan, 1963)

$F_d = (1 + \cos\beta) / 2$
$F_g = (1 - \cos\beta) / 2$
ρ_g = Ground reflectance

The hourly total radiation for January the average day are tabulated in the Table 15.

Table 15: Hourly total radiation on a tilted surface

Jan		ωs	97										
	ω	rd	rh	rb	I_d	I_h	I_b	F_d	ρF_g	$I_b F_b$	$I_d F_d$	$I_h \rho F_g$	I_T
05:30	-97.5	0	0	17.30167	0	0	0	0.976065	0.0072	0	0	0	0
06:30	-82.5	0.0275581	0.020936	0.541577	0.262904	0.424992	0.162088	0.976065	0.0072	0.087783	0.256612	0.003059945	0.347455
07:30	-67.5	0.05509017	0.047047	0.795438	0.52556	0.955054	0.429494	0.976065	0.0072	0.341636	0.512981	0.006876388	0.861493
08:30	-52.5	0.07977476	0.074873	0.874213	0.761051	1.519924	0.758873	0.976065	0.0072	0.663417	0.742835	0.010943451	1.417195
09:30	-37.5	0.09992964	0.100689	0.909695	0.953329	2.043981	1.090653	0.976065	0.0072	0.992162	0.930511	0.014716665	1.937389
10:30	-22.5	0.11418129	0.120623	0.92723	1.08929	2.448643	1.359354	0.976065	0.0072	1.260434	1.063217	0.017630233	2.341281
11:30	-7.5	0.12155849	0.131488	0.934693	1.159668	2.669207	1.509539	0.976065	0.0072	1.410955	1.131911	0.019218293	2.562085
12:30	7.5	0.12155849	0.131488	0.934693	1.159668	2.669207	1.509539	0.976065	0.0072	1.410955	1.131911	0.019218293	2.562085
13:30	22.5	0.11418129	0.120623	0.92723	1.08929	2.448643	1.359354	0.976065	0.0072	1.260434	1.063217	0.017630233	2.341281
14:30	37.5	0.09992964	0.100689	0.909695	0.953329	2.043981	1.090653	0.976065	0.0072	0.992162	0.930511	0.014716665	1.937389
15:30	52.5	0.07977476	0.074873	0.874213	0.761051	1.519924	0.758873	0.976065	0.0072	0.663417	0.742835	0.010943451	1.417195
16:30	67.5	0.05509017	0.047047	0.795438	0.52556	0.955054	0.429494	0.976065	0.0072	0.341636	0.512981	0.006876388	0.861493
17:30	82.5	0.0275581	0.020936	0.541577	0.262904	0.424992	0.162088	0.976065	0.0072	0.087783	0.256612	0.003059945	0.347455
18:30	97.5	0	0	17.30167	0	0	0	0.976065	0.0072	0	0	0	0

11.6.2 Solar water heating collector equation

Glazed or evacuated collectors are described by the following equation

$Q_{coll} = F_R \tau\alpha G - F_R U_L (Ta - Ti)$

11.7 Solar passive hot water heating System

Figure 4 describes the water heating system to be used in this study. It has a standby electricity heating element to be used where solar can not provide the required hot water temperature.

Mathematical model for solar water heating

$mc_p dT_s/dt = A_c[GF_R\tau\alpha - F_R U_L(T_s - T_a)] - (1 + p)U_s A_s(T_s - T_a) - \dot{m}c_p(T_s - T_m)$

m = mass of water in the storage tank
$\dot{m}$ = mass flow rate through the tank due to water usage
c_p = specific heat capacity of water
G = Solar irradiance at a particular location on the earth's surface

F_R = Collector heat removal factor
τ = glass transmittance
α = Surface absorptivity constant

$F_R U_L$ = Collector heat loss coefficient
T_s = Water storage temperature
T_m = Mains water temperature
T_a = Ambient temperature

U_s = Storage tank heat loss coefficient
A_s = Surface area of storage tank
p = proportion of pipe losses with respect to tank storage losses

A_c = Aperture area of collector

Mathematical model for numerical solution of solar water heating

$mc_p\Delta T_s = A_c I_T F_R \tau\alpha - A_c F_R U_L(T_s - T_a)]x3600 - (1 + p)U_s A_s(T_s - T_a)x3600 - m_d c_p(T_s - T_m)$ (i

I_T = hourly total solar radiation falling on a tilted surface

m_d = hourly water demand

The solar collector chosen for this analysis is model SV maxorb manufactured by Edwards hot water. The specifications for this glazed flat plate solar collector are as follows:

Aperture area = 1.81 m^2
F_R ατ = 0.76
$F_R U_L$ = 5.45 $W/m^2{}^{\circ}C$

Q_{coll} is the energy collected per unit collector area per unit time

F_R is the collector's heat removal factor,
τ is the transmittance of the cover,
α is the shortwave absorptivity of the absorber,
G is the global incident solar radiation on the collector,
U_L is the overall heat loss coefficient of the collector,
ΔT is the temperature differential between the working fluid entering the collectors and outside.

Collector tilt angle β = 17.8

The reference point of study was taken to be Harare. The monthly average temperature, average solar radiation data for the location was taken from Retscreen climate database [10].

The latitude for Harare = 17.8˚ due south
The longitude for Harare = +31.05˚

The volume of the hot water storage reservoir was 250 litres and the required temperature of the hot was 55˚C. Where the hot water storage could not supply water at 55˚C, an auxiliary instantaneous electrical hot water element would make up the temperature difference. This value is represented in Table 16 in last column, as $m_d c_p(T_r - T_s)$ which is the energy supply by an auxiliary electrical heating element.

T_r Required temperature (55˚C)

T_s Hot water Storage temperature

$mc_p\Delta T_s = A_c I_T F_R \tau\alpha - A_c F_R U_L(T_s - T_a)]x3600 - (1 + p)U_s A_s(T_s - T_a)x3600 - m_d c_p(T_s - T_m)$ (vi)

For the average day of the month, the solar fraction is , SF is given by:

SF = $\boldsymbol{\Sigma}_{24h}$ $[A_c I_T F_R \tau\alpha - A_c F_R U_L(T_s - T_a)]$ x 3600 – $(1 + p)U_s A_s(T_s - T_a)$ x 3600**]** / $\boldsymbol{\Sigma}_{24h}$ $[A_c I_T F_R \tau\alpha - A_c F_R U_L$ x $(T_s - T_a)]$x3600 – $(1 + p)U_s A_s(T_s - T_a)$ x 3600 + $m_d c_p(T_r - T_s)$**]**

Table 16: Numerical solution table for January

Jan

Time	I_{total}	$I_{total}F_R\tau\alpha$	$AF_RU_L(T_s - T_a)x3600$	$1.2UA(T_s - T_a)x3600$	Demand (kg)	$mc_p(T_s - T_m)$	ΔT_s	T_s	$mc_p(T_i - T_s)$
		MJ	J	J		J		30.15	
00:30	0	0	285873.21	33551.8848	0	0	-0.30421	29.8458	0
01:30	0	0	275069.8882	32283.93875	0	0	-0.29272	29.5531	0
02:30	0	0	264674.8305	31063.90915	0	0	-0.28166	29.2714	0
03:30	0	0	254672.6084	29889.98521	0	0	-0.27101	29.0004	0
04:30	0	0	245048.3763	28760.42456	0	0	-0.26077	28.7396	0
05:30	0	0	235787.8497	27673.5507	0	0	-0.25092	28.4887	0
06:30	0.34745	0.47795862	226877.284	26627.75045	5.6	199654.55	0.02362	28.5123	622989.95
07:30	0.86149	1.18506939	227716.0156	26726.18929	21	750787.68	0.17128	28.6836	2321105.8
08:30	1.4172	1.94949383	233798.3931	27440.05552	22.4	816953.81	0.82981	29.5134	2397777.6
09:30	1.93739	2.66507214	263266.8081	30898.65475	21	839083.53	1.45888	30.9723	2119243.3
10:30	2.34128	3.22066627	315074.8175	36979.16983	19.3	889414.47	1.88495	32.8572	1794891.5
11:30	2.56208	3.52440373	382013.5497	44835.52205	16.8	907207.43	2.08604	34.9433	1415201.2
12:30	2.56208	3.52440373	456093.5961	53530.02401	14	878665.64	2.03439	36.9777	1059712
13:30	2.34128	3.22066627	528339.4289	62009.25107	11.2	798630.44	1.74446	38.7222	765709.98
14:30	1.93739	2.66507214	590289.1818	69280.06519	10.5	825646.9	1.12367	39.8458	668299.15
15:30	1.4172	1.94949383	630193.2599	73963.45974	9.1	758507.4	0.46365	40.3095	561472
16:30	0.86149	1.18506939	646658.3971	75895.91219	10.5	895647.7	-0.41251	39.897	666043.87
17:30	0.34745	0.47795862	632009.3569	74176.60835	12	1002807	-1.17241	38.7246	820282.65
18:30	0	0	590374.3683	69290.06322	16.8	1321204.3	-1.88654	36.838	1281510.1
19:30	0	0	523379.1241	61427.07838	19.6	1386104.9	-1.87706	34.961	1649614.5
20:30	0	0	456720.658	53603.61995	18.2	1143615.1	-1.57518	33.3858	1652191.7
21:30	0	0	400782.5387	47038.3691	16.8	944499.97	-1.32602	32.0598	1618664
22:30	0	0	353692.6555	41511.60311	13.4	678722.76	-1.02279	31.037	1348639.7
23:30	0	0	317371.2163	37248.68968	11.2	519178.74	-0.83219	30.2048	1166367.4
		26.045328	9335777.413	1095705.779					23929716

11.7.1 Solar water heating Scenarios

Three scenarios considered for this study are:

- Glazed collector 1.81m^2 flat plate with 250l tank
- Glazed collector 3.62 m^2 flat plate with 250l tank
- Glazed collector 1.81m^2 flat plate with 250l tank with collector shut out or drain during off to reduce collector losses during none-sun hours.

The first and second scenarios, are similar in their set up. The difference is only in the aperture area of the collectors. The first scenario acts as the base line.

The third scenario is similar to the first scenario. The difference is that for the third scenario the system is either drained or shut off using valves to prevent movement of water from collector to the storage tank during the time when there is no sunshine, before sunrise and after sunset. This was necessary to reduce collector losses during collector non-performance hours. The collector switches its roles during the day and at night. During the day, it acts as a heat source but at night, it acts as a heat sink, reversing the day time gains.

Figure 14 and Table.1, show a comparison of the solar fraction of scenario 1 and scenario 2. Values of solar fraction for the average day of each month were plotted against their corresponding months. It can be deduced from the graph that, increasing the collector area, increases solar radiation energy absorbed into the system and hence the solar fraction. Increasing the collector area by a factor of two resulted in an increase of solar fraction of 46%.

Table 17: Comparison of Solar Fraction

Month	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Solar Fraction 1.81 m^2	0.395	0.399	0.4	0.401	0.362	0.313	0.331	0.407	0.495	0.491	0.45	0.389
Solar Fraction 3.62 m^2	0.575	0.581	0.584	0.577	0.532	0.47	0.49	0.597	0.723	0.713	0.649	0.566

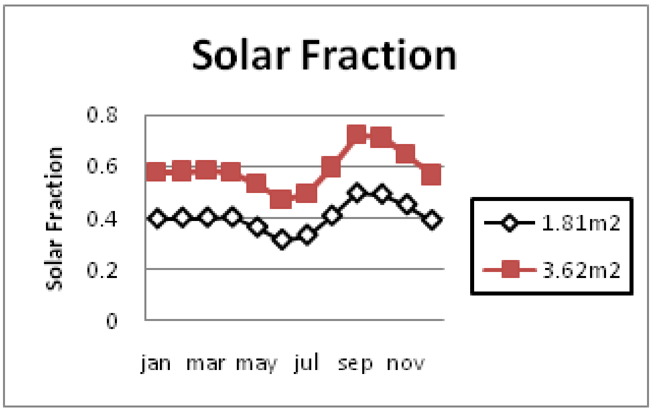

Figure 14: Solar fraction comparison

Figure 15 and Table 18; show a comparison of the solar fraction of scenario 1 and scenario 3. For the same collector area, scenario 3 yielded an improved solar fraction through reduction of collector losses during night. The value of solar fraction is improved by 20%.

Table 18: Comparison of Solar Fraction

Solar Fraction	0.395	0.399	0.4	0.401	0.362	0.313	0.331	0.407	0.495	0.491	0.45	0.389
Solar Fraction with shutoff	0.465	0.471	0.471	0.483	0.451	0.404	0.428	0.5	0.586	0.571	0.518	0.453
Month	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec

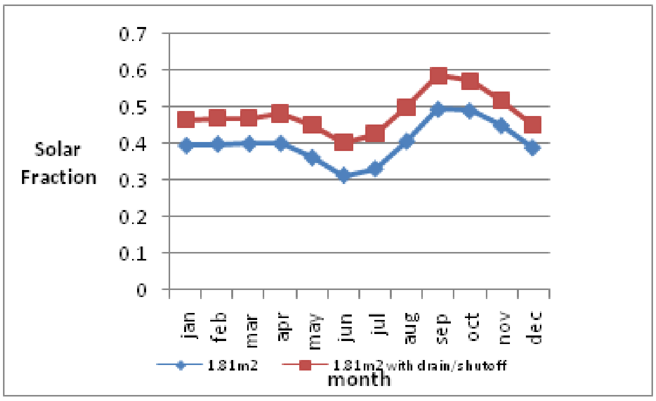

Figure 15: Comparison of solar fraction

Economic Analysis of scenario 1

Table 19: Energy Savings

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Solar energy used per da	15613845	15774525.1	15604958.56	15680405	14337344	12369912	13083311	16065127	19564974	19393406	17812693.4	15373944
Duration	31	28	31	30	31	30	31	31	30	31	30	31
	484029188	441686702	483753715.3	470412144	444457672	371097351	405582631	4.98E+08	586949211	601195580	534380802	476592259
Energy(kWh) per month	134.45255	122.690751	134.376032	130.67004	123.46046	103.0826	112.66184	138.3386	163.04145	166.99877	148.439112	132.38674
Annual Solar Savings ($)	83.751145											
Energy(kWh) per year	1610.5989											

Table 20: Cost analysis

Operating and Maintenance Costs	
Fixed Operation	
Operating Costs	
Installation costs @$150 per unit	**34,050,000.00**
Investment Costs **227000 @ $590 per unit**	**133,930,000.00**
Energy saved per year	
1,610.6 kWh x 227,000 = ***365,606,200 kWh*** Distribution and transmission efficiency = 0.8485 Equivalent Energy Saved = ***365,606,200 kWh/0.8485*** = ***430,724,808*** kWh	
Energy Savings per annum ***430,724,808*** kWh ***kWh*** x 0.0502	
Energy saved per year with shutoff	
1,610.6 kWh x 227,000 x 0.48342/0.4028 = ***430,724,808 kWh***	
Energy Savings per annum ***430,724,808 kWh*** x 0.0502	**21,508,544.37**
Reduction in Peak Electrical Power Demand	

Calculating LCOE

Energy Savings per annum = US$21,508,544.37

n = 25

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

TLCC = I + OM $[(1 + d)^n-1]/ [d(1 + d)^n]$

I = **34,050,000.00**+ **133,930,000.00** = 167,980,000.00

TLCC = 167,980,000.00

TLCC = US$ 167,980,000.00

LCOE = TLCC / $[\Sigma_n Q / (1 + d)^n]$

Q = Energy saved per year

= ***430,724,808 kWh***

Amount of energy saved in the analysis period = $[\Sigma_n Q / (1 + d)^n]$

$[\Sigma_n Q / (1 + d)^n]$ = Q x $[(1 + d)^n-1]/ [d(1 + d)^n]$

= ***430,724,808 kWh*** x 9.34

= 4,022,969,707 ***kWh***

LCOE = US$ 167,980,000.00 /4,022,969,707 ***kWh***

= **US$ 0.04175/kWh**

Economic Analysis of scenario 2

Table 21: Energy Savings

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Solar energy used per day	22667344.5	22867601	23249627.8	22623479	20803033	18448483	19216125	23431561	28315192	28061423	25462939	22263302
Duration	31	28	31	30	31	30	31	31	30	31	30	31
(J)	702687680	640292836	720738460	678704368	644894031	5.53E+08	595699884	726378379	849455753	869904107	763888184	690162356
Energy(kWh) per month	195.191022	177.85912	200.205128	188.52899	179.13723	153.7374	165.47219	201.77177	235.95993	241.64003	212.19116	191.71177
Annual Solar Savings ($)	121.857097											
Energy(kWh) per year	2343.4057											

Table 22: Cost analysis

Operating and Maintenance Costs	
Fixed Operation Disposal *Costs*	
Variable Operating Costs	
Installation costs @$170 per unit	**38,590,000**
Investment Costs **227000 @ $1180 per unit**	**267,860,000**
Energy saved per year	
2.343 kWh x 227,000 = ***531,861,000 kWh*** Distribution and transmission efficiency = 0.8485 Equivalent Energy Saved =***531,861,000 kWh/0.8485*** = ***626,824,985.3*** kWh	
Energy Savings per annum ***626,824,985.3*** kWh x 0.0502	**31,466,614**
Reduction in Peak Electrical Power Demand	

Calculating LCOE

Energy Savings per annum = US$31,466,614.26

n = 25

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

TLCC = I + OM $[(1 + d)^n-1]/ [d(1 + d)^n]$

I = **38,590,000.00** + **267,860,000.00** = US$ 306,450,000

TLCC = US$ 306,450,000

LCOE = TLCC / $[\Sigma_n Q / (1 + d)^n]$

Q = Energy saved per year

= ***626,824,985.3*** kWh

Amount of energy saved in the analysis period

$= [\Sigma_n Q / (1 + d)^n]$

$[\Sigma_n Q / (1 + d)^n] = Q \times [(1 + d)^n - 1] / [d(1 + d)^n]$

= **= *626,824,985.3*** kWh x 9.34

= 5,854,545,360 ***kWh***

LCOE = US$ 306,450,000/5,854,545,360 ***kWh***

= <u>US$ 0.0523/kWh</u>

Economic Analysis of scenario 3

Table 23: Energy Savings

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Solar energy used per day	18445616	18659047	18788771	18893236	17881712	16000864.8	16963397	19865664	23179811	22593712	20558738	19003939
Duration	31	28	31	30	31	30	31	31	30	31	30	31
	571814090	522453314	582451913	566797068	554333072	480025944	525865319	615835586	695394344	700405076	616762128	589122121
Energy(kWh) per month	158.83725	145.12592	161.7922	157.44363	153.98141	133.34054	146.0737	171.06544	193.1651	194.55697	171.32281	163.64503
Annual Solar Savings ($) Energy(kWh) per year	101.4182 1950.35											

Table 24: Cost analysis

Operating and Maintenance Costs	
Fixed Operation Disposal *Costs*	
Variable Operating Costs	
Installation costs @$160 per unit	**36,320,000.00**
Investment Costs **227000 @ $590 per unit**	**133,930,000.00**
Energy saved per year	
1,950 kWh x 227,000 = ***442,650,000 kWh*** Distribution and transmission efficiency = 0.8485 Equivalent Energy Saved = ***442,650,000 kWh/0.8485*** **= *521,685,327*** kWh	
Energy Savings per annum ***521,685,327*** kWh **x** 0.0502	**26,188,603.42**
Reduction in Peak Electrical Power Demand	

Calculating LCOE

Energy Savings per annum = US$26,188,603.42

n = 25

d = (1 + i) / (1 + f) – 1

= (1 + 0.132) / (1 + 0.0338) – 1

= 0.095

$TLCC = I + OM [(1 + d)^n - 1] / [d(1 + d)^n]$

I = **36,320,000.00** + **133,930,000.00** = 170,250,000

TLCC = <u>US$ 170,250,000</u>

$LCOE = TLCC / [\Sigma_n Q / (1 + d)^n]$

Q = Energy saved per year

= ***521,685,327*** kWh

Amount of energy saved in the analysis period $= [\Sigma_n Q / (1 + d)^n]$

$[\Sigma_n Q / (1 + d)^n] = Q \times [(1 + d)^n - 1] / [d(1 + d)^n]$

= ***521,685,327*** kWh x 9.34

= 4,872,540,954 ***kWh***

LCOE = US$ 170,250,000/4,872,540,954 ***kWh***

= <u>US$ 0.03494/kWh</u>

12. Discussion of Results

To determine a better understanding of the impact of these strategies they are compared one against the other with solar water heating as the baseline. The strategies are ranked in their order of addressing the following [3]:

- meeting energy demand
- meeting instantaneous power demand
- economically viable
- environmentally suitable

The amount of CO_2 emitted per kWh by thermal power generation is given as 830g/kWh, for natural gas the statistic value is 370g/kWh. Table 25 gives a summary of the possible power development projects with energy generated or saved, ozone depleting gas amount and cost involved.

Table 25: Power development projects

	Energy (kWh)	CO_2 (ton)	NOx (ton)	SO_2 (ton)	Project Costing (US$)
Hwange Stage 3: 2 x 300MW	5,256,000,000	4362480	5676480.0	63072.0	600,000,000.0
Kariba South Extension 2 x 150 MW	2,628,000,000	-2181240	-2838240.0	-31536.0	300,000,000.0
Gokwe North 2 x 350 MW	6,132,000,000	5089560	6622560.0	73584.0	1,400,000,000.0
Batoka Gorge 4 x 200 MW	7,008,000,000	-5816640	-7568640.0	-84096.0	1,350,000,000.0
Lupane Gas 2 x 150 MW	2,628,000,000	2181240	2838240.0	31536.0	300,000,000.0
LED	922,716,558.00	-765854.7	-996533.9	-11072.6	149,288,360.2
CFL	802,053,624	-665704.5	-866217.9	-9624.6	52,543,377.2
Solar Water Heating	430,724,808	-357501.6	-465182.8	-5168.7	167,980,000.0
Ripple control	0	0	0.0	0.0	18,000,000.0
Timer	0	0	0.0	0.0	15,890,000.0
Temperature Adjustment	44,293,492.00	-36763.6	-47837.0	-531.5	47,190.0

12.1 Impact on energy demand

At the current PowerCo generating rate is 1 115 MW and annual energy deficit of 2,702,600MWh.

The LED lights solution would cause the biggest reduction in energy imports. The impact of CFL is very much comparable to LED. However only one lighting solution will be required, in this case the LED solution seems to be a better option. The impact of solar water heaters is about half of LED. The difference was caused mainly by numbers. There are 5.5 million bulbs compared to 227 000 geysers. Table 26 shows the energy comparisons against energy deficit. The timer and ripple control options do not have a significant impact on energy as they are not exactly meant to reduce energy demand. These interventions shift loads from peak periods to off peak periods.

Table 26: Comparison of energy impact

	solar	LED lights	CFL	Geyser temperature	Timer	Ripple Control	Zesa DEFICIT
Energy (kWh)	430,724,808	922,716,558.60	802,053,624	44,293,492.04			2,702,600,000

12.2 Impact on peak power demand

The LED lights option would have the biggest reduction in peak power demand. The impact of CFL is very much comparable to LED. The impact of solar water heaters on instantaneous peak power demand may not be significant because of the use of an auxiliary electric heating element. There is a huge chance that all the electric elements could be engaged at the same time. However, the duration of the peak period will be reduced significantly, because the geysers energy requirements will have been reduced to 52% corresponding to a solar fraction of 0.48. Table 27 compares the power impacts of the various strategies. If the solar fraction was 1, then reduction in power demand would be the same as that for timers. The difference is that the reduction in power demand would be for the whole 24 hour period instead of just peak periods.

A complete solution for water heating should incorporate energy demand reduction and instantaneous power demand. If the solar water heating solution incorporates an auxiliary heating element then, timer switches or ripple control should be incorporated.

A combination of ripple control or timers and LEDs or CFL could well address the peak power deficit problem.

Table 27: Comparison of power impact

	solar	LED lights	CFL	Geyser temperature	Timer	Ripple Control	Zesa Peak Deficit
power (MW)	0	275	238.5		342.515	270	630

12.3 Total life cycle cost (TLCC) and Levelized cost of enrgy (LCOE)

The cost of solar water heating is more significant than that of the other options. Solar energy is diffuse in nature and as such it requires relatively large surfaces of area in order to harness solar radiation to meet a specific requirement. The equipment tends to be large, making it expensive to set up. The life cycle costs of solar and LED are comparable. In the case of a limited budget the CFL option is better than the LED. Table 28 shows the life cycle costs of the various options.

Table 28: Total Life Cycle Costs (US$)

solar	LED lights	CFL	Geyser temperature	Timer	Ripple Control
167,980,000	149,288,360.20	52,543,377.24	47,190.00	15,890,000.00	18,000,000.00

12.4 Levelized cost of energy (LCOE)

The levelized cost of energy, is highest for solar energy. This means that the break even cost for solar thermal energy is 4.175 US cents. This is just lower than the average cost of generating electricity, while LED and CFL are really lower. From the perspective of costs, it is more viable to invest in Solar water heating than investing in coal thermal power plants as can be seen by comparing the two. The LCOE for Timers or ripple control are zero because these are load shifting strategies which do not significantly bring about any energy gains.

Table 29: Levelized cost of electricity (US$)

	solar	LED lights	CFL	Geyser temp	Timer	Ripple Cont	Kariba	Hwange	Small thermals
lcoe	0.04175	0.0175	0.017	0.00011288			0.0239	0.0604	0.1414

13. Research study recommendations

The profile of the hot water demand curve has a shape almost similar to the electrical power demand curve. Thus reducing hot water demand would also reduce significantly, the demand for electrical energy. Addressing the production and use of hot water is key to energy problem.

Programs to encourage reduction in hot water usage will improve solar fraction by 12% if hot water usage is reduced by 20%. This document is based on a water usage rate of 269 litres per household per day. The average size of the household, is 3.5 persons.

The use of two collectors would increase solar fraction by 38%, to a solar fraction of 0.59 compared to a case of using one collector per household with a solar fraction of 0.40. However, this comes at an increased cost. The LCOE for this case is US$ 0.0523/kWh. This value is just more than the cost of importing electricity US$0.0502/kWh but it is less than the cost of running coal thermal power plants.

Draining off the water from the collector during night hours, causes an increase in solar fraction of 20% from 0.40 to 0.48. This will reduce the LCOE from US$0.04175 to US0.03494. This may be achieved at a slight increase in the cost of installing the solar panels so as to incorporate drain off fixtures. This value makes solar water heating, a viable option.

The solar fraction for the case of two collectors can potentially improve through the use of drain off and hot water reduction.

SF = 0.58 x 1.2 x 1.12 = 0.78

This gives a solar fraction of close to 80%. In this particular case it may possible to remove the auxiliary heating element such that this solution would address both energy demand deficit and peak power deficit. The energy savings for this particular system would be 841,483,935.1 kWh per year. This comes at a TLCC of about US$300,000,000.00

Carbon emissions results from thermal power generation while solar option results in emission savings of CO_2 which is sustainable for the environment according to the dictates of cleaner production.

14. Conclusion

Comparing the LCOE and generation costs values, it is more feasible to invest in solar water heating than in coal thermal power plants. These can significantly reduce the energy deficit of 2,702,600MWh by more than 16%, for a solar fraction of 0.40 or 32% for solar fraction of 0.8. For both cases the LCOE is more than the generation costs for Hydro but less than the generation costs for thermals.

Total demand for electrical energy is estimated at 12 500GWh and demand for electrical energy attributed to water heating is 1300 GWH. With a solar fraction of 0.4, the potential for solar water heating is 523 GWh or with a solar fraction of 0.8, it is 1047 GWh.

The reduction in green house gas emissions with a solar fraction of 0.40 would be 357,500 tons of CO_2. The reduction in SO_2 emissions would be about 5170 tons and the reduction is NOx would be 465000 tons. While the contribution of strategies like temperature setting and geyser insulation might appear insignificant economically, but they play a major in reducing emissions when their total effects are added up.
Finally the overall power development plan, in the context of a tight budget, can be read from the values of LCEO as they rank according to their values. The projects order attractiveness would be CFL, followed by solar water heating.

15. Further research

Thermal energy generation is one of the leading contributors to the production of green house gases which cause global warming. They also contribute to acid rain precipitation. At the generation rate indicated, existing thermal power station would produce 4362480 tonnes of CO_2 per year, hence the need for sustainable power development strategies. It is recommended that further investigation into energy management strategies is undertaken and to explore their impact on cleaner production and general resource utilization in local industry. Also pre-paid meter impact could be assessed electrical energy consumption as consumers would ensure using only what they really require and avoid wastage associated with energy billing system.

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Ignatio Madanhire graduated with a B.Sc. Mechanical (Hon) Engineering and M.Sc. in Manufacturing Systems and Operations Management in 1993 and 2010 respectively from the University of Zimbabwe. He has been a mechanical engineer with Department of Water – Large Dam Designs, and also worked as a Senior Lubrication Engineer with Mobil Oil Zimbabwe as well as Castrol International dealing with blending plants and lubricants end users. Currently, he is a lecturer with the University of Zimbabwe in the Mechanical Department lecturing in Engineering Drawing and Design. Has published works in Cleaner Production and Maintenance in a number of journals.

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