Design Aspect of the Dish Stirling System and the Prospect of Power Generation in Bangladesh

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Abstract: This paper presents the design aspect of the dish Stirling system and the prospect of this type of power generation in Bangladesh. In addition, the various prospects of dish Stirling system are studied. Bangladesh is a developing country with a perpetual shortage of electricity and numerous hardships towards meeting the demand. The dish Stirling engine is a new technology using the solar ray to convert it to usable electricity. The economic aspect of this technology delivers significant advantages over the existing solar home system. This work presents the working principle, grid connectivity and economic viability of the Stirling engine system incorporating with the effective design of solar tracking system to enhance the efficiency. A prototype model is implemented to display its feasibility of this technology in Bangladesh. Simulation results and practical outcomes properly demonstrate its effectiveness.

Keywords: *Dish-Stirling System, Renewable Energy, Solar-Ray, Solar Home System, Stirling Engine*

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1. Introduction

Over the last two decades, the demand for electrical energy has increased significantly. Since fossil fuels are non-renewable and require finite resources which are declining because of environmentally damaging retrieval technique, there are needs for nonconventional methods to reduce ongoing energy crisis. Due to such concerns, developing countries like Bangladesh are facing setbacks in sustainable development. Research shows that about 42% of the population of Bangladesh has no access to electricity. The rest of 58% of people has a maximum demand of 10,390MW per day in which day peak demand and evening peak demand are 5,515 MW and 6,987 MW respectively [1]. However, the total capacity of electricity generation is about 8,709 MW which accounts for a deficit of 2081 MW [1]. Despite having such huge deficits only 3.3 % of electricity is being generated by renewable sources [2]. As in other countries, the demand for power generation in Bangladesh is increasing rapidly. Currently, 78% of people have access to electricity in Bangladesh [3].

Dish-Stirling System is one of the most effective solar power generation systems, which is targeted for many applications in current power generation race. The dish Stirling systems use a parabolic dish solar concentrator, tracking the sun and focusing solar energy onto a receiver where it is absorbed and transferred to the Stirling engine or generator. This technology can be termed as concentrating solar power (CSP) system. This system has a concentrator, a thermal receiver and a heat engine or generator which is located at the focus of the dish. To increase this percentage, solar power generation system can be very effective in Bangladesh because of the country's geographical location. In Dhaka city, the average solar insulation is 4.73 kWh/m^2 and the daily average sunshine hour is 7.55 hours [4]. To use this solar energy entirely Dish-Stirling system can be the best choice because of its high efficiencies, for long term and low maintenance operations. Likewise, Dish-Stirling systems are modular, so they can be assembled into plants ranging in size from a few kilowatts to megawatts. Therefore, in this work, we propose a prototype mode for generating electricity through dish Stirling technology in Bangladesh.

The remaining sections of this paper are organized as follows. Section 2 shows the present energy situation of Bangladesh. The methodology of Dish Stirling System and our proposed method are presented in Section 3. A prototype model with simulation results is presented in Section 4. Finally, we conclude our work in Section 5.

2. Present Energy State of Bangladesh

2.1. Renewable Energy

In Bangladesh, solar energy is becoming popular. It can save oil and other kinds of energy. Biogas produced from garbage and cow dung can significantly meet up the shortage of electricity. Generation of electricity from fuels is very expensive; hence, its alternative is expected. The population of Bangladesh is increasing alarmingly and so the demand for electricity is also increasing. At present, the government is thinking of the use of atomic energy in producing electricity [5]. The atomic reactors are very dangerous for the community where they operate and numerous health hazards always remain in question. Therefore, green energy is the most feasible way of achieving the demand of electricity worldwide. A few electricity generation stations can be observed in Bangladesh. The electricity generation of renewable sources is increasing in Bangladesh at a slow rate [6]. Figure 1 displays the total electricity generation from the year 2009 to2018.

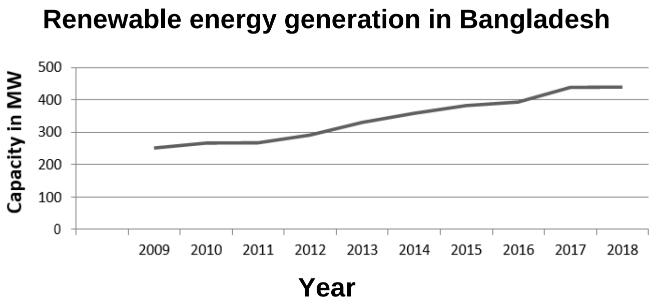


Fig. 1. *Bangladesh's Total Renewable Energy Capacity in Years 2009-2018 [7].*

2.2. Solar Energy

Bangladesh occupies a great potential for solar energy. On an average solar energy brings about 46.5 kWh/m^2/day, and also harnesses an average of 10.5 hours of the sun per day, in which 4 to 4.5 are peak sunlight hours and also 300 clear sunny days per year [8] [9]. At present, Bangladesh is now considered a market leader when it comes to solar home system (SHS), and standalone photovoltaic systems [8]. Solar photovoltaic (PV) systems are in use in Bangladesh with over 2.9 million family installations having a capacity of 122.2 MW (April 2014). Scaling-up of solar photovoltaic systems are being implemented by the development partners through Infrastructure Development Company Limited (IDCOL), Rural Electrification Board (REB),Local Government Engineering Department (LGED), Bangladesh Power Development Board (BPDB), NGOs and Private Organizations implementing in the solar energy program. Bangladesh is a strong potential for solar energy.

Dissemination of the solar home systems (SHSs) is being upgraded mainly by IDCOL, private sector companies and NGOs based on direct-sale nearest and also provision of refinancing funds for micro-financing of solar home systems to participating the organizations through IDCOL. Table 1 shows the solar electricity generation of Bangladesh in the year of 2009 to2018.

Table 1 Bangladesh's Solar Energy Capacity 2009-2018 [10]

Year	09	10	11	12	13	14	15	16	17	18	19	20
Capacity (MW)	18	32	43	66	95	122	145	155	200	201	249	200

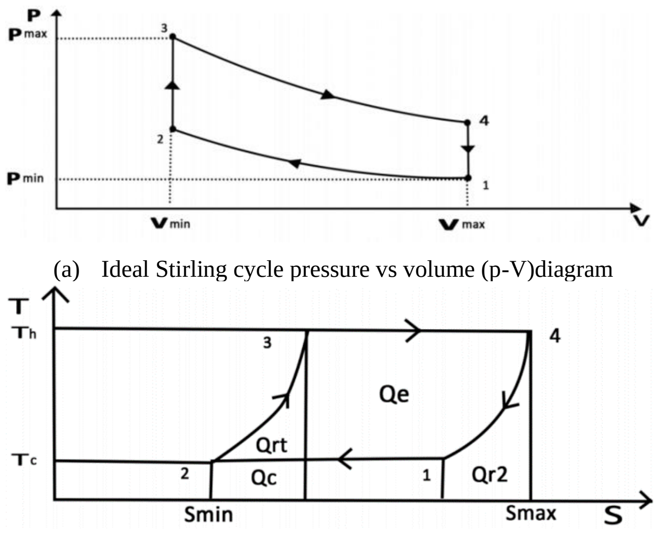
3. Methodology

3.1. Stirling Engine

Stirling engine is an external combustion engine. Stirling engine basically converts thermal energy to mechanical energy by the Stirling cycle. In the year 1816, Robert Stirling and his brother James created the Stirling engine [11]. The Stirling cycle system has hot space, heater, regenerator, cold space and the cooler. These engines are capable of converting heat energy into mechanical energy in a clean climate-friendly manner.

3.2. Principle of Operation

Theoretically, a Stirling engine is a very efficient engine compared to solar PV system ranging about 30-40% with a temperature range of 700-800 degrees Celsius and operating speed of about 2000-4000 rpm [12]. Stirling engine works on the Stirling cycle. An ideal Stirling cycle has three theoretical advantages. Firstly, the thermal efficiency of the Stirling cycle is equal to the Carnot cycle with ideal regeneration. Secondly, the advantage is obtained by substitution of two isentropic processes with two constant-volume processes over the Carnot cycle. These result in increasing the *p–v* diagram in the area. The third advantage is compared with all mutual piston heat engines working at similar temperature limits, the similar volume ratios, the similar mass of ideal working fluid, the similar external pressure, and the mechanism of the similar overall effectiveness. The ideal Stirling engine has the maximum feasible mechanical efficiency [12]. An ideal Stirling cycle p-V diagram and T-s diagram are shown in Fig. 2. Stirling engine works on the Stirling cycle and comprises of four processes as can be seen in Figure 3 [13].



(a) Ideal Stirling cycle pressure vs volume (p-V)diagram

(b) Ideal Stirling cycle temperature entropy (T-s)diagram

Fig. 2. *Different stages of Stirling cycles: (a) Pressure versus volume, (b) Temperature entropy.*

3.2.1 Isothermal Compression: At this stage, the power piston travels inwards. In this stage, gas is compressed and volume is reduced which in turn raises the pressure. The area between points 1 and 2 under the p-V diagram indicates the work done to compress the gas, W_c. In this process heat is removed to the environment by the cooled cylinder and the removed heat, Q_c is the area between points 1 and 2 under the T-s diagram.

3.2.2 Isochoric Heating: At this stage, the piston remains at its most inwards point and the volume is kept constant. Heat is added to the gas and its temperature is raised from cooling temperature, T_c to heated temperature, T_h. Gas pressure reaches the maximum point, P_{max}. The area between points 2 and 3 under the T-s diagram depicts the heat added from the regenerator, Qr.

3.2.3 Isothermal Expansion: At this stage, the expanding heated gas pushes the power piston outwards and energy transferred to the piston is We which equals the area between points 3 and 4 under the p-V diagram. In this stage heat added from the heat source to the heated cylinder is Q_e and it represents the area between points 3 and 4 under T-s diagram. This stage also increases the overall volume and lowers the pressure.

3.2.4 Isochoric Cooling: At this stage, the piston remains at its outer most point and the volume is kept constant. Heat is absorbed from the gas and its temperature is lessened from T_h to T_c. Gas pressure gets down to the minimum point P_{min}. Heat absorbed by the regenerator is $Q_{r2}$and it equalsQ_{r1}.

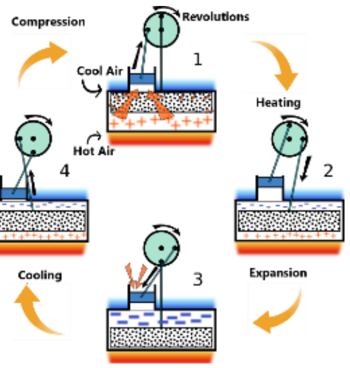


***Fig. 3**. Stirling cycle.*

3.3. Engine Power Output

Stirling engine output power can be calculated from the Beale formula. According to Beale, the power output of the Stirling engine could be calculated approximately from the following equation:

$$P = B.P_m.f.V_p \tag{1}$$

Here, P is the power output of the Stirling engine, B is the Beale number which range is from 0.11 to 0.15, P_m is the mean cycle pressure in Mpa, f is the cycle frequency in Hz, V_p is the displacement of power piston in cm^3 [14]. This formula can be used for all types of Stirling engine. Beale number is a function of both source and sinks temperature.

3.4. Working Process of Dish-Stirling System

Three basic components have a Dish-Stirling system. These are: the concentrator, the receiver, and the power conversion unit. At first energy from the sun is reflected by the parabolic dish and focused onto a Stirling engine, This Stirling engine is the high-efficiency power conversion unit of this system. If no losses occur in the concentrator, the concentration factor C will be higher. Concentration factor C is the ratio of the outgoing energy density and the incoming energy density. It can also be described by the inverse ratio of the concentrator entrance aperture area and exit aperture area [15].

$$C = E'/E = A/A' \tag{2}$$

Here, E' is the outgoing energy density; E is the incoming energy density. A is the concentrator entrance aperture area in square meter and A' is the exit aperture area in square meter.

Those reflected, highly concentrated rays hit the receiver of the power conversion unit with heat. Basically, the receiver is the device that converts concentrated solar radiation to heat. The useful heat collected by the receiver Q can be calculated by the following equation:

$$Q = A_{AP}.[\alpha.C.E^S - \varepsilon.\Sigma.(T_A)^4 - U_L(T_A - T_a)] \tag{3}$$

Here, A_{AP} is the aperture area, α is the average absorptivity of the absorber with respect to the solar spectrum, C is the concentration factor, E^S is the radiation density of the direct solar radiation, ε is the average emissivity of the absorber with respect to the black body radiation at the absorber temperature T_A, σ is the Stefan-Boltzmann constant, U_L is the heat loss coefficient due to convection and conduction and T_a is the ambient temperature [15].

After transferring the heat from the absorber, this time the working fluid in the temperature difference is needed. The other expression for the necessary energy is that:

$$Q = A_{ab}.\ U_I.\ (T_A - T_F) \tag{4}$$

Where U_I = inner heat transfer coefficient from the absorber to the fluid. TF = average temperature of the heat transfer fluid and Aab = absorber area [15]. From these two quation, energy balance equation can be rewritten as follows.

$$Q = A_{AP}[F.\alpha.C.E^S - F.\varepsilon.\sigma(T_F)^4 - F.\ U_L(T_F - T_a)] \tag{5}$$

The thermal efficiency of the receiver η is the ratio of the useful heat and the incoming solar radiation.

$$H_{th} = Q/A_{AP}.C.E^S \tag{6}$$

The variation of thermal efficiency of a receiver is shown in Fig. 4.

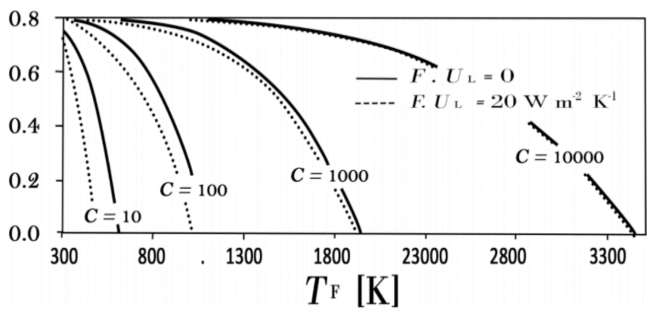


***Fig. 4.** The thermal efficiency of a receiver ηth as a function of the fluid temperature TF andthe concentration factor C.*

When the highly concentrated rays hit the receiver 600-800 degrees Celsius, it causes the working gas to expand and drive the pistons of the Stirling engine. Pistons turn a generator which produces electrical output far more efficiently than any other solar power technology. The current produced by this system is 3 phase AC and it is directly connected to the grid. The working process of the Stirling engine is the same as described earlier. At sunset the concentrator goes into a safe position and rotates back to the sunrise point, ready for the next day operation.

3.5. Dish Stirling Power to Grid System

The Dish Stirling system is shown in Figure 5. It produces electricity using concentrated solar thermal energy to drive a Stirling engine. The main components of this system are dish collector, cavity receiver, Stirling engine, generator, converter, batteries bank, and inverter. The system utilizes a parabolic mirror equipped with dual-axis tracking to concentrate solar radiation onto a thermal receiver integrated in the Stirling engine. The function of the receiver is to transfer the absorbed solar energy to the working fluid in the Stirling engine. The Stirling engine converts the absorbed thermal energy into mechanical power by compressing the working fluid when it is cool and expanding it when it is hot.

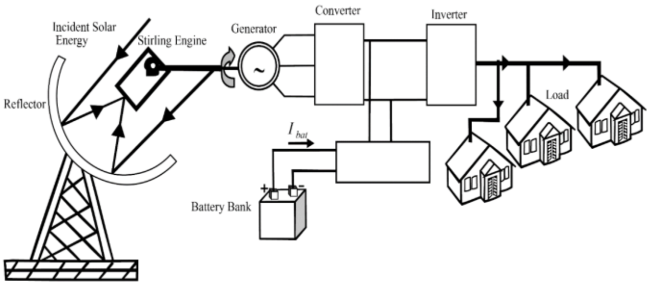


Fig. 5. *Schematic diagram of the dish system.*

3.6. Proposed Design

This part demonstrates a design of the dish Stirling system which involves the concentrator, tracking system, SOLO 161 Stirling engine, and the receiver.

3.6.1 The Concentrator: To construct a dish Stirling system at first, we need to design the concentrator. For this system, we choose a paraboloid dish, which has a diameter of 8m. So, the projected mirror area is calculated at 50.3 square meters. To construct the concentrator, we will use silvered glass. There are 12 facets of glass and each of them are 0.8 mm thick. The reflectivity of the concentrator is selected 0.94 and the height and width of the concentrator are selected 9m. The approximate weight will be 4000 kg. For this concentrator focal length is selected 4.5m and the intercept factor is 0.94. For this type of solar concentrator typical temperature range is 650-800 deg. Celsius [15]. Solar concentrator measurement is shown in Table2.

Table 2 Specification of solar concentrator [15]

Type	Paraboloid
Number of facets	12
Projected Area	50.3 square meter
Height	9 m
Width	9 m
Reflectivity	0.94
Weight	4000kg
Focal length	4.5 m

3.6.2 The Tracking System: At first to track the sun and also to operate the system correctly, it is needed to use a tracking system with two axial tracking systems. The whole structure stands on six wheels. These six wheels move the concentrator towards the sun. The movement of the wheels is done by a small servo motor. The whole tracking system is controlled by a microcontroller. Maximum allowable wind speed is 15m/s for the system.

Table 3 Technical data of the tracking system

Tracking Equipment	System info
Max. wind velocity	15 m/s
Drive	Servo Motor
Drive Velocity	60 deg. Per min
Control System	PC, microcontroller

3.6.3 SOLO 161 Stirling Engine: In this dish Stirling system, we use concentrated solar power to run the Stirling engine and produce electricity. For this case, we have selected the SOLO 161 Stirling engine, which is capable of producing 3 phases alternating current. The length, depth, and height of this type of engine is 1280 mm, 700 mm and 980 mm respectively [16]. This engine is rated 10 KW. It has 2 cylinders and the cylinder capacity is 160 cc. The rated speed for this engine is 1500 rpm or 25 Hz. The operating gas is helium. Helium gas is used here due to the good thermal and aerodynamic properties [16]. The output power can be adjusted by controlling the operating gas pressure between 50 to 200 bar and this will be done by a small piston pump. This type of engine has a water-cooling system for the low-temperature side [17]. A specification of SOLO 161 Stirling Engine is presented in Table 4.

Table 4 Specification of SOLO 161 Stirling engine [17]

Type	SOLO 161
Swept Volume	160 cc
Rated Power Output	10 KW
Working Gas	Helium
Gas Pressure	50-200 bar
Power Control	Pressure Control

3.6.4 The Receiver: The connection between the concentrator and the Stirling engine is the receiver. It has basically absorbed the solar radiation reflected onto it from the concentrator and it passes this energy to the Stirling engine in the form of heat with the least possible losses. Among two types of receiver, the directly illuminated tube receiver is selected. These tubes are directly connected to the cylinder head of the Stirling engine. The diameter of these tubes is 3 mm which resist very high temperature [15].

3.7. Proposed Design Analysis of Dish Stirling System

It is important to see the effect of the proposed design in bulk power generation. To observe the effect, we have designed a plant using the dish Stirling system.

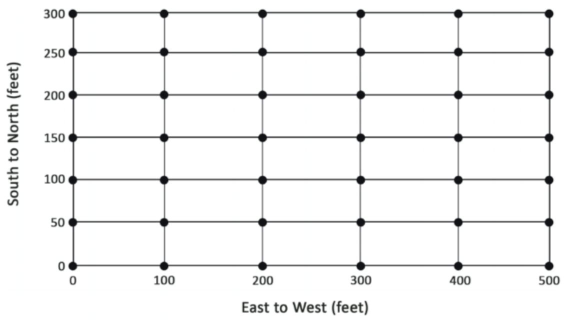


Fig. 6. *Osborn's rectangular layout model.*

Designing the field along with the sun, the east-west distance and the north-south distance of two units will not be similar. Upon solving this problem,we have decided to follow Osborn's rectangular layout model (see figure 6). Osborn modeled this layout basedon shade interaction between round dishes and energy production. According to his model, in east-west, the gap between two units needs to be 100 feet which is 30.48 meter. On the other hand, in south-north, the gap needs to be 50 feet which is 15.24 meters. For selecting this distance, he basically considered the shading impact, but cost also has a great impact. Increased spacing will also increase wire cost, land cost, maintenance drive times, wind impacts, etc. But most importantly it will increase energy loss. By using the 15 minutes 1977 meteorological data from the Solar One Central Receiver Project, he had shown how the shading effect reduces the performance of the system. Figure 7 shows the impact of shading and shading degradation factor on the system performancecurve.

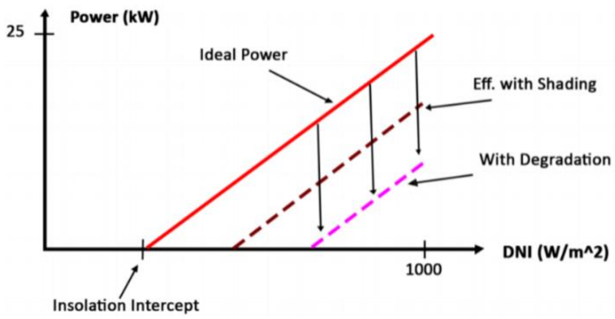


Fig. 7. *Impact of shading and shading degradation factor on the system performance curve.*

To verify Osborn's model, Sandia National Laboratories modeled a field of 20,000 dishes system in Barstow, CA using the same meteorological data. In their study, they have shown that Osborn's model can cause loss of energy and revenue. Then they tried to develop the model by staggering the layout. But they found that when the field is staggered there is a reduction in energy production and revenue [17]. All calculations were performed with the dish spaced 52 feet north to south and 104 feet east to west. In the end, they found that the optimum layout of a dish field is a rectangular grid without stagger, considering only the revenue and energy steams. Effect on Revenue and Energy production of variations in the North-South and East-West dish spacing is shown in Figure 8.

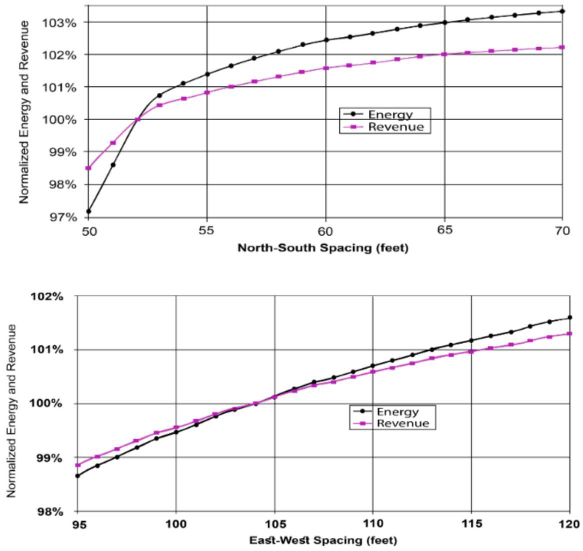


Fig. 8. *Effect on revenue and energy production of variations in the north-south and east-west dish spacing.*

After reviewing this analysis, we have also selected east-west dish spacing 100 feet or 30.48 meter and south-north dish spacing 50 feet or 15.24 meter. We have selected 1 acre of land, which is 4046.86 square meter = 63.61*63.61 meter. In this amount of land, we can set up 15 units of dish-Stirling system. We can arrange them in 5 rows and 3 columns. By installing them we can generate 150 kW. This is far more than PV panel output 78.91 kW in the same amount of area, which will be discussed in the next chapter. The field layout of the proposed design on 1 acre of land is shown in Fig. 9.

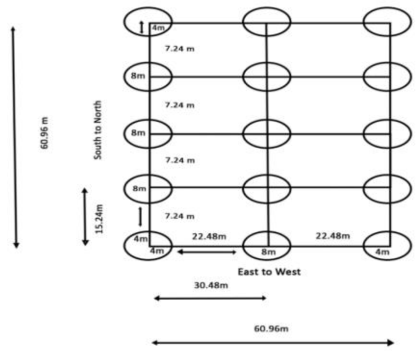


Fig. 9. *Field layout of the proposed design on 1 acre of land.*

3.8. Prototype Model

We have designed a small-scale prototype model to justify the practicability of our proposed method. This model has a concentrator, a thermal receiver and a heat engine or generator which is located at the focus of the dish. We have three conditions to apply for measuring output voltage & measuring current: the sunshine condition, shadow condition, and flippest condition. These six times multimeter show six different values. First three times, in the sunshine condition, the output voltage increases rapidly, in the shadow condition, the output voltage decreases rapidly, and in flippest condition, the value is increased from the shadow

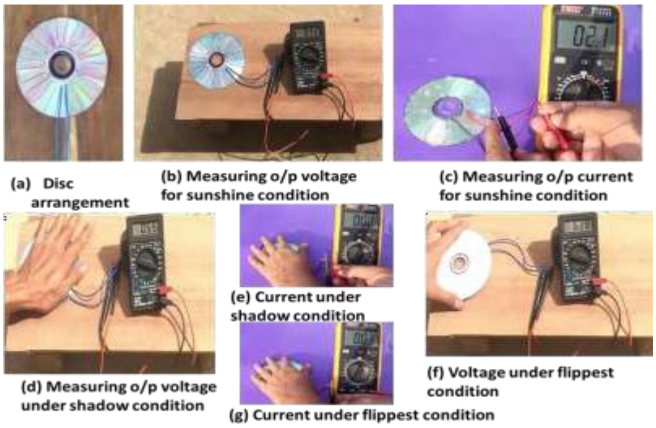


Fig.10. *Dish Stirling prototype model: different parts and their output quantities. (a) Disc arrangement, output voltage and current measurement under (b)&(c) sunshine condition, (d)&(e) shadow condition and (f) and (g) flippest condition.*

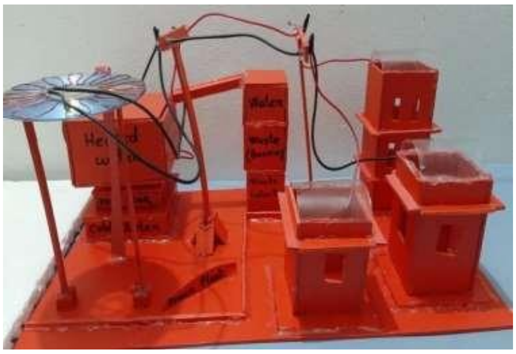


Fig. 11. *Dish Stirling Base Power System: A prototype model.*

condition and decreased from the sunshine condition. In the second three times, the sunshine condition pushes the output current up rapidly but in the shadow condition, the output current becomes zero, and in flippest condition, the value is decreased from the sunshine condition. Discs are very good at capturing light. Figure 10 displays our proposed prototype model made of locally available components. A detail measurement of voltage and current under three different cases are presented in Figure11.

4. Results

4.1. Simulation Results

An output power vs pressure curve is shown in Figure 12 using MATLAB**.** As the output power of the Stirling engine depends on the pressure it gets, in Figure 12, it can be seen that increasing in the pressure level the output varies linearly.

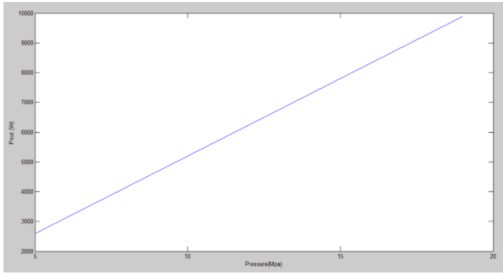


Fig. 12. *Output power of a Stirling engine as a function of pressure.*

4.2. Implementation Results

In the modern age, many music-lovers have discarded CDs in favor of iTunes, MP3s and Windows Media Player. The portable music players are no larger than a silver dollar. And it easily connects to computers for music updates. So, this leaves music aficionados with blank and burned CDs they no longer need. We could simply toss or recycle them, but we could also take advantage of their reflective surfaces to create our own solar heating panel. Therefore, we use these CDs for our prototype model. We also used lower cost Zener diode and copper wire. Zener diode has a unique characteristic of flowing current in the reverse direction under a constant voltage drop at its terminals which we utilize for our prototype model. Copper wires are a cylindrical shape which the most common wires used in electronic components. These things are available in local markets.

Table 6 and 7 present input-output power measurement and total maximum output power in three different conditions respectively. The efficiency of our proposed model is approximately 30% which is much better than the solar PV system. The overall output power is measured 20MW under scaling up to our proposed prototype model. The maximum power is achieved at sunshine condition.

Table 6. Implemented Result

Input Power Calculation	Output Power Calculation
Diameter, D = 8m Project area = $\pi/4 \times D^2$ = 50.3 m^2 Average solar irradiance in Dhaka = 375 W/ m^2	Displacement volume = 160 cc Operating Speed = 1500 rpm = 25 Hz Helium gas pressure = 50-200 bar (variable) = 5-20 Mpa Receiver temperature = 800 degree Celsius = 1073 K Beale number = 0.13 Maximum Output Power = 0.13 × 160 × 25 × 20 = 10400W
Input Power = (50.3×375) W = 18862.5 W	Efficiency = 10400/35210 = 29.5%

Table 7. Project Management System

Case-1: For Sunshine Condition	Case-2: For Shadow Condition	Case-3: For Flippest Condition
Output voltage = 9.42 mV Output current = 2.1 mA So, the output power = 9.42×2.1 = 19.8 MW	Output voltage = 0.55 mV Output current = 0 mA So, the output power = 0.55×0 = 0 MW	Output voltage = 6.28 mV Output current = 0.03 mA So, the output power = 6.28×0.03 = 0.2 MW
Hence, the total output power = (19.8+0+0.2) MW = 20 MW		

In the field of solar thermal power generation system, Dish-

Stirling technology is really striking because of its high efficiency and modular design. Our Prototype Model can convert around 30% of incoming solar power to electricity. This is higher than the power tower or parabolic trough designs or PV panel, which generates around 15-16%. To observe the efficiency of Dish-Stirling system, total power generation on 1 acre of land is calculated. From the result it can be seen that this system can generate 150KW of electricity. At the same amount of land PV panel (a-Si) can produce 78.91 KW of electricity, which is far less than Dish-Stirling system. In the same time, it is observed that installing Dish-Stirling system in a bigger range can also make this system more efficient and cost-effective.

Even though there are not widely used evidences of conversion potential and practical applications of the discussed methods, more efforts should be devoted to material research, structure optimization and commercialization.

5. Conclusions

This paper presents the possibility of generating a significant amount of power in megawatt range in Bangladesh through our proposed Dish-Stirling technology. Based on the geographical location of BD a huge solar energy can be converted with usable electricity. The efficiency of our proposed method is better than the solar power generation. Prototype model and simulation results demonstrate the practicability of the method. Our results show that it is possible to generate large scale power with low cost.

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