Using Compound Parabolic Solar Collectors in Asphalt Industry

Ahmed E. Ismail and Manoel A.Fonseca-Costa

***Abstract*—**This paper presents thermal, economic and environmental evaluation of a solar heating system (SHS) which is used in an asphalt plant from computational simulation with TRNSYS 15. The process chosen is the bitumen heating from the storage up to the mixing temperature, using mineral oil as heat transfer fluid (HTF). The system components are the HTF-bitumen heat exchanger, the compound parabolic concentration solar collector (CPC), the auxiliary heater and the circulation pump. The TRNSYS simulation computes the mass and energy balances in the HTF closed loop every hour. Rio de Janeiro typical meteorological year (TMY) hourly weather data was used in order to perform this paper. In many instances, HTF temperature reached more than 210˚C, showing that the CPC is suitable for this application. Fuel savings and avoided emissions were taken into account for economic and environmental analysis. The results, though, made it possible to address environmentally sound public policies to encourage solar energy use in the Asphalt Industry. Moreover, it will help in reducing the high emission of the green house gases in this industry.

***Keywords*—**Asphalt Plant, Compound Parabolic Collector, Solar Heating, Thermal Simulation.

I. Introduction

The world is moving towards using the renewable energy sources more efficiently to reduce the usage of conventional energy sources and consequently the green house gases (GHG) emissions. The solar energy can intensively contribute to achieve this goal. Sukhatame [3], Kalogirouet al [4] and Luminosu & Fara [11] , among others who address the incipient participation of solar energy on industrial process heating, due to some technical difficulties and many economic barriers, though the same researchers emphasize its huge potential.

This paper presents a technical and economical study for solar heating system (SHS) application in an asphalt plant in Rio de Janeiro (Brazil) using the international fuel prices. It focuses only on the heating of bitumen, from the storage temperature up to the mixing temperature, without encompassing any other asphalt plant heating processes.

The Asphalt Industry is a very fossil fuel consuming, emitting high amounts of the green house gases, given that each ton of asphalt needs 10 liters of fuel in order to reach the mixing temperature [1]. The choice for this particular kind of industry and thermal process was based on data from the temperature range for the most common processes. For the application treated in this paper, the compound parabolic concentration solar collector (CPC) has shown to be the most suitable type.

There are few studies reported in the literature about process heating using the solar heating systems (SHS) in the asphalt industry, mainly done throughout the past 40 years. Henderson, Wiebelt and Parker [10] have constructed, operated and researched a solar-heated asphalt storage system in Oklahoma City, USA for two years. The storage of the asphalt water emulsion which was used in highway maintenance had required the control of temperatures between about 18 °C and 60 °C in order to avoid physical separation of the emulsion. The solar-heated asphalt storage system had performed satisfactorily and proved to be both cost-effective and maintenance-free. Hankins [12] researched other plant in Texas, USA in which the solar energy was used to compensate the energy losses from the high temperature asphalt to the environment. Luminosu and Fara [11] have constructed a laboratory installation for researching on bitumen preheating by using solar energy in Timisoara, Romania and found that the daily average temperature reached by the bitumen is within its softening temperature range.

Gudekar et al. [13] presented an experimental demonstration unit of CPC system for the application of process steam generation, highlighting that it is easy for fabrication, operation and has a lower cost compared to other available concentrating solar collector systems with further possibility of lowering the cost. Panse [19] constructed a CPC system for steam generation for industrial purpose which proved to be economic and efficient. Kalogirou [9] researched the application of solar energy in sea-water desalination. The parabolic-trough solar-collector was selected mainly due to its ability to function at high temperatures with high efficiency. The economic analysis performed, showed that results could be achieved at low investment cost.

Although the solar resource is countrywide available throughout all seasons, there is few published works about solar application in the Brazilian industry, as Dantas & Fonseca-Costa [15].On the other hand, the industrial sector

Ahmed E. Ismail is with the State University of Rio de Janeiro, Rio de Janeiro, Brazil (phone: +5521980866858; e-mail: ahm.ismail@yahoo.com).

Manoel A.Fonseca-Costa is with the State University of Rio de Janeiro, Rio de Janeiro, Brazil (phone: +5521999630864 e-mail: manoelantonio.costa@gmail.com).

accounts for 25% of energy use GHG Brazilian emissions [20]. In 2009, as a result of the 15th Conference of Parties to the UNFCCC (COP 15), Brazil has committed to reduce by at least 36% its projected emissions of greenhouse gases for the year 2020, with an expected contribution of the industry sector through a voluntary 5% emissions cut [21].

As about half GHG emissions from the Brazilian industry comes directly from process, very expensive or even impossible to reduce without undesirable production cuts, it is expected that the largest mitigation contribution in the short and medium term will come from energy efficiency measures and the use of renewable energy sources, both directed to thermal applications, because almost 80% of the electrical power production in Brazil comes, already, from renewable sources [22].

II. MATERIALS AND METHODS

A. Computational Simulation Tool

Solar energy simulations were executed using TRNSYS 15, which is a computational tool developed and commercialized by the University of Wisconsin, U.S.A. It is used to simulate the transient behavior of systems and is commercially available since 1975 [14], being developed and updated constantly.

The graphical user interface called IISiBat, one of the parts of the program package, can be used for mounting the systems. Each component is modeled mathematically by a system of equations and TRNSYS solves these systems for each time interval, using analytical and numerical methods and information flow between components. Moreover, new TRNSYS components can be created using FORTRAN language

The components have a number of parameters for defining the calculation models and constants that will be used in the simulation. After choosing the units that will be part of the system, the components must be properly connected, that is, the inputs and outputs must be properly configured, ensuring the flow of information.

B. Site and Weather Data

The case studied is heating bitumen to reach its mixing temperature in an asphalt plant in Rio de Janeiro (Brazil). Typical meteorological year (TMY) data for the city of Rio de Janeiro were used which were built from EPW files obtained at LabEEE (2013) web site [24], loaded to TRNSYS using TYPE 9a component. Data consisted on total and diffuse horizontal irradiation both hourly (I, I_d), ambient temperature (T_a) and also the temperature of the bitumen (70 ˚C) before entering the heat exchanger. Tables 1 and 2 shows the Parameters and inputs, respectively, for TRNSYS component TYPE 16 Solar Radiation Processor

Table 1 Parameters configuration for TRNSYS component TYPE 16 Solar Radiation Processor

Parameter	**Value**
1 (Horizontal radiation mode)	5 (I and Id)
3 (Sky method)	1 (isotropic diffuse)
5 (Latitude)	Local latitude
6 (Solar constant)	1,353 W/m2

Table 2 Inputs for TRNSYS component TYPE 16 Solar Radiation Processor

The inputs	**Value**
1-I	EPW file
2-Id	EPW file
5-ρ (ground reflectance)	0.2
6-β (collector inclination)	Local latitude
7-γ (azimuth)	0° (to the equator)

Available solar radiation was calculated using the isotropic diffuse sky method developed by Liu and Jordan (1963), detailed in [5]. The radiation on the tilted surface is considered to include the three components: the beam radiation, the isotropic diffuse radiation, and solar radiation reflected from the ground.

From the horizontal values of global (I) and diffuse (I_d) radiation, available in the EPW file, the value of beam radiation on a horizontal surface (I_b) was calculated by making the simple subtraction:

$$I_b=I-I_d$$

C. Case Studied

The case studied is heating bitumen to reach its mixing temperature (more than 150˚C) with mass flow rate of 9tons/hr in Rio de Janeiro (Brazil). The industrial site consists on a medium size industry, using very typical machinery that is used in many of the asphalt plants all over the world.

There are two most commonly used types of Asphalt Plants: Batch heater and the drum mix asphalt plants.

The batch heater has the capacity ranges from 50 to 200 ton/hr. Moreover, it is working in batches, this means that this type produces one batch each time interval while heating the other batch in the mean time. The capacity of the plant is determined by the type of the mixture and the batch size [1].

Secondly, the Drum Mix Plants which have the capacity ranging from 100 to 700 ton/ hr. The aggregates are dried and heated on a large drum on continuous bases then go through the mixing process. This type is recommended for large contracts where large quantities of the same material are required over a long period of time [1].

Asphalt Mix need about 5-10 % of bitumen that should be mixed with 90-95% of aggregates which should be previously

ISBN: 978-1-61804-324-5

dried in 160 ˚C to remove the moisture from it [1].

The System is to raise the temperature of the Heat transfer fluid (HTF) in order to achieve the desired temperature of the bitumen. Therefore, the plant will produce from 90 to 180 tons/day of asphalt mix. Moreover, mineral oil will be used as the heat transfer fluid due to its high boiling temperature. Table 3 shows the properties of HTF and the Bitumen

Table 3 properties of HTF and the Bitumen

Properties	HTF (Mineral oil)	Bitumen
Mass Flow Rate (kg/hr)	4400	9000
Density (Kg/m^3)	822	1010
Minimum Desired temperature (°C)	210	150
Specific heat capacity(KJ/Kg. °C)	2.13	1.82

D. The Solar Heating System Model

The proposed solar heating system (SHS) (figure 1), in which the HTF is circulating in closed circuit to feed the heat exchanger.

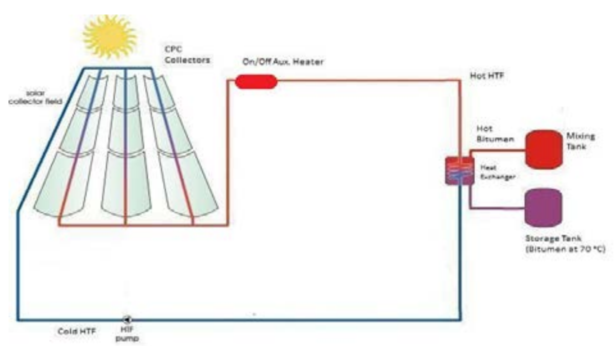

Figure1: Solar Heating System Model

It consists of a pump with a controller to circulate the HTF to the CPC´s through steel pipes, only if there is a net solar energy gain. The HTF will be heated by the CPC´s then it will flow through the pipes to go for the coil inside the heat exchanger at which the bitumen enters at 70°C. The Heating of bitumen will take place in the tank using the following equations in order to reach a minimum temperature of 150 °C.

$Q = C_b (T_{b,o} - T_{b,i}) = C_f (T_{f,o} - T_{f,i})$

In which Q is the heat transfer rate inside the exchanger, while subscripts b, f, i and o is bitumen, HTF, inlet and outlet respectively, C_b and C_f is the heat capacity rates of the bitumen and HTF while T is temperature.

Maximum temperature difference that can occurs is

$\Delta T_{max} = T_{f,I} - T_{b,i}$

Maximum Possible Heat transfer is

$Q_{max} = C_{min} (T_{f,i} - T_{b,i})$

While C_{min} is equal to the smaller value of $C_f = \dot{m}_f C_{pf}$ and $C_b = \dot{m}_b C_{pb}$.. $\dot{m}$ and C_p are mass flow rate and specific heat capacity respectively.

There is an on/off auxiliary heater that has T_{set} = 210°C which is the lowest temperature of the oil to make the bitumen reaches 150°C. This has a control system to measure the oil temperature before entering the heat exchanger. When the auxiliary heater inlet temperature is above the set point temperature, the auxiliary heater will not work so it will not add any heat to the HTF. On the other hand, when the auxiliary heater inlet temperature is below the set point temperature, the auxiliary heater will work to add the heat needed to the HTF in order to reach 210 ˚C.

The hot bitumen after will go to the mixing process with the aggregates while the cold HTF will go again to the collectors through the pump and so on.

This way in heating bitumen is widely used in many asphalt plants that are using conventional fuel.

E. Compound Parabolic Concentration Solar Collector

Table 4 shows different types of solar collectors and their temperature ranges [4]

Table 4

Motion	Collector type	Absorber type	Concent. ratio	Temp. range(°C)
Stationary	Flat-plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
	CPC	Tubular	1-5	60-240
Single axis tracking			5-15	60-300
	Linear Fresnel reflector (LFR)	Tubular	10-40	60-250
	Cylindrical trough collector (CTC)	Tubular	15-50	60-300
	Parabolic trough collector (PTC)	Tubular	10-85	60-400

In order to reach the above mentioned temperature, the most efficient solar collector with the least price that is able to reach it should be chosen.

CPC is the most appropriate in this case as it can reach till 300 °C without tracking system. On the other hand, the Flat Plate Collector (FPC) is the cheapest and the most available but it cannot reach this temperature level. Therefore, it can be used only as preheating solar system or in fluidizing the bitumen only. On the other hand, FPC is generally used for domestic solar water heating, while the application of CPC lies in industrial process and power generation.

CPC is a special type of solar collector fabricated in the shape of two meeting parabolas. It belongs to the non-imaging family, but is considered among the collector having the highest possible concentrating ratio. Normally, it does not require tracking and can accept incoming radiation over a relatively wide range of angles by using multiple reflections [17].

The height and aperture area for a CPC are calculated as per the desired operating temperature. To reduce the cost the height is generally truncated to half as it slightly affects the concentration ratio [6]. Table 5 presents parameter configuration for TRNSYS component TYPE 74 CPC

Table 5

Parameter	Value
2. area of collector	700m2
3. Cp of HTF	2.13 kJ/kg°C
6. wall reflectivity ρ_R	0.9
7. θc half acceptance angle	36°
8. height truncation ratio of CPC	0.67
10.absorbtance of the absorbance plate	0.95
11.no. of cover plates	1
12.index refraction of material (glass)	1.526

III. Economical Analysis

The whole economic modeling uses the United States Dollars (USD). Price surveys were carried out on April/2015.

The SHS is used in order to raise the temperature of the bitumen from the storage temperature (70°C) to the mixing temperature of (135 °C to 190.6 °C) [16], on the other hand, it should not exceed (230°C) in order to prevent auto-ignition [2]. The system used in this research can make a maximum temperature of bitumen below this temperature and with minimum temperature of 150°C. This is because the heat losses are excluded in the heat exchanger. It can permit the efficiency of the heat exchanger till 90 percent.

In order to reach this temperature range by conventional fuel, will be so costly and will have a very high emission of GHG. On the other hand, it is not cost effective to operate the system solely on solar energy due to the relatively high cost of the equipment and the high percentage of inactive time. Therefore, there is an on/off auxiliary heater that has T_{set} = 210°C which is the lowest temperature of the oil to make the bitumen reaches 150°C.

In order to reach this temperature Range with each system were calculated the British Thermal Units (BTU) required monthly and yearly so the system need a yearly total of 4,028,865,409 BTU. Depending on that the plant is working from 9:00 to 16:59 (Monday –Saturday)

On the other hand, the difference in the amount conventional fuel used between the two systems is calculated. Therefore, it is translated to amount of money depends on the price of the fuel. The price was compared to a CPC that is already installed in India as a reference.

$\dot{Q} = \dot{m}\, C_p\, \Delta T$

Where ΔT in the points that did not reach the mixing temperature is:

1. Fuel System: the difference between the exit and the inlet temperature of bitumen which is equal to (150°C – 70°C)
2. SHS: the difference between the set 210 °C and the inlet temperature of the HTF in the auxiliary heater.

Figure 5 The Monthly Btu required from conventional Fuel for the bitumen heating between Fuel and Solar Heating Systems

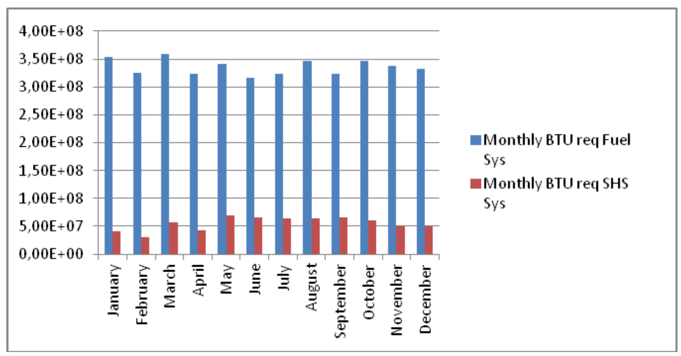

Figure 5

After calculating the net BTU required by both systems the yearly Solar Fraction found is about 83.7%. By using the low heat value (LHV) and the universal price (USD) of each fuel, a yearly difference was calculated by USD using the discount rate of 15% and the operating life-cycle of 15 years.

It was difficult to find the price per m^2 for the CPC but there was a system that was already installed in India by Enersun Power Tech Pvt. Ltd [19]. The Price of the CPC per m^2 is 100 USD. Therefore, it will be 70000 USD for our model because our model has area of 700 m^2.

Table 6 shows the properties of each type of fuel that is used in the comparison and the economic criteria allover the life-cycle of the CPC [7]-[23]

Table 6

Fuel Type	**LHV (Btu/gallon)**	**Price/gal (USD)**	**Yearly Difference (USD)**
Crude Oil	129670	1.43	37219.3
Diesel	129488	1.2	31498,2
LPG	84250	0.56	22410.8

Fuel Type	NPV (USD)	Payback Period (years)	IRR
Crude Oil	147,635	3	53%
Diesel	114.182	3	45%
LPG	61,044	5	31%

IV. Environmental Study

Emission avoided, presented in Table 7, were calculated from official Brazilian official emission factors, those are in accordance with the International Panel of Climate Changes (IPCC).

Table 7

Fuel Type	Emission Factors (t CO_2/t)	Saved fuel tons (t/year)	Avoided emissions (tCO/year)
Crude Oil	2.91997	83.33	259.74
Diesel	3.11685	83.13	259.36
LPG	3.11997	76.96	224.71

V. Conclusion

The World faced many energy crises in the last century and in the beginning of this century too. This leads to more research about renewable sources of energy. In 2002, the amount of solar energy that reaches the Earth's surface every hour is greater than humankind's total demand for energy in one year [18]. The CPC proved to be economically and thermally efficient for such application, despite of its high investment cost and the large area of land that should be occupied by the collector. The study case serves as an indicative that energy policies are needed for increasing the solar energy penetration of high temperature industry. The urge to increase sustainability and reduce the environmental footprint on all human activities, promote the continuous pursuit of solutions for the constraints involving industrial solar heating systems.

The results, though, made it possible to address environmentally sound public policies to encourage solar energy use in the Asphalt Industry. Moreover, it will help in reducing the high emission of the GHG in this industry.

Acknowledgment

The authors thank Pablo de Abreu Lisboa, researcher from Cepel (Centro de Pesquisas de Energia Elétrica) and Fabrício dos Santos Dantas from INT (Brazilian National Institute of Technology) for the support with TRNSYS.

Ahmed E. Ismail thanks FAPERJ for the scholarship.

References

[1]J. Read, and D. Whiteoak. "*The Shell Bitumen Handbook*", 5th ed. London: Thomas Telford, 2003. pp. 268-74

[2] *"The Shell Bitumen Industrial Handbook"*. London: Thomas Telford, 1995. Ch. 3

[3] S.P.Sukhatme and J.K. Nayak. "*Solar energy principle of thermal collection and storage*", 3rd Edition, India: Tata Mcgraw hill, 2008, Page No.233, 234.

[4] S. A. Kalogirous, *"Solar Energy Engineering Process and Systems*", 2nd Edition, Oxford: Elsevier, 2014, pp 126.

[5] J.A. Duffie, W.A. Beckman," Solar Engineering of Thermal Processes", Wiley Interscience Publication, New York, 1991, pp. 94-95.

[6] K. Sukhatme, and Suhas P. Sukhatme. "*Solar Energy: Principles of Thermal Collection and Storage".* 2nd edition, India: Tata Mcgraw hill,1996,pp.237

[7] B. Boundy,S. W. Diegel, L. Wright, S. C. Davis. "Biomass Energy Databook." 4th edition, 2011,Apenddix A

[8]S.A Kalogirou. "Solar thermal collectors and applications". Prog. Energy Combust. Sci. 2004, 30, 231–295

[9]S.A Kalogirou. Solar Use of parabolic trough solar energy collectors for sea-water desalination. Applied Energy 60 (1998) 65-88

[10]J.B.Henderson,J.A. Wiebelt andJ.D. Parker. "Use of Solar Energy For Heating Asphalt In Storage Tanks." Applied Science Publishers Ltd, England. (1980) 221 *228*

[11]I. Luminosu, L.Fara. "Experimental research on bitumen preheating (fluidization) by using solar energy in passive mode." International Journal of Thermal Sciences 48 (2009) 209–217

[12]K.D.Hankins. "Solar Heating An Asphalt Storage Tank" 229-1, June 1978

[13]A. S. Gudekar, A. S. Jadhav, S. V. Panse, J. B. Joshi, A. B. Pandit "Cost effective design of compound parabolic collector for steam generation." Solar Energy 90 (2013) 43–50

[14]KLEIN, S. et al. A method of simulation of solar processes and its application.Solar Energy, v. 17, n. 1, p. 29 – 37, 1975.

[15]F. Dantas and M. Fonseca-Costa. "Thermal and Economical Analysis of the Solar Preheating of Steam Boiler Feed Water". **2014** Journal of Energy and Power Engineering 8 (2014) 775-784.

.[16]R. C. West, D.E. Watson, P.A. Turner, J. R. Casola "Mixing and Compaction Temperatures of Asphalt Binders in Hot-Mix Asphalt".Washington:National Academy of Sciences, 2010

[17]G. M. Kaplan. "Understanding Solar Concentrators", Volunteers in Technical Assistance, Inc. Virqinia, USA.1985.

[18] Oliver Morton, "Solar energy: A new day dawning?: Silicon Valley sunrise". Nature journal,443, 6 ,2002

[19] S. Panse. "Compound parabolic solar collectors for solar process heat" Wels, Austria: International Conference Solar Process Heat,2011 http://www.wsed.at

[20] Brazilian Government / Ministry of Science and Technology, 2011, *Second Official Brazilian Communication to COP - IPCC (executive summary).* CGMGC, 2010. Brasília. http://www.mct.gov.br/upd_blob/0215/215070.pdf Accessed on April, 4th. 2015. In Portuguese.

[21] Brazilian Government / Ministry for the Development of Industry and Commerce (MDIC), 2012. *Sectorial plan of mitigation of climate change for a low carbon emission economy in the transformation industry*). Brasília/DF. In Portuguese.

[22] EPE [Empresa de Pesquisa Energética], 2014. *National energy balance – base year 2013 – final report*. CDU 620.9:553.04(81). Brasília/DF, 2014

[23]"Petroleum Marketing Monthly." U.S. Department of Energy, Washington, DC, April,2015 http://www.eia.gov

[24]Brazilian EPW Files [Online], LabEEE, 2013, http://www.labeee.ufsc.br/.