Domestic Concentrated Solar Thermal Co-generation Plants for Pakistan

PHY 491/492 Senior Project Synopsis

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1 Problem Statement

The country is facing an electricity crises, the culprits both burgeoning demand and the inability of the government and private producers to setup large scale plants due to lack of investment and political issues. This has had drastic effects on both the quality of life and the economic activity in the country.

Second, there is an over reliance on fossil fuel based production strategies. In the face of the shortage, and the consequent increase in the prices, of fossil fuels this does not seem to be sustainable strategy.

Third, and perhaps most importantly, there is very little thought put into the environmental impact of the production strategies used in the country. On one hand fossil fuels have contributed mindlessly to increased levels of pollution. On the other hand, hydal power projects, though more environmentally friendly and sustainable, have their effects on the natural ecosystems.

Fourth, renewable energy has been an active area of research across the world for the past few decades and economically feasible solutions have been developed using various such technologies. Even though these technologies and solutions can sometimes be imported, there will always be a need to adapt and optimize them taking local conditions into account.There is however a dearth of renewable energy research in the country.

Fifth, academia and industry collaboration in the country is not at praiseworthy levels. There is a severe need to encourage academically driven solutions to industrial problems.

2 Aims and Objectives

We plan to create power generation units that are suitable for powering an average household in Pakistan, through the use of solar concentration technology, popularly known as Concentrated Solar Power (CSP). This will entail the design, analysis and modeling of such a system as well as the construction of a prototype.

We hope to address all the problems outlined above in this manner.We hope to provide a power solution that does not rely on large scale investments, a solution that relies on renewable and environmentally friendly fuel. This will not be an academically driven solution to an industrial problem but as noted below will be done in collaboration with a commercial enterprise.

2.1 Academic Aims

Current solar collector producers are placed in technologically advanced settings and therefore can produce system with low error, and can so focus their design focus on improving efficiencies. In developing countries however, practical production is far from optimum and errors are significant given limitations in production and maintainence. Therefore there is a different optimal design for such construction environments[2]. For example increasing the diameter of the absorber radius increases thermal losses and reduces the maximum optimal operating temperature resulting in further inefficiencies downstream. Therefore, existing collectors prefer small absorber radius. However, large absorber radius drastically reduces the effects of optical errors due to bad tracking, misplacement of the absorber or trough deformation due to wind or thermal expansion. Similarly, a small rim angle reduces the cost of the collector, as less material is required for the same aperature area however, small rim angles are more prone to tracking errors.[3] This gives us a three way optimization problem i.e. making the system thermally and optically efficient, error minimization and cost minimization which will be solved given local conditions. Moreover, the model produced will hopefully be transferable and useful to other projects in developing countries. This optimization will take into account the whole system.

Furthermore, to make it a more complete model we will then simulate the system. While there are existing models for simulating solar thermal systems there are limited simulations focusing on scales as small as 1kW. Most models simulate large scale power plants. They see whether they are economical and optimize their functioning. We will simulate the parts independently and then the system as a whole in which we will also see its economics. There exist a large number of software[1] that can simulate the optics of the solar collector. Also individual parts such as the organic Rankine cycle, Tesla turbine etc have been modeled separately. We will base the simulations on these previous simulations to compile an effective model of a micro scale concentrated solar thermal power plant.

Lastly, a group of MIT graduates have formed a research group that is developing solutions to a very similar scale to our models. Their total output is between 1-3 kw. They too are using solar troughs along with an organic Rankine cycle to generate electricity. However, their engine, heat exchange etc uses old parts from discarded cars and air conditioners. They began theoretical and lab work in 2004 and have started field tests in 2009. While a few steps ahead they have won numerous grants and awards based on their work. This shows us that the very small scale field is very undeveloped. Furthermore the group will not make its plans freely available upon completion and has applied for patents in USA and India and will give select local producers rights of manufacturing[7] Our work will help validate and support their work and we will open source our designs as well.

2.2 Non Academic

Although the study has several key points of academic interest it is also driven by the lack of electricity available in Pakistan. It is not a purely academic venture but motivated by the construction of a practical solution to part of the electricity problem. We are partnered with Convergence who also posses an interest in developing and marketing the final product. While they are doing this to promote social uplift, they are more concerned with the completion of a final product rather than the publication and development of mathematical models. Convergence was already pursuing the replication of an implemented design. It incorporates a solar trough collector, followed by an organic Rankine cycle which feeds heat to a Tesla turbine. The non-academic aims therefore entail the replication of this setup, designed by Phoenix Navigation. Detailed designs of the turbine have already been purchased by Convergence. While this reduces freedom of movement it helps reduce complexity and makes the project realizable by the support provided by Convergence. It also focuses our energies to specific tasks. A preliminary study has shown that troughs are indeed the most cost effective collector to implement and that organic Rankine cycles are favored by new small scales power generation projects due to its higher efficiencies and lower operating temperatures.

3 Outline

We will be discussing the outline of the project in terms of the various sections of our concentrated solar thermal unit. This will allow us to clearly demarcate the project outcomes and give a clearer picture of the project.

We have chosen to keep our system design highly modular. Such a scheme is suitable since it will allow future replicators freedom to make improvements selectively while only keeping take care of the interfaces between modules. It will also allow ease of modeling and simulation.

The three main modules are the solar collector, the organic Rankine cycle, and the electricity distribution mechanism. We will also we looking into the possibility of heating and cooling modules. The organic Rankine cycle stage is further subdivided into three sub-modules. The turbo-generator, evaporator and condenser.

One lack of modularity is the coupling of the turbine and the electricity generator. This is due to our dependence on the designs from Phoenix Navigations.

3.1 Solar Collector Model

There are a host of possible places where errors can seep in as elucidated by the Figure 1. These errors can be modeled by normal distributions and a universal error derived from them[8].

$$\sigma_{tot} = \sqrt{\sigma_{sun}^2 + 4\sigma_{slope}^2 + \sigma_{track}^2 + \sigma_{mirror}^2}$$

However, this gives the designer no help in improving his or her model. Other approaches make some errors more detailed while choosing to clump the rest together to keep the models simple. Therefore, we can remove some of the approximation to a normal distribution of some of the error and geometrically define them. One example is given below gives γ which contains information of all the optical errors according to [20] which is then which is then minimized given local parameters[3]

$$\sigma_{tot} = \sqrt{\sigma_{sun}^2 + 4\sigma_{slope}^2 + \sigma_{mirror}^2}$$

$$\gamma = \frac{1 + \cos\Psi_{rim}}{2\sin\Psi_{rim}} \int_0^{\Psi_{rim}} \frac{erf(M) - erf(N)}{1 + \cos\Psi} d\Psi$$

Where,

$$M = \frac{\sin\Psi_{rim}(1 + \cos\Psi)(1 - 2d^* \sin\Psi) - \pi\beta^*(1 + \cos\Psi_{rim})}{\sqrt{2}\pi\sigma^*(1 + cos\Psi_{rim})}$$

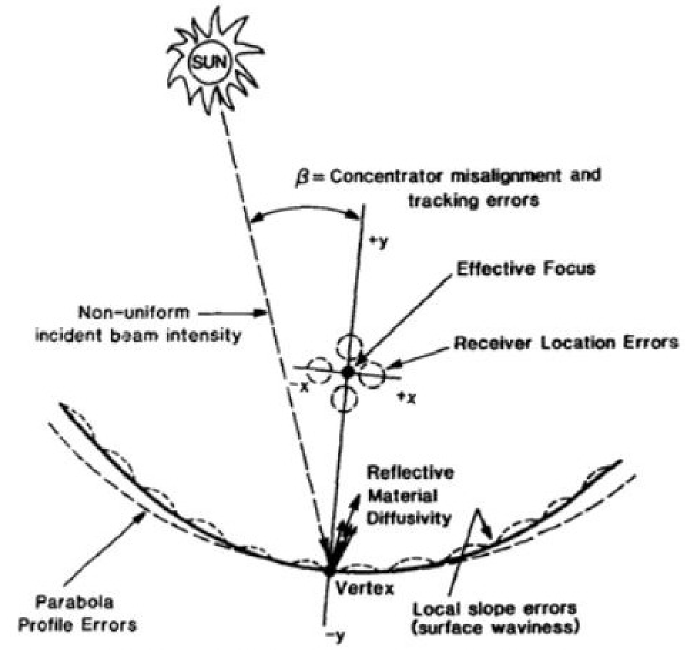

Fig. 1. Description of potential optical errors in parabolic trough collectors.

Figure 1: Errors in a Solar Collector[3]

$$N = \frac{\sin \Psi_{rim}(1+\cos \Psi)(1+2d^* \sin \Psi) + \pi \beta^*(1+\cos \Psi_{rim})}{\sqrt{2}\pi \sigma^*(1+cos\Psi_{rim})}$$

Here d^* is the universal nonrandom error parameter due to receiver mislocation, β^* is the universal nonrandom error parameter due to angular errors and σ^* is the universal random error parameter.

d^*: universal nonrandom error parameter due to receiver mislocation
β^*: universal nonrandom error parameter due to angular errors
σ^*: universal random error parameter.

3.1.1 Construction

These details will come to light once we start looking into the available tools and materials available in the market. The objective will always to be keep costs as low as possible.

3.1.2 Simulation and Validation

The simulation will be different from the initial error analysis. It will be closer to the current simulations of troughs used in large scale projects. In this way we will be able to compare our trough to existing ones. We will use freeware such as SolTrace to perform ray trace analysis of the geometries of our proposed designs along with generating simulated daily/monthly/seasonal predictions of the concentration ratios etc and the thermal output

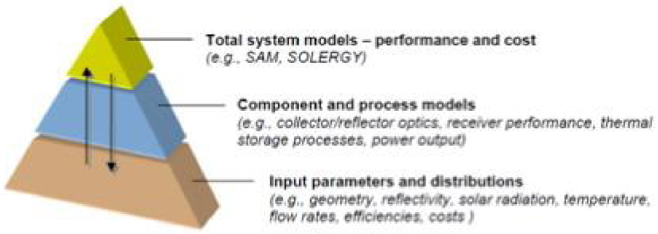

Figure 2: The Modelling Pyramid[1]

of the collector given the incoming insolation. This will be aided by thermal models that take into account heat loss by the absorbing tube. These simulations take into account heat escape via conduction convection and radiations which are governed by parameters like absorber material, working fluid temperature, the laminar or turbulent flow of the working fluid etc[**?**]. Simulations will be valited by data collected from the collector as mentioned in the next section. They will be rigorous and take into account the geometric, optical and thermal properties of the system.

3.1.3 Testing of the equipement

A large amount of literature is present which talks about the analysis and performance of solar trough collectors[CITE], often in the form of undergraduate senior year thesis [4, 5] which offer us a replicable approach. We will try to follow trough specific ASHRAE [9] guidelines, while picking up cheap, effective and perhaps novel testing techniques from literature.

3.2 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is a variation of the standard Rankine cycle which generates over 90% of the electric power of the world [6]. In the ORC the working fluid is an organic compound with a low boiling point instead of water of the Rankine Cycle. This makes it suitable for use in situations where a low temperature heat source is available.

The working principles of an ORC are similar to those of the Rankine Cycle. An evaporator boils off the working fluid. This high pressure, high temperature vapor drives a turbine and ends up at low pressure and low temperature. A condenser is used to liquefy the vapors. This is then pumped back to the evaporator [10, 11].

The three main parts of the ORC cycle are discussed below.

3.2.1 Turbine

Convergence has obtained the designs of a Tesla Turbine coupled to a generator from Phoenix Navigation. We will be replicating these designs, the reasons for which have already been discussed.

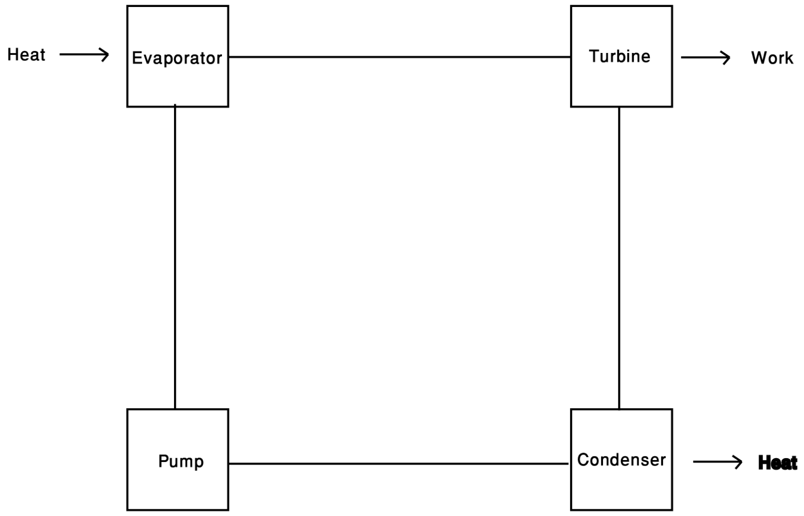

Figure 3: Organic Rankine Cycle

A Tesla Turbine is a bladeless turbine that depends on the boundary layer effect of a fluid moving across a surface to generate power. [12, 13]

The particular designs we have obtained claim to generate up to 1KW, our proposed power output.

We aim to rigorously model the turbine. When we have constructed prototype, we will be able to test our model against it and fixate upon the correct simulation parameters. This should allow us to reliably predict the input-output characteristics of variations of our design.

3.2.2 Evaporator/Condenser

These are both heat exchangers. The evaporator transfers heat from the solar collector fluid to the ORC working fluid, while the condenser cools down the ORC working fluid once it has passed through the turbine. The heat carried away by the condenser may later be exploited for the heating and cooling systems discussed below.

For the construction of our prototype we aim to purchase an industrially available solution. The spirit of our project is to not reinvent the wheel, but also to use one suitable for the job.

However, as with the rest of our system, we will be modeling the heat exchanger.

3.3 Electricity Distribution

Electricity produced needs to be distributed and stored as per needs. Technologically, this is a very mature field and and as such requires little from us other than to select the system which is both cheap and suitable for the needs of the end user.

3.4 Solar Cooling and Heating

Though the main aim of our setup is electricity generation, it is standard practice in the industry to improve overall efficiency and reduce cost per kilowatt by complementing the system with cooling and heating setups running off the waste heat [19].

The standard refrigeration cycle is an energy expensive operation, primarily due to the compression stage. There are three mature solar based technologies that can be used to provide this energy.

The simplest method is to provide electric power to the compressor of a standard cooling system using electricity generated from either solar photovoltaic or solar thermal. Another solution is to use a turbine running of solar thermal to mechanically run the compressor. This approach is referred to as thermo-mechanical cooling [14].

The third method is known as sorption cooling [15], a variation of the standard refrigeration cycle, with two core changes. First, the single refrigerant is replaced with two. This may be a combinations of various states: solid/liquid, solid/gas, liquid/liquid, liquid/gas. Compression can therefore be replaced by a process whereby one of the substances is absorbed/adsorbed by the other till its concentrated and then boiled off using heat from solar thermal. The net is hot vapor turning into high pressure saturated vapor, the same operation that a standard compressor achieves.

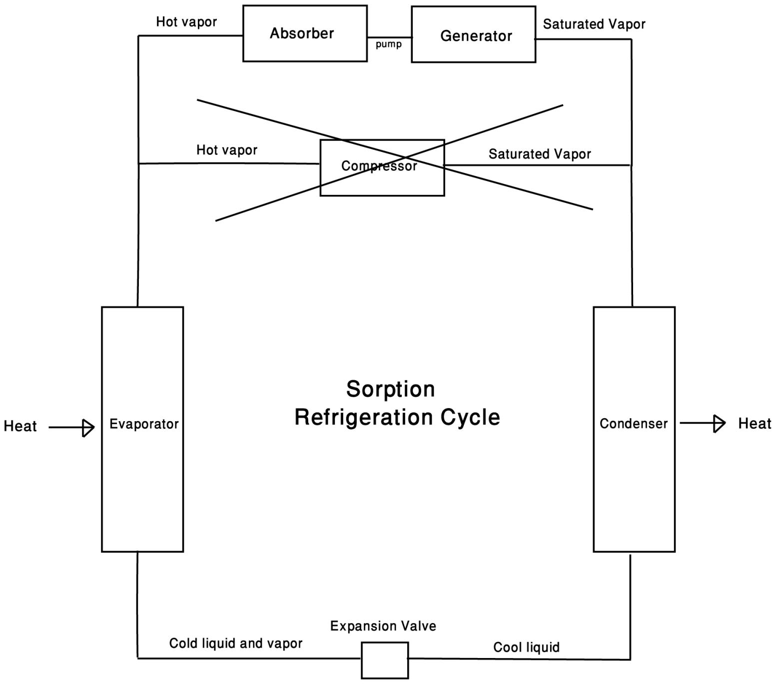

Figure 4: Sorption Refrigeration Cycle

None of these technologies have conclusively been shown to be universally preferred. However, it has been shown that sorption technologies require much less initial capital outlay, though working at lower COP than other technologies. They also have the advantage over thermo-mechanical setups in systems where the turbine is already being used to generate electricity, systems such as ours

As a side-goal of our project we will explore the possibility of implementing an sorption based cooling system to run a refrigeration unit, preliminary calculations showing that space-cooling of any reasonable value will require several times the current collector area.

Hot water and heating systems running off waste heat are much simpler to implement than solar cooling. We also plan to outline how waste heat from the heat cycle can be stored and used for heating water.

To simulate this system, we will need the results of the profiling and/or simulation of the ORC. This will give us the ranges of waste heat available to us under various conditions. Using this as our main fixed input parameter, we will optimize the COP (both cooling and heating) of our system. A number of previous studies have been done in this way [16, 17, 18], mainly depending on the commercial software TRNSYS and its various libraries.

3.5 Proposed Scaling of Project

We made some priliminary calculations based on the results of similar projects [21]. We have yet been unable to gain the performance characteristics of the tesla turbine and alternator, therefore a typical value of 20% is being assumed.

Direct Solar Irradiance	850 W/m^2
Collector Area hline Collector Efficiency	12 m^2 50%
Available Thermal Energy	6800 W
Thermal to Electric Efficiency	15%
Peak Electrical Output	1 KW

Table 1: Prototype scaling for electricity generation

Similar calculations are possible for the cooling cycle.

Available Waste Heat	1 KW
COP of Cooling	0.5
Cooling	500 W

Table 2: Prototype scaling for Cooling

4 Time Table

The proposed timeline for our project is given in Figure. 3.

Early November	Project synopsis submission
November 1st	Begin simulation and modeling phase Begin material testing
December 1st	Start of construction of prototype
January 1st	Completion of preliminary simulations
April 1st	Completion of prototype Begin testing and linking of results with simulations
May 1st	Completion of project and report submission

Table 3: Proposed Timeline

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