

## Thermal and stored heat energy for the generation of power

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### Abstract

This research aim is to design, simulate and produce a prototype of a combined solar-thermal and sensible heat energy powered by a Stirling engine. The research philosophy is applied research and the empirical study conducted is experimental. The output of the research prototype will be compared to a standard photovoltaic installation of similar power output. The data collection methodology is quantitative in nature. The results for this paper will be generated from the simulation software package MATLAB, as the prototype is still under construction at this stage. The output expectation is that the compatibility of the prototype is at least equal, if not higher, than the standard photovoltaic construction. The advantage of the prototype result may include energy availability from the prototype during the evenings when a traditional photovoltaic system is incapable of producing energy.

**Keywords:** Stirling engine; Solar thermal energy; Thermal energy storage; Photovoltaic system

### 1. Introduction

The Stirling engine was patented in 1816 by Robert Stirling and is a type of heat engine that is operated by the cyclic compression and expansion of air or other gas (the working fluid) between different temperatures, resulting in a net conversion of heat energy to mechanical work (Walker 1980:1; Pendrid 1917:516). "Like any heat engine, the Stirling engine goes through the four basic processes of compression, heating, expansion, and cooling" (Martini 1983:4). When heat is added to the hot cylinder, the gas inside expands and pushes the piston down, as the gas cools down, the piston returns and pushes the working fluid through the channel towards the cold cylinder. Here the gas is cooled down and compressed by the cold piston and pushed back to the hot cylinder for the process to be repeated (Martini 1983:6). The regenerator is located between the hot and cold cylinders and acts as an internal heat exchanger. It stores heat energy from the working fluid temporarily as the gas flows from the hot cylinder to the cold cylinder. When the cycle is reversed, i.e., the gas flows from the cold cylinder to the hot cylinder, the heat is then "released" back into the working fluid (Rinker 2018:3).

Concentrated solar power is the process of generating electricity by concentrating the heat energy of the sun onto a collector, which in turn transfers that energy into a medium (water, air or other working fluid) that drives a conventional power cycle (Hagumimana, Zheng, Asemota, Niyonteze, Nsengiyumva, Nduwamungu & Bimenyimana 2021:3). Concentrated solar power systems are made up of concentrators, collectors, thermal energy storage systems and the power-block. Concentrators (also called reflectors) are usually made up of mirrors and used to concentrate the sun's heat onto a specific point where a collector is located. Collectors (receivers/absorbers) are responsible for collecting and transferring solar (heat) energy to a heat transfer fluid or working fluid. The thermal energy storage system stores the thermal energy into a thermal energy storage medium like liquid molten salt, silica sand or other material to use when the sun is not shining. Power block lock uses the heat transfer fluid to boil water to generate steam which drives steam turbines to generate electricity (Alalewi 2014:6-9). Concentrated solar power can be divided into four types based on structure and how the solar radiation is concentrated: parabolic trough, linear Fresnel reflector, solar tower and parabolic dish. These technologies all use solar tracking equipment to maximise efficiency.

The sole purpose of water heating systems is to generate hot water by using solar energy (Ogueke, Anyanwu & Ekechukwu 2009:043106-2). Solar water heating systems can be broadly classified into active and passive systems. Active solar heating is when the water/heat transfer fluid is actively pumped from the storage tank through the collectors and back into the tank. Passive systems use natural convection to circulate heated household water/heat transfer fluid through the system (Bayoumi & Moharram 2021:7; Ogueke *et al.* 2009:043106-2; Samo, Siyal, Siyal & Jatoi 2011:3). Solar water heaters can be further divided into direct and indirect systems. In a natural system, the working fluid passing through the solar panel is the end-use fluid, while in an indirect approach, the working fluid is called a heat transfer fluid and circulates through a solar panel and then goes to the storage tank to exchange heat with the end-use fluid. (Bayoumi & Moharram 2021:6; Ogueke *et al.* 2009:043106-3-5; Samo *et al.* 2011:3). Sarbu and Sebarchievici (2017:71) stated that the energy storage capacity of a thermal water storage system operating over a determined temperature difference is given by equation (1).

$$Q_s = m \times c_p \times \Delta t_s \dots \dots \dots (1)$$

Where:

$Q_s$  = Energy storage capacity in kilojoules (kJ)

$m$  = Mass of the material in kilogram (kg)

$c_p$  = Specific heat of the material in kilojoules per kilogram degrees Celsius (kJ/kg°C)

$\Delta t_s$  = Differential temperature in degrees Celsius (°C)

Table 1 contains a list of everyday materials and their thermal storage characteristics.

**Table 1. List of thermal storage materials (Sarbu & Sebarchievici 2017:70)**

Medium	Fluid type	Temperature range (°C)	Density (kg/m <sup>3</sup> )	Specific heat (J/(kg·K))
Sand	–	20	1555	800
Rock	–	20	2560	879
Brick	–	20	1600	840
Concrete	–	20	2240	880
Aluminium	–	20	2707	896
Water	–	0-100	1000	4190
Engine oil	Oil	≤ 160	888	1880
Ethanol	Organic liquid	≤ 78	790	2400
Propane	Organic liquid	≤ 97	800	2500
Butane	Organic liquid	≤ 118	809	2400
Isotunaol	Organic liquid	≤ 100	808	3000
Isopentanol	Organic liquid	≤ 148	831	2200
Octane	Organic liquid	≤ 126	704	2400

The solar collector is the most significant component of any solar system. The three main types of solar collectors for solar water heating are flat plate collectors, evacuated tube collectors and stationary compound parabolic collectors (Sonawane & Raja 2017:1-2). In contrast to concentrated solar power systems, these collectors are static and do not track the sun.

This paper will now investigate how to combine all the above technologies to create a small stand-alone power plant and compare its capabilities to that of PV-solar systems – one using lithium-ion batteries and one using deep-cycle gel batteries.

## **1.1 Objective**

To design and simulate a combined solar-thermal and sensible heat energy powered Stirling engine and investigate its power generation capabilities. The cost of building such an engine will be compared to similar sized solar PV systems with the two central backup systems: lithium-ion batteries and deep-cycle gel batteries.

## **2. Proposed model**

This research uses easily accessible parts purchased at hardware and auto-spares retail outlets. Together with thermodynamical equations, the dimensions and properties of these materials will be used to simulate the operation of the system using MATLAB 2018a accurately.

### **2.1 Materials selected**

To design a large bore engine, the selected pistons belong to Toyota's 2TR-FE engine and have a cross-sectional diameter of 95mm. The conrods, crank-arms and base are modelled out of 25 x 25mm mild-steel square tubing, owing to the following factors: easily accessible, economical, high tensile strength and easier to work with than other materials like aluminium. The only drawback of using mild steel is the increased overall weight of the engine and requiring higher starting power input due to increased inertia. Standard-sized bearings, pulleys and belts will be used in the drive train. The cylinders are stock machined to accommodate the pistons and have an overall length of 210mm. The regenerator will be designed to accommodate a brass kitchen sponge inside a thermal-resistant container.

The solar water heater tank will consist of a refurbished 210ℓ steel drum, and the solar collector tubes will be black HPE PVC irrigation pipes with a diameter of 50mm. A galvanised IBR sheet will have the dual function of providing structural support while also reflecting solar energy to the collector tubes. All thermal insulation areas will be covered by commercially available glass wool of 100mm thickness.

### **2.2 Simulink model**

The Stirling engine will be modelled using Simulink Multibody by incorporating each part's physical dimensions and properties into the program. Simulink will use these parameters to simulate the piston movement taking into account factors such as inertia and friction. In the case of the water heater, the physical dimensions and properties of the different materials will be used in Simulink, Thermal and Thermal-Liquid function blocks.

### **2.3 Mathematical model**

Thermodynamical equations will be used to estimate the starting point of the two Simulink models within a certain degree of accuracy. For the Stirling engine, thermal heat transfer and ideal gas equations will be used to determine the maximum possible power output under certain conditions. Engine losses such as thermal, pumping and mechanical losses will be subtracted from the ideal power output to achieve more realistic results. The resultant brake output energy will be linked to the Stirling Simulink model to simulate functionality.

For the water heater, thermal heat transfer equations will determine the energy input into the solar collector during the day and energy output during the night. These values will be linked to Simulink's solar hot water model to determine its overall performance.

Finally, all the results from the proposed method will be compared to similar rated PV solar systems.

## **3. Methodology**

Thermodynamical equations will play an essential role in determining the system's overall performance, and the different parts of the system need to be evaluated separately to achieve good results. The solar concentrator will not be analysed in detail; however, its

focused temperature on the Stirling receiver will be taken as the input temperature on the hot cylinder.

This paper will first analyse the Stirling engine by examining the heat transfer mode of each part of the engine. According to Araoz, Salomona, Alejob, Torsten and Franssona (2014:6), the heat transfer model considers the thermal energy that flows in and out of the engine. The heat flow is transferred to the working fluid via the heat exchangers at the hot and cold sides. The internal heat transfer model is calculated using heat transfer correlations for steady-state internal forced convective flow for the hot and cold cylinders (Araoz *et al.* 2014:5). Mass flow equations analyse the regenerator by assuming that the air inside the regenerator and the brass wool is in thermal equilibrium. Once all the internal temperatures and pressures are calculated, the maximum available output will be obtained using the ideal gas equations. The pumping loss will also be calculated and subtracted from the maximum available output. The mechanical losses are constant and will be inferred from online research instead of an estimated flow chart of this proposed method.

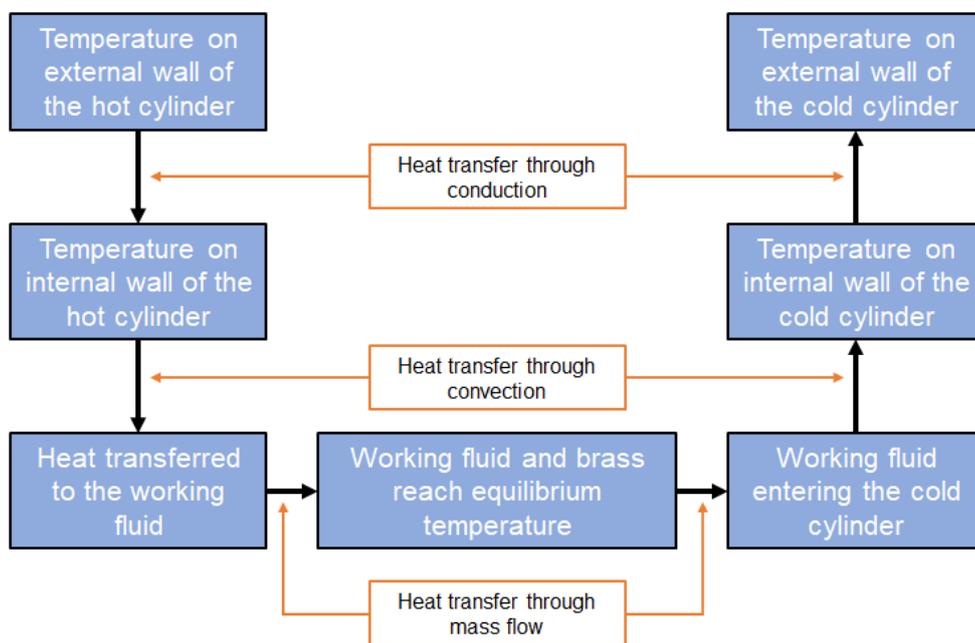


Figure 1. Flow chart describing the heat flow model (Self-generated)

### 3.1 Heat flow in the hot and cold cylinders

The conduction heat transfer through the wall follows the Fourier law of conduction, while the convection heat transfer rate is consistent with Newton’s cooling Law (Araoz *et al.* 2014:7) This can be expressed in terms of the thermal resistance of each mode, i.e., conduction through the wall and convection through the air surrounding the border.

The total heat border entering the hot cylinder is expressed as:

$$Q_{hot\_in} = \frac{(T_{hot\_cyl\_outer} - T_{hot\_air\_inner})}{(R_{cond\_hot\_cyl} + R_{conv\_Hot\_cyl})} \dots \dots \dots (2)$$

Where  $T_{hot\_cyl\_outer}$  and  $T_{hot\_air\_inner}$  represent the outer surface temperature and inner air temperature of the hot cylinder in Kelvin respectively.  $R_{cond\_hot\_cyl}$  is the conduction resistance of the cylinder wall while  $R_{conv\_Hot\_cyl}$  is the convection resistance of the air inside the cylinder.

The conduction and convection resistances of a cylindrically shaped wall are given by:

$$R_{cond} = \frac{\ln(r_{inner}/r_{outer})}{K_{mat} \cdot 2\pi \cdot L} \dots\dots\dots(3)$$

$$R_{conv} = \frac{1}{h_{liquid} \cdot (r_{in} \text{ or } r_{out})} \dots\dots\dots(4)$$

Where  $K_{mat}$  is the conductivity of the wall material and  $h_{liquid}$  is the convection coefficient of the liquid or gas flowing around the wall surface. The variables  $r_{inner}$  and  $r_{outer}$  represent the inner and outer diameter of the cylinder wall.

Equations (2) to (4) can also be used to solve the heat transfer model of the cold cylinder as the heat transfer model out of the cold cylinder is the same as the heat transfer model for the heat energy entering the hot cylinder, except that flow direction of flow is heat out instead of heat in.

**3.1.1 Heat transfer model of the regenerator**

The regenerator material's physical mass and gas need to be established to solve the regenerator's heat transfer model. The brass wool will be weighed on a kitchen scale, while the mass of the gas will be calculated using the following equations:

$$P \cdot V = m \cdot R \cdot T \dots\dots\dots(5)$$

- Where:
- $P$  = Pressure in Pascal
- $V$  = Volume in  $m^3$
- $m$  = Weight in kg
- $R$  = Specific gas constant of the working fluid in J/kg.K
- $T$  = Temperature of the working fluid in Kelvin

For the mass flow calculations, the gas inside the regenerator is assumed to be in thermal equilibrium with the brass wool. This means that the working fluid's heat equals the heat energy "gained" by the brass wool.

Thus:

$$m_{gas} \cdot C_{p_{gas}} \cdot (T_{gas} - T_{regen}) = -m_{brass} \cdot C_{p_{brass}} \cdot (T_{regen} - T_{brass}) \dots\dots\dots(6)$$

The variables  $m$ ,  $C_p$  and  $T$  represent the mass, specific heat constant and absolute temperature materials' absolute temperature, respectively subscripts represent the two materials in question, namely: the working fluid (gas) and the regenerator material (brass). Re-arranging equation (6):

$$T_{regen} = \frac{(m_{gas} \cdot C_{p_{gas}} \cdot T_{gas}) + (m_{brass} \cdot C_{p_{brass}} \cdot T_{brass})}{(m_{gas} \cdot C_{p_{gas}}) + (m_{brass} \cdot C_{p_{brass}})} \dots\dots\dots(7)$$

**3.1.2 Pumping loss**

Gas flow generates a pressure drop across the regenerator matrix resulting in loss of piston work and decreasing the overall performance (Ishii, Bouzawa & Hamaguchi 2012:2). To calculate the pressure, and drop, the friction coefficient of the regenerator pipe must first be established. This is achieved by calculating the volumetric flow inside the generator:

$$Q_{flow} = \frac{(\pi.D^4.\Delta P)}{(128.\mu.L)} \dots\dots\dots(8)$$

Where:

- $Q_{flow}$  = Volumetric flow in m<sup>3</sup>/s
- $D$  = Diameter of the pipe in meters
- $\Delta P$  = Differential pressure of the system in Pascal
- $\mu$  = Dynamic viscosity of the working fluid in Pa.s
- $L$  = Length of the pipe in meters

The velocity of the working gas in m/s can be inferred by:

$$V = \frac{Q_{flow}}{\left(\frac{\pi}{4}\right).D^2} \dots\dots\dots(9)$$

From the velocity, the Reynolds number can be obtained:

$$R_e = \frac{\rho.D.V}{\mu} \dots\dots\dots(10)$$

Where  $\rho$  is the density of the working fluid in kg/m<sup>3</sup>.

If the Reynolds number is less than 2300, the flow is said to be lamina; if the flow is above 4000, then the flow is turbulent. If the flow is laminar, the friction coefficient is:

$$f = \frac{64}{R_e} \dots\dots\dots(11)$$

Using the friction factor obtained in equation (11), the pressure drop across the regenerator will be determined by:

$$J = \frac{f.L.V^2}{2.g.D} \dots\dots\dots(12)$$

Where  $g$  represent the gravitational acceleration of earth as 9.81 m/s<sup>2</sup>. As the working fluid flows through the regenerator twice for each cycle, the pumping loss will be:

$$W_{pump\_regen} = 2.J.\Delta V \dots\dots\dots(13)$$

Where  $\Delta V$  represents the differential volume in m<sup>3</sup> through which the working fluid must flow. The pressure drop across the regenerator accounts for 70% to 90% of the pressure drop through the heat transfer components (Araozet al./ 2014:10). Thus, the total pumping loss becomes:

$$W_{pump\_total} = \frac{W_{pump\_regen}}{0.7} \dots\dots\dots(14)$$

### 3.1.3 Crank angle vs piston stroke

Stirling engines are by design valveless, and the hot and cold cylinders are directly connected via the regenerator. Calculating the engine's minimum and maximum volumes is not as simple as deducting the total stroke volume from the compression space volume. To establish minimum and maximum volume, the piston stroke position must be obtained concerning the crank angle. This can be done by using Pythagorean trigonometry as shown below:

Superscript  $x = r.\cos A + \sqrt{L^2 - r^2.\sin^2 A} \dots\dots\dots(15)$

Where  $x$  is the piston position concerning the bottom dead centre and  $r$  represents the length of the crank arm.  $L$  and  $A$  represent the conrod length and the crank, angle respectively. Figure 2 shows the relationship between the hot and cold piston in relation to the crank angle.

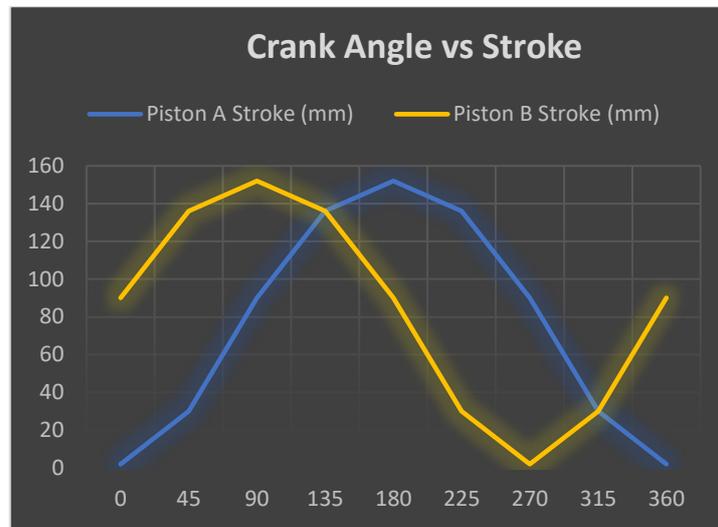


Figure 2. Graph depicting crank angle vs stroke for both pistons (Own work)

### 3.1.4 Network output of the Stirling engine

In order to determine the network output of the engine, the work done by the hot and cold cylinders need to be added together, while the pumping loss and mechanical losses need to be subtracted as shown in equation (16).

$$W_{out} = P_{hot} \cdot \Delta V + P_{cold} \cdot \Delta V - W_{pump\_total} - W_{mech\_loss} \dots \dots \dots (16)$$

The mechanical efficiency of a four-stroke engine is approximately 80% to 90% (Mohammed, Abdallah, & Taha 2015:11). Thus, the automatic loss will be taken as 20% of the break work done by the engine.

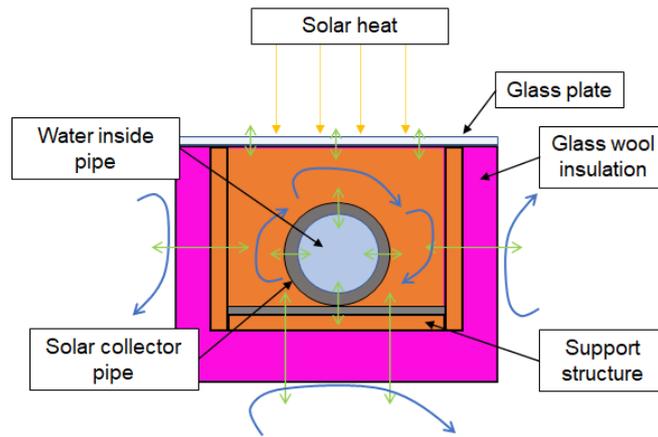
### 3.2.1 Solar collector model

In order to estimate the total solar energy entering the collector, the peak sun hour method will be used. The definition of a peak sun hour is the equivalent number of hours per day when solar irradiance averages 1000 W/m<sup>2</sup> (Riza & Gilani 2014:109). According to the Department of Energy of South Africa (nd:1), The average peak sun hours for South Africa is 4.5 to 6.5 hours per day.

Determining the total maximum energy received by the collector:

$$Q_{solar\_in} = 1000 \cdot \text{Surface area of the collector} \dots \dots \dots (17)$$

The heat flow of the solar collector is shown in Figure 3, where the green arrows represent conduction heat transfer and the blue arrows show the convection heat transfer for each part of the collector.



**Figure 3. Cross-sectional area for a solar collector with a single pipe (Own work)**

Using figure 3, equations (2) and (17), the heat transfer model will be:

$$Q_{sol\_in} = \frac{(T_{col\_water} - T_{solar\_in})}{(R_{cd\_gl} + R_{cv\_in} + R_{cd\_p} + R_{cv\_p\_in} + R_{cd\_ins} + R_{cv\_ins})} \dots\dots\dots(18)$$

Where:

- $T_{col\_water}$  = Water temperature inside the collector pipe in Kelvin
- $T_{solar\_in}$  = Ambient Temperature in Kelvin
- $R_{cd\_gl}$  = Conductive resistance of the glass cover
- $R_{cv\_in}$  = Convective resistance of the space around the collector pipes
- $R_{cd\_p}$  = Conductive resistance of the collector pipe wall
- $R_{cv\_p\_in}$  = Convective resistance of the water inside the collector pipe
- $R_{cd\_ins}$  = Conductive resistance through the insulation wall
- $R_{cv\_ins}$  = Convective resistance of the air over the insulation wall

Re-arranging equation (16) to solve for the water temperature inside the collector pipe:

$$T_{col\_water} = Q_{sol\_in} \cdot (R_{cd\_gl} + R_{cv\_in} + R_{cd\_p} + R_{cv\_p\_in} + R_{cd\_ins} + R_{cv\_ins}) + T_{solar\_in} \dots\dots(19)$$

### 3.2.2 Hot water – Stirling heat transfer interaction

To determine the backup hours of the hot water system, the thermal efficiency and the engine's output energy needs to be established. Using MATLAB Simulink, the final temperature inside the hot water tank can be established and the time the hot water can keep the engine running at night. Useful formulae needed to set parameters needed for the Simulink program:

Thermal efficiency of Stirling engine at night:

$$\eta_{Thermal\_night} = \frac{T_{tank} - T_{ambient\_night}}{T_{tank}} \dots\dots\dots(20)$$

Output work of the engine at night:

$$\text{Increment } W_{out\_night} = P_{hot\_night} \cdot \Delta V + P_{cold\_night} \cdot \Delta V - W_{pump\_total} - W_{mech\_loss} \dots\dots\dots(21)$$

Input energy needed from the hot water:

$$W_{in\_night} = \frac{W_{out\_night}}{\eta_{Thermal\_night}} \dots\dots\dots(22)$$

Mass of the hot water that needs to be in contact with the heat transfer area:

$$e_{\text{Subscript}} \quad Mass_{\text{water}} = \frac{W_{\text{in\_night}}}{(C_{p_{\text{water}}} * (T_{\text{tank}} - T_{\text{ambient\_night}}))} \dots\dots\dots (23)$$

Water flow in litres per minute:

$$Flow = Mass_{\text{water}} \cdot 60 \dots\dots\dots (24)$$

The lowest amount of input energy needed to overcome engine losses:

$$W_{\text{min}} = W_{\text{pump\_total}} + W_{\text{mech\_loss}} \dots\dots\dots (25)$$

Lowest temperature the hot water tank may go and still produce output power:

$$T_{\text{tank\_min}} = \frac{(W_{\text{min}} - (C_{p_{\text{water}}} * Mass_{\text{water}} * T_{\text{tank}}))}{(C_{p_{\text{water}}} * Mass_{\text{water}})} \dots\dots\dots (26)$$

### 3.3 Solar PV model

The output power of the Stirling engine will be used to determine the size of the PV array and the inverter rating. The battery bank size will be selected from the hot water tank performance. This information will be used to obtain the capital cost of each proposed system and compare them to the capital cost of the Stirling system.

## 4. Results

Certain conditions must be assumed before any equations or simulations can be done. These include the focussed solar temperature on the Stirling receiver, the temperature in the shade (in the case of the cold cylinder), and ambient temperature at night:

- $T_{\text{solar\_in}} = 100^{\circ}\text{C}$  or 373 Kelvin
- $T_{\text{ambient\_shade}} = 25^{\circ}\text{C}$  or 298 Kelvin
- $T_{\text{ambient\_night}} = 17^{\circ}\text{C}$  or 290 Kelvin

Air will be chosen as the working fluid inside the Stirling engine, and the internal system pressure of the system will be raised to 200 kPa; thus, the thermal properties of air will be used:

- $\rho_{\text{air}} =$  Density of air taken as 1.225 kg/m<sup>3</sup>
- $\mu_{\text{air}} =$  Dynamic viscosity of air taken as 0.0018 Pa.s
- $h_{\text{air\_free}} =$  Convective coefficient of free air taken as 50 W/m<sup>2</sup>.K
- $h_{\text{air\_forced}} =$  Convective coefficient of forced air taken as 100 W/m<sup>2</sup>.K
- $R_{\text{air}} =$  Specific gas constant of air taken as 287 J/kg.K
- $C_{p_{\text{air}}} =$  Specific heat capacity of air taken as 1000 J/kg.K

Conductivity of chosen materials:

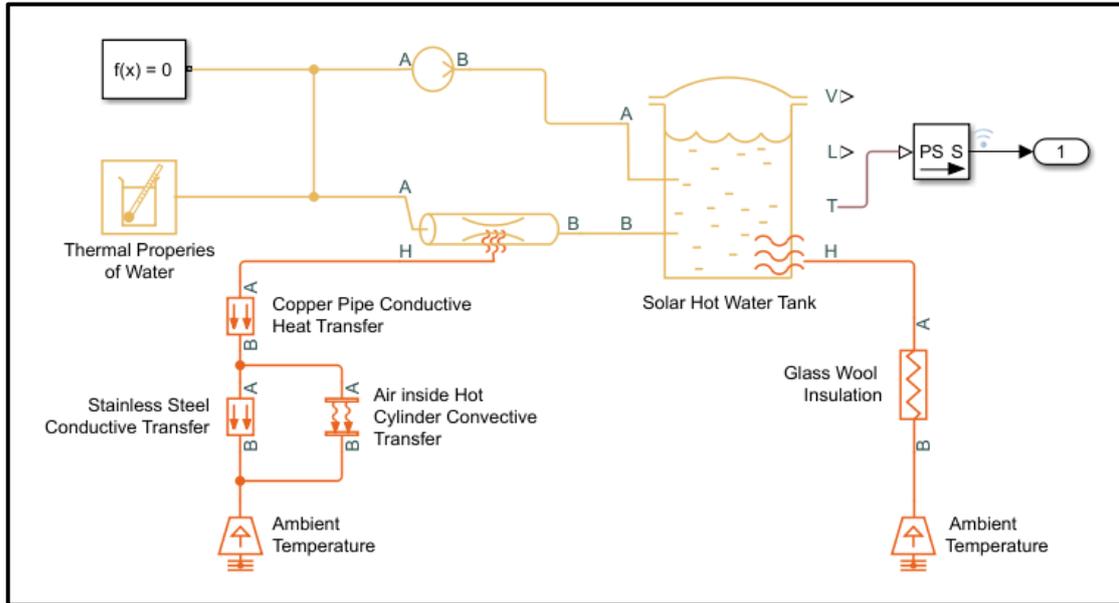
- $K_{\text{stainless\_steel}} = 16.2$  W/m.K
- $K_{\text{copper}} = 399$  W/m.K
- $K_{\text{glasswool}} = 0.03$  W/m.K
- $K_{\text{glass}} = 0.02$  W/m.K
- $K_{\text{pvc}} = 0.16$  W/m.K

Specific heat capacity of thermal storage material (water) and regenerator material:

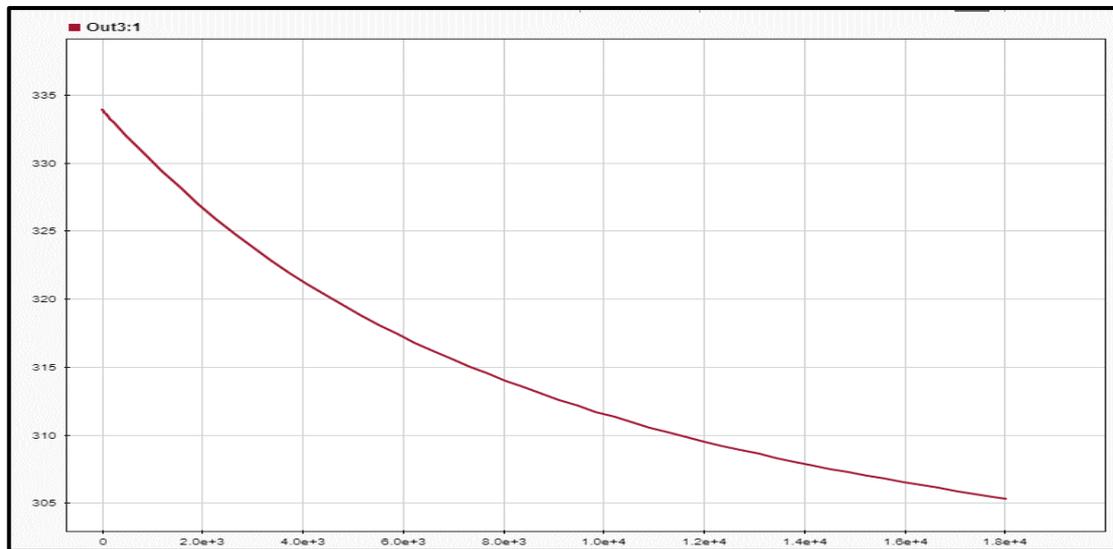
$$C_{p\_water} = 4200 \text{ J/kg.K}$$

$$C_{p\_brass} = 920 \text{ J/kg.K}$$

The engine stroke is taken as 150mm and the bore is 95mm, the generator is accepted to have an overall efficiency of 80% and the volume of water inside the tank is taken as 100 litres. Figure 4 and 5 show the Simulink model and output for the hot water tank performance during operation at night.



**Figure 4: Simulink model for the hot water – Stirling interface**



**Figure 5: Output of Simulink model – Temperature over time**

Figure 6 and 7 show the Simulink model and output of the solar collector performance during the day. The total collector surface is 1.6 m<sup>2</sup> and there are five collector pipes with dimensions: 50 mm x 2 m.

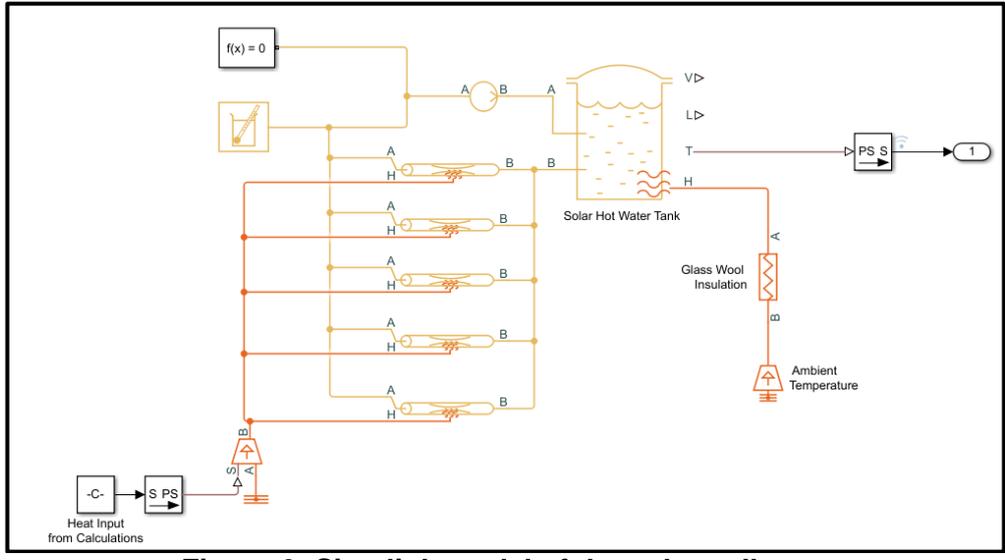


Figure 6: Simulink model of the solar collector

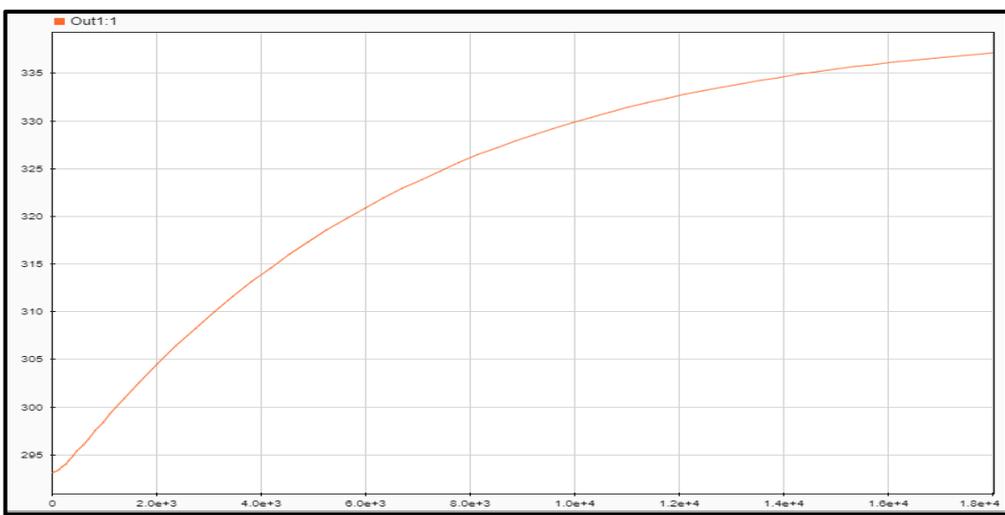


Figure 7: Output of Simulink model – Temperature over time

4.1 Stirling output

Table 2 shows the Stirling engine's peak performance and thermal storage system.

Table 2: Peak performance characteristics of the Stirling engine

Stirling peak power output during the day (W)	Stirling peak power output during the night (W)	Backup time (hours)
242	225	3.2

4.2 PV solar model

From the results obtained in 4.1, the PV solar system rating for the different equipment was calculated using an excel spreadsheet:

**Table 3: Total Watt-hour rating of the system**

Device	Power Rating	Quantity	Usage per Day (Hr)
Stirling Engine	242	1	5
TOTAL W(Hr)			1210

**Table 4: Results for PV system (deep-cycle battery backup)**

	Column1
Days of Autonomy	0.1333
Total Power Needed From The PV Panels:	1573
Available Size of PV Panel (each)	330
Short Circuit Current of PV Panel	9.6
Total Peak Watt Rating:	327.7083333
Total Number of Panels Needed:	1
Inverter Size (W):	302.5
Inverter Input Voltage:	12
Battery C-Rating (AMPS)	45
Battery Voltage:	12
Depth of Discharge (%):	50
Size of Battery Bank:	31.62607843
No of Batteries in Parallel:	1
No of Batteries in Series:	1
Total Number of Batteries Needed:	1
Solar Charger Controller Size (A):	12.48

**Table 5: Results for PV system (lithium-ion battery backup)**

	Column1
Days of Autonomy	0.1333
Total Power Needed From The PV Panels:	1573
Available Size of PV Panel (each)	330
Short Circuit Current of PV Panel	9.6
Total Peak Watt Rating:	327.7083333
Total Number of Panels Needed:	1
Inverter Size (W):	302.5
Inverter Input Voltage:	12
Battery C-Rating (AMPS)	20
Battery Voltage:	12
Depth of Discharge (%):	80
Size of Battery Bank:	19.76629902
No of Batteries in Parallel:	1
No of Batteries in Series:	1
Total Number of Batteries Needed:	1
Solar Charger Controller Size (A):	12.48

#### 4.2.1 Capital costs

Tables 6 and 7 depict the capital costs of the 2 PV systems based on the results obtained in Tables 4 and 5.

**Table 6: Capital cost for PV system with lithium-ion battery backup**

Part Description	Quantity	Price
330W solar panel	1	R2,300.00
500W inverter	1	R2,200.00
15A smart battery charger	1	R3,100.00
12V, 22Ah Li-ion Battery	1	R2,000.00
16mm <sup>2</sup> solar cable (Red)	10	R200.00
16mm <sup>2</sup> solar cable (Black)	10	R200.00
MC4 connector (pair)	2	R110.00
<b>Total</b>		<b>R10,110.00</b>

**Table 7: Capital cost for PV system with deep cycle gel battery backup**

Part Description	Quantity	Price
330W solar panel	1	R2,300.00
500W inverter	1	R2,200.00
15A smart battery charger	1	R3,100.00
12V, 45Ah gel battery	1	R1,850.00
16mm <sup>2</sup> solar cable (Red)	10	R200.00
16mm <sup>2</sup> solar cable (Black)	10	R200.00
MC4 connector (pair)	2	R110.00
<b>Total</b>		<b>R9,960.00</b>

**Table 8: Capital cost for solar Stirling engine with thermal storage**

Part Description	Qty	Supplier	Estimated lead time	Price Each	Line Total
2TR-FE Toyota Engine Piston (incl. rings and pins)	2	Midas	1 Week	552.00	1,104.00
Steel Sleeves, ID:95mm, OD:99mm, L:212mm	2	Ferro-Tech	2 Weeks	736.00	1,472.00
Ball Bearing, ID:8mm, OD:22mm, W:7mm	4	BMG	3 Days	22.50	90.00
Ball Bearing, ID:20mm, OD:42mm, W:12mm	4	BMG	3 Days	64.60	258.40
25mm Mild Steel Square Tubing per length (6 meters)	1	Stewards & Lloyds	1 Day	203.55	203.55
Refurbished 210l Steel Drum with lid	1	Amtec	1 Day	159.85	159.85
100kPa Pressure Safety Relief Valve	1	Buco	1 Days	509.00	509.00
Glass Wool (Aero-Lite) 135mm x 1.2M x 5M	1	Leroy-Merlin	1 Day	598.00	598.00
22mm Rubber Hose per meter	1	HoseWorld	1 Day	80.50	80.50
22mm Copper Pipe per length (4 meters)	1	Leroy-Merlin	1 Day	429.00	429.00
50mm HDPE Black Irrigation Pipe per meter	40	Builders Warehouse	1 Day	42.00	1,680.00
PVC Bend, 50mm, 90 Degrees	20	Leroy-Merlin	1 Day	19.90	398.00
IBR galvanised Roof sheet (0.4 x 686 x 3200mm)	1	Stewards & Lloyds	2 Weeks	373.45	373.45
12V DC Water Pump (20-30Watt)	1	Takealot	1 Week	649.00	649.00
Angle Grinder, 230V, 850W	1	Adendorff	1 Day	595.00	595.00
600V, 25Amp Bridge Rectifier	1	RS Components	1 Week	45.00	45.00
Day/Night Switch, 6A	1	Builders Warehouse	1 Day	98.00	98.00
U-Bolt, 50mm x 8mm	2	Builders Warehouse	1 Day	35.00	70.00
M20 Stud Bolt, 195mm, Partially Threaded	1	Benoni Bolt	1 Week	86.30	86.30
M20 Bolt, 110mm, Threaded (25mm)	1	Benoni Bolt	1 Week	35.22	35.22
M20 Bolt, 85mm, Threaded (25mm)	1	Benoni Bolt	1 Week	30.05	30.05
M20 Nut	6	Benoni Bolt	1 Week	5.75	34.50
M20 Flat Washer	10	Benoni Bolt	1 Week	0.87	8.70
M20 Spring Washer	6	Benoni Bolt	1 Week	2.22	13.32
Fenner Friction Belt, V-Wedge, 13 x 8 x 1610mm	1	BMG	2 Days	44.62	44.62
SPA Fenner Pulley 80mm	1	BMG	2 Days	77.60	77.60
SPA Fenner Pulley 315mm	1	BMG	2 Days	572.00	572.00
Fenner Taper Lock Bush 1108x20	1	BMG	2 Days	61.00	61.00
Fenner Taper Lock Bush 2012x20	1	BMG	2 Days	99.80	99.80
<b>Grand Total</b>					<b>9,875.86</b>

## 5. Conclusion and recommendations

From the results obtained in section 4 of this paper, it is clear that a Stirling engine coupled with thermal energy storage for backup is a viable alternative to PV systems both in terms of performance and economics.

### 5.1 Recommendations

There are a few factors that can be improved upon in order to increase the efficiency of the Stirling engine namely:

- Use helium as a working fluid as its specific heat capacity is much higher than air at 5193 J/kg.K.
- Raise the initial pressure inside the engine to a higher value than 200 kPa. This will increase the amount of working fluid inside and cause higher break work output for the exact temperature differential.
- Increase the solar input temperature at the hot cylinder. As seen in equation (20), the thermal efficiency of the Stirling engine is directly proportional to the input and output temperatures.
- Decrease the temperature at the cold cylinder as per equation (20).

Factors that may increase the performance of the thermal storage system:

- Use a larger solar collector surface area in order to absorb more solar energy.
- Use more collector pipes as this will absorb more solar energy and help the water inside the tank reach the final temperature sooner.
- Use copper instead of PVC for the collector pipes as copper has a much higher conductivity coefficient.
- Use a more significant amount of water as storage medium. This directly increases the amount of energy that can be stored and will therefore provide longer backup hours.
- Investigate the use of other thermal storage materials for better thermal performance.
- Improve thermal insulation of the entire system.

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