CHAPTER 2

REVIEW OF RELATED LITERATURE AND RESEARCH

To the best of the author's knowledge, there is currently no publicly-available literature documenting the development of a small-scale (i.e. 1.0 MW or less) biomass-hybrid parabolic trough solar power plant similar to the one proposed in this study. Hence, it is not possible to cite the previous work of authors in this specific subject. However, there are some examples of power generating systems in a few countries where related technologies and designs have been used or studied, and a selection of those experiences is presented in this chapter.

2.1 Solar Thermal/Biomass Power Production (Europe, USA)

Much of the present knowledge about power generating systems that use parabolic trough collector or biomass gasification technology, and thermal energy storage, are derived mainly from the experiences in Europe and USA.

2.1.1 Concerning Parabolic Trough Collector

The parabolic trough collector (or solar trough) is one of three types of concentrating solar power (CSP) technology that was developed for the purpose of electricity generation, the other two being the central receiver power tower and the parabolic dish. The solar trough generally operates at a temperature range of 100–400 $^{\circ}$C and is considered the most mature of the three CSP technologies with low technical risk. In general, a solar trough works by focusing direct sunbeam onto a linear receiver. A heat transfer fluid (HTF), usually thermal oil, gets heated up as it flows through the receiver. The hot HTF leaves the collector and is used to produce steam in a typical Rankine cycle. The steam is then used in a turbine/generator to produce electricity.

The origin of modern-day electric generating systems with parabolic trough collectors began with the sun power plant designed by Frank Shuman at Philadelphia

(USA) in 1911, which generated a peak of 32 horsepower (hp) at mid-day and an average of 14 hp over an 8-hr day. That experience led to the construction of another sun power plant at Meadi (Egypt) which produced 1000 lb/hr of steam for a 10-hr operating day. Since then, further development of this promising technology was delayed for several decades because of the two World Wars and cheap fuel.

In 1981, a parabolic trough solar power plant was installed in Tabernas, Almeria (Spain), sponsored by the International Energy Agency under the Small Solar Power Systems Project, and which later became part of the facilities at the Platforma Solar de Almeria, the largest European solar test center. This power plant consisted of three solar fields with a total reflector area of 7602 m^2, a steam generating system, and a conventional steam-turbine cycle power block connected to the local grid. The type of collector used was Acurex-3001 and the heat transfer fluid was Santotherm 55 synthetic oil. Both single-axis and two-axis parabolic trough designs were evaluated and tested until 1986. A significant finding was that single-axis collector was more efficient than two-axis, due to the shorter passive pipelines required for single-axis that consequently resulted in lower heat losses [16].

Meanwhile in the USA, a company known as LUZ International developed a series of nine Solar Electric Generating Systems (SEGS I – IX) from 1984 to 1991 in the Mojave Desert of California (USA), with a combined capacity of 354 MW and total collector area spanning over 2 km^2 (Figure 9). These SEGS plants are the best example of the "state-of-the-art" solar power plants with parabolic trough collectors and they account for more than 95 % of the electricity produced with solar energy worldwide [17]. Over the years, these commercial power plants had fed more than 9 billion kWh to the Californian utility grid and could supply 800 million kWh annually, enough for more than 200,000 households, at a generation cost of about 0.10 – 0.13 USD/kWh [18].

The collector system used in the SEGS plants consists mainly of advanced LS-2 and LS-3 collectors (and some earlier LS-1) from LUZ International, with each collector ranging between 47-99 m in length. These collectors operate with thermal oil as heat transfer fluid and can achieve an overall solar-to-net electric efficiency of 9-14% [16],[19].

Table 1 Characteristics of some commercial parabolic trough collectors

Manufacturer	*Acurex*	*LUZ International*		
Type of collector	**3001**	**LS-1**	**LS-2**	**LS-3**
Year of initial usage	1981	1984	1986	1990
Aperture width (m)	1.83	2.55	5.00	5.76
Aperture length (m)	39.5	50.2	47.1	99.0
Rim angle (degree)	90.0	80.0	79.9	80.2
Surface reflectivity	0.91	0.94	0.94	0.94
Absorber absorptivity	0.96	0.94	0.94	0.96
Absorber emissivity	0.27	0.30	0.24	0.18
Glass transmissivity	-	0.94	0.95	0.95
Intercept factor	0.91	0.87	0.89	0.93
Optical efficiency (%)	77.0	73.4	73.7	77.2
Peak collector efficiency (%)	59	66	66	68

Source: Reference [33] p. 225 & reference [43] p. 38.

Table 1 shows the characteristics of the commercial parabolic trough collectors that were used in some solar electric generating systems in Spain and USA.

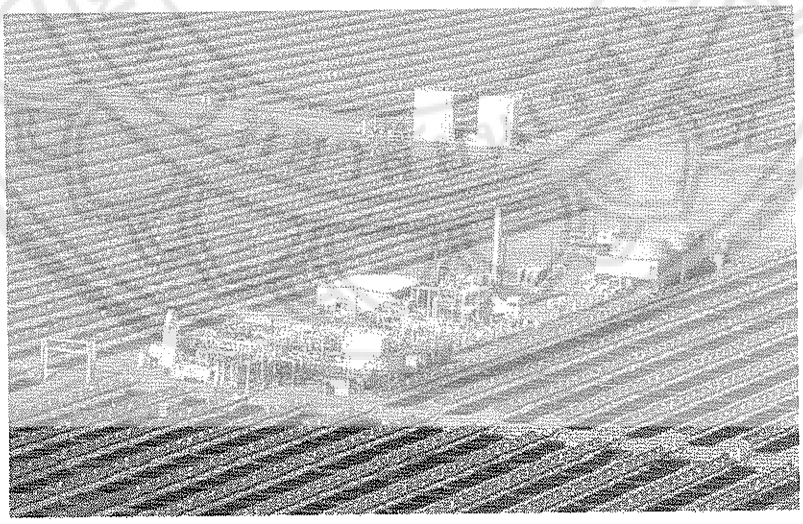

Figure 9 One of the SEGS plants in California, USA

Another notable experience concerning solar trough technology is the DISS (Direct Solar Steam) research facility at the Plataforma Solar de Almeria (PSA). Started in

1996 under the Joule Program of the European Union, the objective of the DISS project is the development of a new generation of solar thermal power plants with improved parabolic trough collectors and direct steam generation (DSG) in the absorber pipes, thus eliminating the oil acting as a heat transfer medium between the solar field and the conventional power block [20]. The DISS test-loop is consisted of nine 50-m and two 25-m LS-3 collectors connected in series, giving a total length of 550 m (Figure 10). After nearly a decade of study, the DISS research concludes that: (a) the DSG process is feasible in horizontal parabolic troughs, (b) the recirculation process is the most attractive option for commercial DSG collector fields, and (c) if steam can be delivered to the turbine inlet at 550 °C & 100 bar instead of the existing maximum of 400 °C & 100 bar, the total conversion efficiency can reach 23% [21],[22],[23]. Despite the achievements to-date, there are still unresolved issues concerning the DSG concept. These are: (a) there are currently no available technology and components for a DSG solar field to operate at temperatures/pressures above 400 °C/100 bar; hence further studies are needed in this aspect, (b) the effects of solar transients on multiple rows of collector have not been investigated yet, and (c) uncertainties still exist concerning the integration of a practical thermal energy storage system with a DSG solar field. In view of the above, it is envisaged that more research is required before the DSG technology can become a fully commercial option.

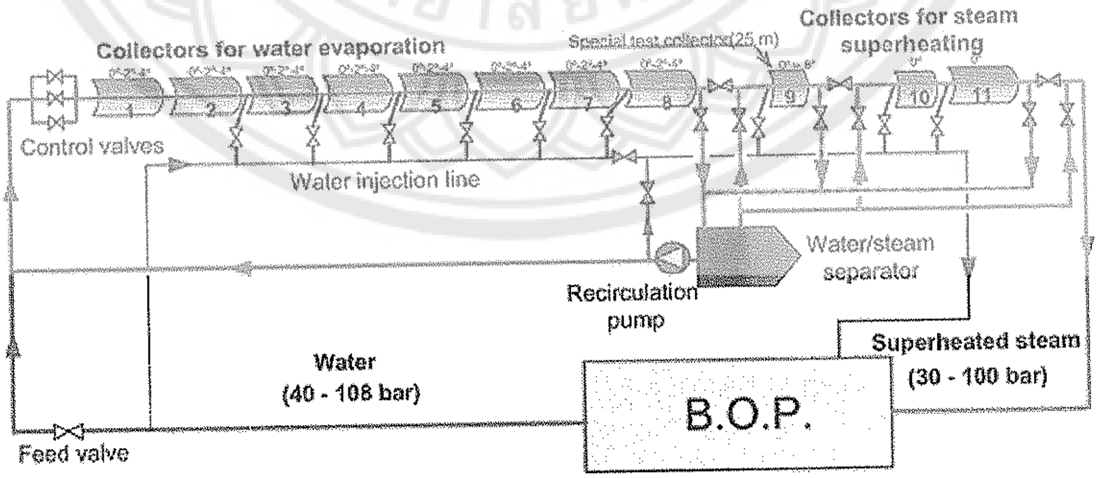

Figure 10 Schematic diagram of the DISS test-loop in PSA

2.1.2 Concerning Biomass Power Production

Gasification is one of the methods used in power production from biomass material, via the partial-combustion energy-conversion process from solid fuel into a combustible gas mixture. The common feedstock for gasification is usually agricultural residues. If air is used as the gasification agent, the resulting gas is known as producer gas. The heating value of this gas varies between 4.0 and 6.0 MJ/Nm^3, or about 10-15% of the heating value of natural gas [24]. Producer gas from different fuels and different gasifier types may considerably vary in composition (Table 2), but it consists always of a mixture of the combustible gases hydrogen (H_2), carbon monoxide (CO) and methane (CH_4), and the incombustible gases carbon dioxide (CO_2) and nitrogen (N_2).

The advantages of gasification over direct combustion are that: (a) the combustible gas mixture burns more cleanly and efficiently than the solid biomass it is derived from, and (b) stored gas can be fired instantly to meet immediate energy demand. In general, a biomass electric generating system is consisted of four main parts: reactor (gasifier), gas cleaning unit, engine and generator. Depending on the cleanliness of the producer gas and quality of the steam, three basic designs of a biomass power system are possible (Figure 11).

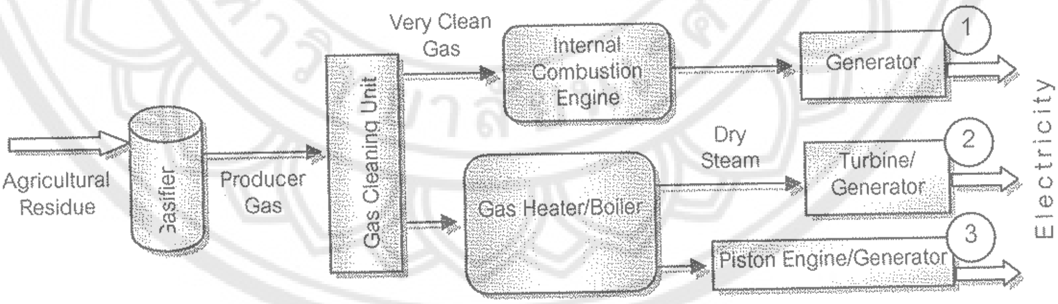

Figure 11 Three possible designs of a biomass electric generating system

Biomass gasification takes place in a reactor in which solid biomass is converted into producer gas. In the case of small-scale gasification, only reactors of the fixed-bed type are considered (larger biomass gasifiers are usually of the fluidized-bed or entrained-flow type). The different fixed-bed reactor types are commonly classified as

Table 2 Typical gas composition for different fuel and reactor types

Gasifier type/Fuel (% moisture in feed)	Updraft/Wood (10 – 20%)	Downdraft/Wood (10 – 20%)	Cross-draft/Charcoal (5 – 10%)
Hydrogen	8-14	12-20	5-10
Carbon monoxide	20-30	15-22	20-30
Methane	2-3	1-3	0.5-2
Carbon dioxide	5-10	8-15	2-8
Nitrogen	45-55	45-55	55-60
Oxygen	1-3	1-3	1-3
Moisture in gas (Nm^3/Nm^3 dry gas)	0.20-0.30	0/06-0.12	<0.3
Tar in gas (g/ Nm^3 dry gas)	2-10	0.1-3	<0.3
Heating value (MJ/ Nm^3 dry gas)	5.3-6.0	4.5-5.5	4.0-5.2

Source: Reference [24] p. 7.

updraft (counter-current), downdraft (co-current) or cross-draft (cross-current) gasifiers. Updraft gasifiers, using wood and other biomass, produce a hot (300-600 °C) gas that contains large amounts of pyrolysis tars as well as ash and soot. The hot gas is suitable for direct combustion in a gas burner. In engine applications, the gas must be cooled, scoured of soot and ash, and cleaned of tars by condensation or another method. Because the tars represent a considerable part of the heating value of the original fuel, removing them gives this process a low energy efficiency. Downdraft gasifiers produce a hot (700-750 °C), tar-free gas from wood and other biomass. After cooling and cleaning from ash and soot, the gas is suitable for use in internal combustion engines. Cross-draft gasifiers only produce a tar-free engine gas if fueled with good-quality charcoal (i.e. charcoal with low volatile matter content).

Although it is not a high-quality fuel, producer gas can be used effectively in several applications. One application is to fuel internal combustion (IC) engines to produce shaft power for generating electricity, water pumping, grain milling, sawing of timber, etc. In such applications, the gasification systems are called *power gasifiers*. Alternatively, producer gas can be used to fuel external burners to produce heat for boilers, dryers, ovens, or kilns. In such applications, the gasifier systems are referred to as *heat gasifiers*. A principal technical difference between the two systems is that power gasifiers must produce a very clean gas because of the strict fuel-quality demands of an IC engine. Thus, the resulting producer gas must be first filtered, cooled, and mixed in an elaborate gas conditioning system, which is an integral part of a power gasifier. In contrast, producer gas combusted in external burners requires little or no gas conditioning. Because they do not require elaborate gas-cleaning systems, heat gasifiers are simpler to design and operate and are less costly compared with power gasifiers.

In the United States, biomass is already the country's leading non-hydro resource of renewable energy. More than 500 electric power plants operate on biomass with a combined rated capacity of 7,000 MW. For example, the McNeil Generating Station in Burlington, Vermont, generates 50 MW of electric power for the city's residents using wood from nearby forestry operations. The gasifier is capable of converting 200 tons of wood chips per day into a gaseous fuel that is currently fed directly into the McNeil Station boiler, enough to generate 8 MW. Currently, the Department of Energy's Biomass Program is working with industry partners to develop small modular biomass systems for producing combined heat & power at scales ranging from 5 kW to 5 MW. One such project involves a private subcontractor, Community Power Corporation, who is developing a fixed bed downdraft gasifier that converts solid biomass to producer gas for consumption in an internal combustion engine coupled to a generator [25].

In Spain, Ganan et al (2005) conducted a study on energy production by means of gasification process of residues sourced in Extremadura. The energy potential of four biomass residues, rice husk, nut shell, pine & eucalyptus wood was determined under controlled gasification conditions, and the results were characterized using proximate analysis, ultimate analysis and heating value evaluation. The experimental setup is consisted of the following: reactor, heating system, temperature control device, gas sample collecting unit and gas chromatograph. The gasification process was carried out using an optimal air flowrate of 200 ml/min and reaction temperature of 800 ^{o}C. From the experimental results, the energy potential of the residues and their viability for use in a gasification plant for electric power production were assessed. One useful finding in the study was that the producer gas yield from rice husk was 1.60 m^3/kg and the gas high heating value was 11.11 MJ/m^3 [26]. A biomass power plant, similar to the installation described in this study, can be found in Mora D'Ebre (Tarragona, Spain). This plant is able to generate 2.4 GWh/year from 2,150 ton of almond shell.

In another study initiated by the Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT), Garcia-Ybarra (2003) reported a project to evaluate the possibility of gasifying different types of residual and cropped biomass that were found in Spain. The final objective is to develop a demonstration plant for power generation from biomass gasification, suitable for rural areas where the dispersion of available biomass requires the installation of small decentralized plants.

The first part of the study is concerned with the modeling of the gasification process for the design of the reactor. The computational results have enabled the main parameters of the reactor design to be defined: a cylindrical reactor with outside & inside diameters of 0.67 m & 0.20 m respectively, a bed of 40 kg silica for temperature up to 850 °C, and an inlet air flow of 120 Nm^3/h (or 2 m/s). Under these conditions, a feeding rate of 80 kg/h of biomass (with 12% humidity, in weight) would generate a flow of 221 Nm^3/h of a gas composed of: 20% H_2, 22% CO, 8% CO_2, 7% H_2O and 43% N_2 [27].

2.1.3 Concerning Thermal Energy Storage

A thermal energy storage system is an optional component of a solar thermal power plant. It is incorporated into a power plant usually for one or more of the following reasons: (a) to shift electricity generation from low value off-peak hours to high value demand hours, (b) to prolong operation after sunset, and (c) as a buffer, to smooth out insolation changes for steady state conversion cycle, and for operational requirements such as component preheating or freeze protection.

The development of thermal energy storage (TES) systems is linked closely to the development in solar thermal power plant technologies. Currently, TES systems can be broadly classified into sensible heat storage, latent heat storage or thermo-chemical storage. In sensible heat storage, liquid media as well as solid media are used. For temperatures up to 300 °C, thermal mineral oil can be stored at ambient pressure, and is

Table 3 Survey of selected major TES systems

Facility (Location)	TES Medium	HTF Medium	Design Temperature		Concept
SEGS I (Daggett, CA)	Oil	Oil	240 °C	307 °C	Two-tank (Cold/Hot tank)
IEA-SSPS (Almeria, Spain)	Oil	Oil	225 °C	295 °C	Single-tank (Thermocline)
IEA-SSPS (Almeria, Spain)	Oil & Cast iron	Oil	225 °C	295 °C	Single-tank (Dual medium)
Solar One (Barstow, CA)	Oil & Rock/sand	Steam	224 °C	304 °C	Single-tank (Dual medium)
CESA-1 (Almeria, Spain)	Molten salt	Steam	220 °C	340 °C	Two-tank (Cold/Hot tank)
Solar Two (Barstow, CA)	Molten salt	Molten salt	288 °C	566 °C	Two-tank (Cold/Hot tank)
IEA-SSPS (Almeria, Spain)	Liquid sodium	Liquid sodium	275 °C	530 °C	Two-tank (Cold/Hot tank)
TSA-Phoebus (Almeria, Spain)	Ceramic & Pebbles	Air	200 °C	800 °C	Single-tank (Dual medium)

Source: Reference [33] p. 205.

the most economical solution [28]. Synthetic and silicone oils, available for up to 410 °C, have to be pressurized and are expensive. Molten salts and sodium can be used between 300 °C and 550 °C at ambient pressure, but require additional effort to avoid freezing. For temperatures above 550 °C, ceramic materials become a competitive alternative.

Depending on the choice of solar plant technology, operating temperatures and HTF material, several design concepts for a TES system may be possible; these are: (a) single-tank or two-tank, (b) single-medium or dual-medium, (c) using the same fluid as HTF and TES material, and (d) using different HTF and TES material. Table 3 gives a summary of some TES concepts that were studied as part of the respective solar plant facilities located in California (CA) and Spain.

2.2 Solar Thermal/Biomass Power Production (Other countries)

Examples cited in this section refer mainly to the experiences and research that originate in countries outside of Europe and the United States.

2.2.1 Concerning Parabolic Trough Collector

Following the successes of the SEGS plants in California and the progressive research in PSA (Spain), countries in the sunbelt region of Northern Africa and the Middle East are becoming more drawn to the idea of using parabolic trough technology for electricity production. One of these countries is Jordan.

Badran & Eck (2006) conducted a study to evaluate two locations in Jordan as possible sites to install a solar thermal power plant. As part of the study, a 5 MW test facility was set up to understand the performance of a parabolic trough power plant under Jordanian climate. The test facility is consisted of nine parallel rows of LS-3 collectors oriented in a north-south axis and tracks the sun from east to west for the maximum annual solar yield. The collectors operate on thermal oil HTF and electricity is generated via a Rankine steam cycle. From the test results, the peak solar-to-net electric efficiency of this 5 MW plant was found to be 15-16%. The levelized electricity cost was calculated to be 0.124 Euro/kWh based on an assumed plant life of 20 years [29].

In Mexico, Almanza & Lentz (2001) [30] investigated the feasibility of electricity production at low powers by direct steam generation with parabolic troughs. The experimental set up consisted of four collector modules connected in series. Each module is 14.5 m long and 2.5 m wide, giving a total aperture area of 145 m^2. The focus of the parabola is 0.625 m. The first three modules are each fitted with a 3.81 cm nominal diameter copper absorber, while the fourth is fitted with a 2.54 cm nominal diameter mild steel absorber. All the absorbers are covered with black chrome.

During operation, demineralized water enters the first module at a flow rate of about 2 liter/min. The four modules in series can produce over 100 kg/hr of steam (using the recirculation process) at an average beam irradiance of about 866 W/m^2 over a period of two hours before and after noon on a clear summer day in Mexico City. Under these conditions, saturated steam at 165 °C and 7.0 bar (~100 psi) can be supplied to a

2.24 kW (3.0 hp) Stuart Swan two-piston steam engine which gives maximum power at 800 rpm and consumes steam at a rate of 93 kg/h (205 lb/hr). From the results, the following efficiencies were obtained: engine efficiency 35%, generator efficiency 28% and efficiency of steam production 42%, giving an overall solar-to-electric efficiency of 4%. The low overall efficiency is due to an improper choice of generator. The use of an appropriate electric generator with a higher efficiency will result in an improved solar-to-electric efficiency.

2.2.2 Concerning Biomass Power Production

Similar to Thailand, another country that is endowed with a large biomass resource is India. Data from the Ministry of Non-conventional Energy Sources (MNES) indicated that the entire country produces about 320 million tons of agricultural residues comprising of mainly rice husk, paddy straw, sugarcane leaf-bagasse and wheat residues. Of these, about 100 million tons of residues are not utilized but are disposed of by burning in the open fields. Over the years, studies were done to develop the gasification technology in order to make better use of the available biomass resource.

In one such study, Jorapur & Rajvanshi (1997) reported the development of a gasifier which can handle low-density and leafy biomass materials like sugarcane leaves and bagasse, and its subsequent tests in an actual user-industry. This commercial-scale system with a thermal output of 1080 MJ/hr (or 300 kW_{th}) is comprised of a reactor, gas conditioning system, biomass feeding system and the instrumentation & controls (Figures 12 & 13). The gasifier is a downdraft, throatless and open-top reactor with an inside diameter of 0.75 m and an active bed height of 1.25 m. It is designed for a heavy-duty cycle of 7500-hour per year operation. An advantage of the gasifier is its dry dust collection system which totally eliminates the problem of wastewater. This is consisted of a high temperature char/ash coarse settler and a high efficiency cyclone separator. A high temperature induced-draft fan ensures that the entire system is under negative pressure. In the event of a leak, the outside air will be sucked into the system but the combustible gas will not leak out; thus making the design very environment-friendly.

The gasifier system is relatively simple to operate. A cold start takes about 10-15 min while a hot start requires less than 5 min. The gasifier was operated on both sugarcane leaves and bagasse for a total of 700 hours. The biomass fuel consumption was 40-100 kg/hr (dry) and the associated gas production rate was 80-225 Nm^3/hr. The gas high heating value was determined to be 3.56-4.82 MJ/Nm^3. The energy content of the gas was computed to be 288-1080 MJ/hr (or 80-300 kW_{th}), and this corresponds to a biomass-to-gas conversion efficiency of 39.7-59.6%. The gas outlet temperature was 450-550 °C and the gas temperature at burner inlet was 300-400 °C.

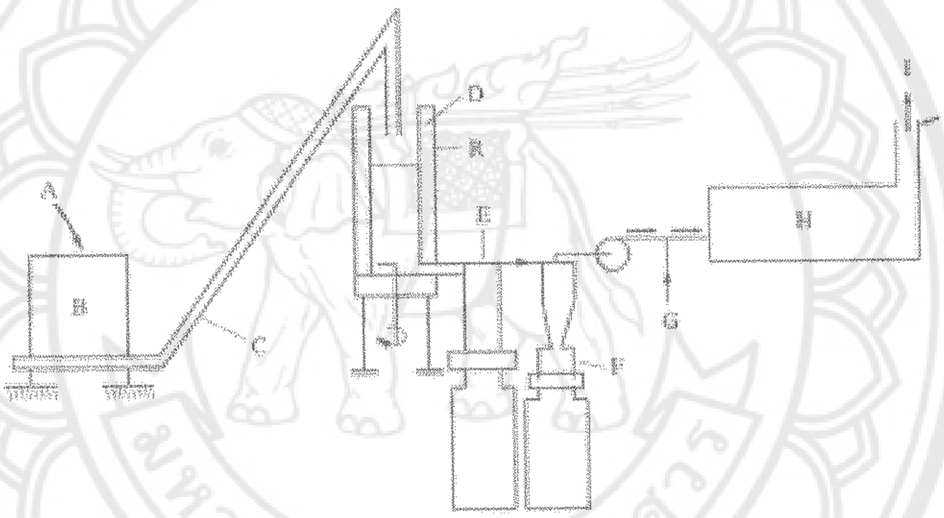

Figure 12 Schematic of sugarcane leaf-bagasse gasifier system: (A) biomass from storage piles, (B) hopper, (C) conveyor, (D) refractory, (E) char collector, (F) cyclone, (G) air, (H) furnace, (I) chimney, and (R) reactor.

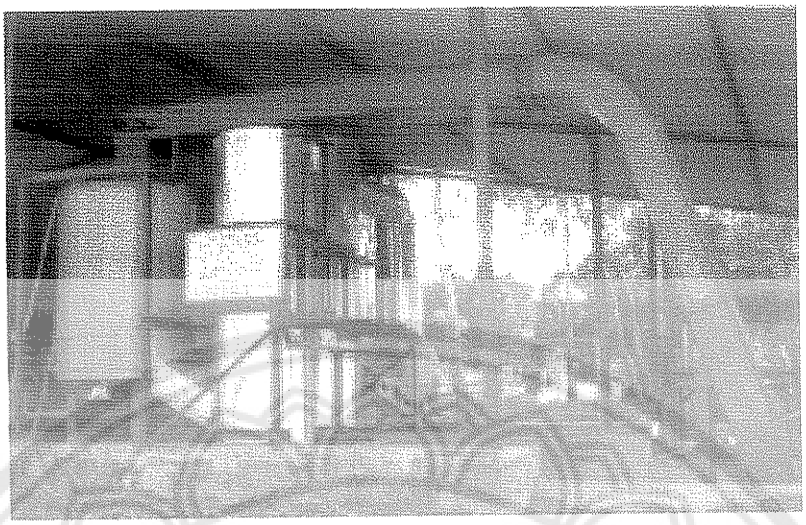

Figure 13 Gasifier system installed in Maharashtra, India

The gasifier could perform optimally if the biomass moisture content was less than 15% w/w (wet basis). A pilot flame to sustain gas combustion was found to be necessary for moisture levels between 20-25%. However, combustible gas was not formed at all if the moisture content exceeded 25%. When the gasifier was retrofitted to an oil-fired ceramic baking furnace, the quality of the product using gasifier was found to be comparable to the oil-fired process. The level of particulates in the gas was found to be acceptable for applications that involve drying, baking of ceramic products, or for generating steam through boilers [31].

China is another country that has a sizeable biomass resource. Downdraft reactors of a very specific design (for gasification of rice husks) have been developed. Hundreds of systems employing these "open-core" rice husk reactors have been built in China since the mid-1960s. Since then, plants of this type were also installed in countries such as Mali and Surinam. Because of its simplicity, the reactor is being further developed in India. The objective is to construct small reactors that can gasify wood & agricultural residues. The gas is then used in small diesel engines for water pumping.

2.3 Solar Thermal/Biomass Power Production (Thailand)

To-date there appears to be no documented studies concerning a biomass-hybrid parabolic trough solar power plant in Thailand. However over the years, there have been some separate studies on solar trough collector and biomass gasification carried out by a few academic institutes and government agencies. A brief review of their experience is given in this section.

2.3.1 Concerning Parabolic Trough Collector

The history of high temperature concentrating solar collector research and testing in Thailand can be summarised by the following developmental milestones. It began about two decades ago with the installation of a small prototype trough collector with an aperture area of about 6 m^2 at the Asian Institute of Technology (AIT) in Bangkok. Then about five years later, the Electricity Generating Authority of Thailand (EGAT) decided to conduct its own study on high temperature solar thermal power by experimenting with a concentrating collector of about 10 m^2 aperture area. The next major solar trough collector was installed at the King Mongkut Institute of Technology Thonburi (KMITT) about 10 years ago. With an aperture area of almost 15 m^2, it was the biggest laboratory-scale trough collector to be tested and studied at that time. Since then, research interest in the subject had reduced due to the view that the relatively high level of diffuse radiation was not favorable to the development of concentrating solar power technology in the country.

To-date, there are no published studies of any electric power plant in Thailand that uses both solar thermal energy and biomass energy in the same system. However in 2005, there was a proposal by a German company to build a solar thermal power plant with rated output of 70 kW_{th} (thermal) and 10 kW_e (electric), using 160 m^2 of solar trough hybridized with a biomass boiler, in Chonburi province. No further update is available regarding this issue.

2.3.2 Concerning Biomass Power Production

Thailand is an agro-industrial country with approximately 40% arable and permanent cropland and about 25% forest and woodland. It has a vast resource of biomass energy particularly in the form of agricultural residues. The Department of Alternative Energy and Efficiency (DEDE) has identified about ten crops that have high residue potential. From the data in 2001, the energy potential from the combined residues of four common crops, sugarcane, rice, maize & palm oil, was estimated to be more than 500,000 million MJ [6]. By weight, the amount of bagasse, sugarcane tops & leaves and rice husk produced in the entire country was 2.37, 14.72 and 1.97 million ton respectively.

Due to the favorable conditions in Phitsanulok, large areas of the province are devoted to agriculture. Rice is the most important crop grown in the province in terms of tonnage. Wilaipon (2002) presented an overview of the potential of agricultural residue utilization for power production using small-scale gasifiers in Phitsanulok. According to the yearly report of the Phitsanulok Agricultural Office, the yields of five major crops in 2001 were given as: rice (1,395,909 ton), sugarcane (1,086,974 ton), cassava (334,933 ton), maize (142,130 ton) and soybean (18,889 ton). From the crop yield, the amount of residue can be estimated using the residue-to-product (RP) ratio. The RP ratios of some common residues are given as: rice husk (0.267), rice straw (1.695), bagasse (0.29), sugarcane tops & leaves (0.15), cassava stalk (0.167), maize cob (0.273), maize stalk (2.0) and soybean stalk (2.5) [32]. Using rice as an example, the amount of rice husk available in Phitsanulok was 372,707 ton and this constitute 18.9% of the total rice husk produced in the country in year 2001. Based on a high heating value of 13.1 MJ/kg for rice husk, the energy potential of this residue is estimated to be about 4882 million MJ. The study by Wilaipon (2002) concluded that there is a high residue potential in Phitsanulok, particularly from rice and sugarcane, and this resource is best utilized to produce electricity with the assistance of small-scale gasifier systems.

2.4 Simulation Modeling of the Solar Parabolic Trough Collector and Power Plant

A review of papers related to simulation modeling of parabolic trough collector and power plant has shown that all previous studies are based on actual installed systems. The models created for the actual systems are usually validated against the measured data of the commercial SEGS plants and the results are typically presented as graphs. In general, most of the papers tend to be rather brief about the modeling and validation aspects but detail about the application of the model for performance simulation. In contrast, the BSPP model created in this study is based on a proposed power plant where only the parabolic trough collector is installed. Furthermore, the power block in the BSPP model adopts a simple Rankine cycle design and no external professional power cycle program is used. Also, none of the papers reviewed has reported the creation of a power plant model that is exactly the same as the BSPP model. The following examples summarize the major studies that have been conducted in the past decade from 1995 to 2006.

Heinzel et al (1995) [52] developed a model for the simulation of parabolic trough collectors and linked with the transient system simulation package TRNSYS. Optical as well as heat transfer phenomena were implemented in order to model the performance of the collector under different conditions. The aperture was partitioned in equal sections. The angle dependent reflection at the glass mirror, the transmittance through the glass tube and the absorption at the selective surface were modeled. One module of the model simulates perfectly parallel light and a perfect reflector. Another module allows the simulation of the conical shape of an incident beam of light. The absorber tube is partitioned in axial section to calculate the heat transfer to the fluid. Heat losses are calculated through iterations of the absorber temperature in each section. However in this paper, all the simulation results were presented in the form of efficiency and temperature curves versus varying radiation levels.

Odeh et al (1996) [53] developed a simulation model linked with the TRNSYS simulation program to analyze the performance of parabolic trough collectors for operation with synthetic heat transfer oil and water. In this work, a detailed analysis of the thermal performance of the LS-2 trough collector was carried out. A collector efficiency equation was developed in terms of the absorber wall temperature by computing radiation and convection losses and using test data for the LS-2 collector to determine conduction losses through residual gas and the end bellows. The model was then applied to Australian weather data to determine the annual performance. The model was validated by comparing the analytical results of the collector thermal loss with the experimental results for different collector fluid temperatures. The measured and computed values were found to be very close in the temperature range between 250 – 400 °C (at wind speed 3 m/s) which covers the operation range of a typical power plant. The model was used to compute the annual performance of the LS-2 (DSG) collector at three different Australian sites (Alice Springs, Darwin & Longreach). The simulated yearly thermal output of the DSG collector was found to be similar to the collector (modified for steam generation) at the SEGS power plants at Daggett California.

Eck et al (2000) [54] used a detailed transient model based on FORTRAN-algorithm to investigate and compare the dynamic performance of the different DSG concepts at the PSA DISS test facility. The model was used to simulate the thermohydraulics of an absorber pipe subjected to rapid solar transients. The simulation model was validated by comparing the predicted fluid temperatures with measured data after temporary shading of the 10th and the 11th collectors. The results were presented in a graph and it was observed that the predicted data matched the measured data well. The analysis also showed that the most critical point of the once-through concept is the variation of the axial position of the border between the evaporation section and the superheating section. Later experimental results have proven the occurrence of fluctuation at the end of the evaporation section and the associated high temperature transients.

Quaschning et al (2001) [39 & 55] described a simulation environment known as "Greenius" which is a new simulation software tool used for the simulation of parabolic trough power plants. The greenius software tool is formulated based on the analysis of three parts of the power plant, namely, trough collector, trough field and the power block & operation. The computation of the heat losses in the collector is based on an empirical model which was established from several collector tests so that the model can be applied to common collectors depending on the temperature difference of the mean collector fluid temperature and ambient temperature. Likewise for the trough field, the heat losses in the trough field is based on an empirical model since a complete analytical description of the heat transfer through the pipe isolations, losses in connections, fixings and other circuit components is not easy to find. As for the power block and operation, they are computed with heat cycles. These are a group of equations that describe the form & property changes of the working fluid (i.e. steam, gas, flue gas, air, water) associated with the cycle components such as turbines, heaters and pumps. The solution of such complex equation systems was done using external professional applications such as ISPEpro and GATE Cycle. The greenius simulation software was then used to evaluate the annual electricity generation, efficiency and LEC for a proposed 50 MW solar trough power plant under varying radiation levels. The results showed that the LEC is inversely proportional to the annual electricity generation and the amount of direct irradiation.

Stuetzle (2002) [56] developed a nonlinear model of the 30 MW_e SEGS VI trough power plant consisting of a dynamic model for the collector field and a steady-state model for the power block. The collector field model was described in the form of partial differential equations for energy balance. The model was validated through a comparison between predicted and measured collector outlet temperatures for both sunny day and partly cloudy day. The results were presented in graphical form and the simulated results were observed to match the measured results well. The collector field model was then combined with the power block model to form an entire plant model. The simulated gross power output of the plant model was found to be very close to the measured values of the actual power plant. In addition, a model predictive controller was developed for the SEGS VI plant model. Its task is to maintain a constant collector outlet temperature by adjusting the HTF flow rate automatically while solar radiation changes. The automatic controller was found to be able to hold the collector outlet temperature close to the specific set point for a long period of time and was considered better than the conventional manual control by a human operator.

Eck et al (2003) [22] used a simulation model that can give detailed calculations of the temperature distribution in the absorber pipe in the presence of a two-phase as well as of a single-phase flow. This simulation tool has been adapted to the DISS test facility and was validated successfully. The model was then used to evaluate the pressure drop of the superheating section and also the maximum temperature difference in a cross-section as a function of the superheater length for different fluid outlet temperatures. From the analysis, it was found that in order to limit the maximum temperature difference to 25 K, a length of the superheating section between 100 and 200 m is necessary. The total length of a collector loop is the sum of the preheating, evaporation and superheating sections. Approximately, the relative lengths of the sections are proportional to the ratios of the corresponding differences of the inlet and outlet enthalpies. Hence the superheater represents approximately 20% of the collector length. So, if a length of 150 m is chosen for the superheating section, the collector row will have a length of 750 m.

Badran & Eck (2006) [29] carried out a simulation study of a 5MW solar power plant in Jordan consisting of nine parallel rows of parabolic trough collectors. Each row is made up of six LS-3 (LUZ System 3) collectors connected in series. The solar field was initially designed using the earlier version LS-2 collector system and later modified to the newer LS-3 type. To simulate the power plant, the simulation package IPSEpro (Version 3) was used. Analytical and empirical models were used in IPSEpro to estimate the system performance and to calculate the amount of power output, temperature increase through the collectors, enthalpy, and the fluid mass flux for the hourly direct normal irradiation (DNI) of selected days. Using actual insolation and weather data collected, the thermal performance of two generations of collector system (LS-2 & LS-3) were analyzed and compared with measured results. The simulated results of the fluid mass flux of the LS-2 & LS-3 collector modules were found to be less than 2% of the measured results. Using the numerical model, the peak solar-to-net electric efficiency of the power plant was evaluated to be about 16%.