An Assessment of Demand for Industrial Process Heat, Viability of Solar Thermal and Sensible Heat Storage Technologies in Zimbabwe

Luckywell Seyitini*, Basim Belgasim**,***, Christopher Enweremadu*‡

*Department of Mechanical Engineering, College of Science, Engineering and Technology, University of South Africa, Science Campus, Florida 1710, South Africa

**Centre for Solar Energy Research and Studies, Libyan Authority for Scientific Research, Tajoura, Libya

***Department of Mechanical Engineering, Faculty of Engineering, University of Benghazi, Libya

(12789208@mylife.unisa.ac.za, basim.belgasim@yahoo.com, enwercc@unisa.ac.za)o

‡ Christopher Enweremadu; University of South Africa, Science Campus, Florida 1710, South Africa, Tel: +27 11 471 2057, enwercc@unisa.ac.za

Received: 01.09.2023 Accepted:11.01.2024

Abstract- Thermal energy accounts for more than 50 % of the total final energy being used worldwide. This is attributed to the demand of heat for domestic and commercial purposes which include water and space heating, electric power generation and industrial process heat. Most of this heat is obtained from fossil fuels which are the major drivers of global warming and climate change. The present study assesses the demand for low temperature thermal energy for some typical industrial processes and analyse the potential of adopting solar thermal technologies and sensible heat storage systems in Zimbabwe. A survey was conducted to gather data on heat requirements for various industrial processes including, food processing, chemical and beverage production, agro-processing, and mining. TSOL and Systems advisor model (SAM) software were used to simulate proposed solar thermal technologies to assess their feasibility as alternate source of industrial process heat. Also, literature data was used to assess the potential of utilising sensible heat storage systems to mitigate the intermittent nature of solar resources. Results revealed that it is technically and financially feasible to adopt solar thermal technologies for industrial applications in all the sectors considered in this assessment. It was found that cost effective, sensible heat storage technology can effectively address the discontinuous availability of solar thermal energy. In addition, heat storage systems were observed to have a great potential to enhance efficiency of existing heating systems through heat recovery methods.

Keywords Feasibility, heat demand, industrial process heat, solar thermal energy systems, sensible thermal energy storage.

1. Introduction

Thermal energy might not be as popular as electrical power and transportation energy in terms of public policy deliberations, but of all the energy being consumed worldwide most of it is in form of heat. As of 2018, thermal energy accounted for about 51 % of the total final energy being consumed in the world [1]. This high demand for thermal energy is due to various crucial uses for both domestic and commercial applications including water and space heating, electric power generation in thermal power stations as well as the need for industrial process heat [2]. The industrial sector which usually processes natural materials into valuable finished products, accounts for about 32 - 35 % of the final global total energy and 74 % of it is required in form of heat as illustrated in Fig. 1 [3, 4]. Most of this industrial process heat is obtained from combustion of fossil fuels with reports indicating that, they are contributing about 90 % of the total heat energy consumed for all industrial applications [5, 6] and as such, industrial operations are the major producers of carbon emissions, contributing up to 40 % of the global total carbon emissions [7-9]. The disastrous effects associated with emissions of greenhouse gases, has convinced mankind to swift towards considering sustainable energy sources as evidenced by the inclusion of the 7th goal of the Sustainable Developmental Goals by the United Nations. Several high level international follow up deliberations such as Conference of the Parties (COPs) are also being pursued to continuously provide updates and guidance to the global efforts of saving the earth from global warming and climate change.

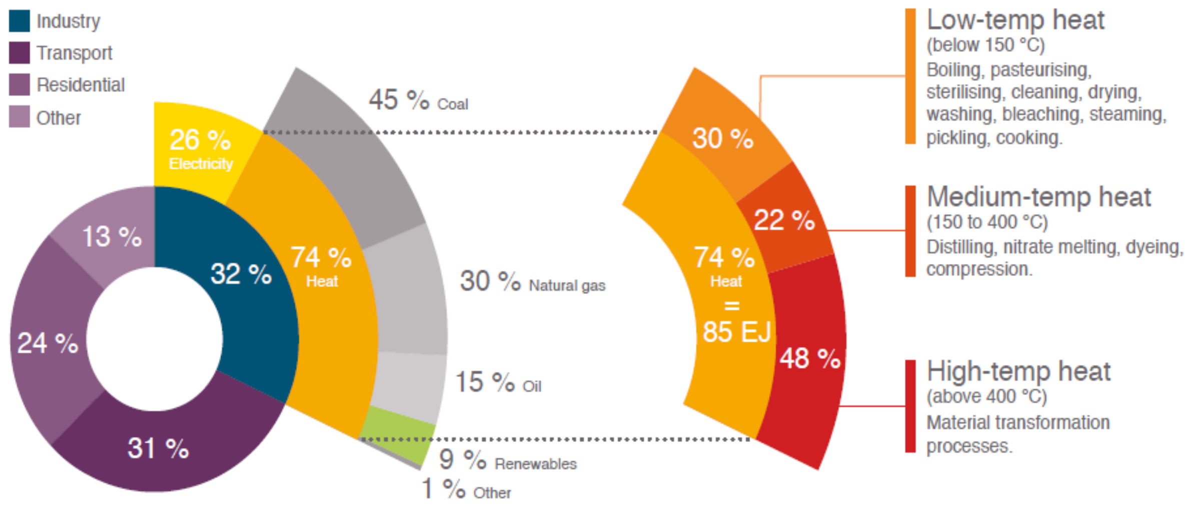

Fig. 1. Global total final energy consumption [2].

Solar thermal technologies have emerged as practical alternatives to be considered for clean production of thermal energy for industrial applications. Already, there is ongoing work in terms of research and development activities as well as investments in solar thermal systems as reported by the International Renewable Energy Agency [1]. In a recent update by the International Energy Agency, it was highlighted that, a total global solar thermal capacity of 522 GW_{th} was achieved by 2021, when additional solar thermal energy systems (STES) of capacity 21 GW_{th} were installed in the same year, with China leading the other active nations in the international solar thermal market [10]. Several other countries which are actively competing in include, Germany, Turkey, India, Austria, Mexico, Brazil, and the United States among others [11].

However, there are several challenges still being experienced that limit the uptake of STES for industrial applications which include the following:
- high starting capital for installations of industrial solar thermal systems as well as lack of promotional incentives and regulatory policies [12],
- reluctance in taking risks of operational disruptions of already existing industrial processes since most captains of industries are logically much worried about profits and losses [13].
- lack of knowledge and confidence in STES together with the discontinuous availability of the solar resource, also hinder the uptake of solar heat systems [14].

The aim of this study is to assess the consumption of heat for some typical industrial processes and analyse the potential of adopting solar thermal technologies and heat storage systems for industrial applications in Zimbabwe. The assessment considers the following objectives:
- to establish the quantities of heat energy being consumed and the required temperature ranges for some typical industrial processes.
- to assess the viability of adopting STES to meet the industrial process heat.
- to assess the potential of utilising thermal energy storage systems for industrial applications.

1.1. Types of Solar Thermal Energy Technologies

Solar thermal systems produce thermal energy directly from solar radiation by means of different solar collector techniques. There are various solar thermal technologies in the market, and they can be classified broadly as fixed and tracking solar thermal systems [15, 16]. Fig. 2 illustrates some of the solar thermal collector systems being currently used worldwide. The fixed type includes technologies whose solar collectors are stationary, like the evacuated tube and flat plate collectors which can be glazed or unglazed. The systems are generally cheap and easy to install but have low temperature outputs with conventional flat plate collectors (FPC) delivering heat at temperatures between 30 °C and 100 °C, while conventional evacuated tube collectors (ETC) can yield higher temperatures up to 120 °C [17]. Some improved versions of these solar thermal collector systems are also emerging in the market, where transparent insulation materials as well as multiple glazing techniques are being used on FPC, which has seen the production of heat at higher temperatures of about 110 °C to 150 °C [18]. Also, performance of ETC systems have been enhanced by applying ultra-high vacuum in the ETC and this has resulted in the achievement of higher temperatures up to about 150 °C as highlighted by Foeste et al., [19].

On the other hand, the tracking solar thermal collector technologies which are also called concentrating solar power (CSP) systems, are used to produce heat at high temperatures that ranges from 200 °C up to above 400 °C depending on the type and scale of the system [20-22]. These solar heat collectors are designed to be moveable to enable sun tracking as they focus solar radiation on to a receiver system. Varieties of CSP systems include parabolic trough, linear Fresnel, concentrating dish and the central tower technologies [23, 24].

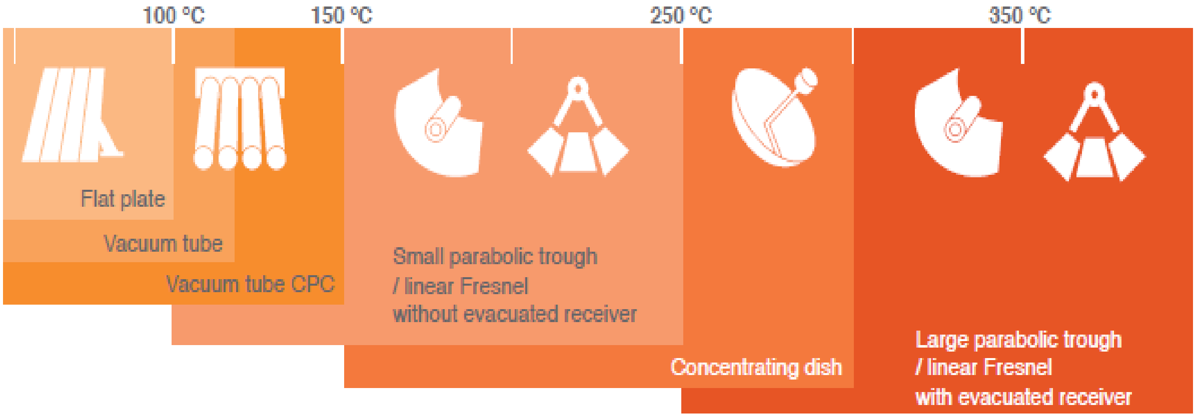

Fig. 2. Types of solar thermal technologies [15].

1.2. Potential for Industrial Solar Thermal Systems

A wide range of investigations have been ongoing in different parts of the world which include, assessing technical and financial viability of applying STES in different industrial sectors as alternate source of industrial process heat. Brent et al., [25] analysed the potential of deploying solar thermal technology in South Africa. The study involved exploring the international trends of solar thermal technology and its applications in the electric power generation sector and process heat for industrial applications. A great potential was reported and some short- and long-term strategies were suggested to counter some anticipated barriers.

Lauterbach et al., [26] extensively assessed the potential of utilising solar thermal systems in Germany. The study was motivated by the need to inform the strategy of implementing STES in terms of prioritising suitable industrial sectors as well as identifying processes that can be easily powered by solar thermal technologies. The results showed that in all the identified sectors with good potential, the temperature range of much interest to be considered for solar heating systems is 100 - 200 °C.

Feasibility of applying parabolic trough solar thermal collector system to generate steam for industrial food processing applications was investigated by Silva et al., [27]. The findings revealed that the technology can indeed meet the greater part of the process heat demand and the need to consider heat storage systems when deploying solar thermal technologies was also emphasised.

In India, Sharma et al., [28] investigated the potential of adopting solar thermal technology for industrial process heat in the paper industry, which consumes heat within the temperature range of 50 - 300 °C. The study indicated that, using the parabolic trough solar thermal collectors, enough thermal energy can be harnessed to meet the needs for industrial operations. It was reported that, about 111 hectares of land will be required for the solar thermal collector to produce up to 30 % of industrial process heat required in the Indian paper industry. Also, it was indicated that, implementing this technology will reduce the annual carbon emissions by about 0.34 million tonnes.

Michael et al., [29] reviewed the research works on STES meant for industrial applications. The review highlighted that most research and developmental activities were concentrating on electric power generation applications with minimum work on producing low temperature industrial process heat and as such this was declared as an area worthy pursuing for development in renewable energy sector.

Potential analysis for adoption of STES for industrial applications must also consider how these solar thermal technologies can be integrated to existing conventional heating systems. Ismail et al., [30] highlighted that, there are challenges which can significantly affect the effectiveness of STES as industrial thermal energy solutions. It was emphasised that, careful integration designs must be done to avoid serious heat losses when it is generated and transferred from a STES to the actual point of industrial process [31].

An integration guideline has been developed by the

International Energy Agency [32] which recommends two main integration strategies namely process level and supply line level. The process level integrates STES with the actual intended industrial process while the supply line level links the STES to the main thermal energy supply channel for all the industrial processes.

1.3. Successful Applications of Solar Thermal Energy systems for industrial process heat

It is estimated that, as of 2020, there were 819 operational solar thermal systems worldwide supplying industrial process heat [12]. Some of the documented installed solar thermal systems are tabled in Table 1.

Table 1. Selected operational solar thermal systems for industrial applications.

Organisation /Company	Industrial process	Temperature range (°C)	Solar thermal technology	Source
Daly Textile, China	Pre-heating water for dyeing textiles.	55	Flat plate collector covering 13 000 m^2-Capacity 9.75MW_{th},	[33]
Cape Brewing Company, South Africa	Process hot water	70 - 90	Flat plate collector Aperture area 120 m^2 Capacity 84 kW Delivering 29.6 % of the required heat	[3]
Amul Fed Dairy, India	Process steam for, milk pasteurisation and sterilisation	140	Parabolic trough solar collector. Collector area - 561 m^2 Capacity of 393 kW supplying 59 % of the total steam demand.	[3]
RAM Pharma Pharmaceuticals producer, Jordan	Process steam for, sterilisation, drying and fermenting.	160	Linear Fresnel collector Capacity 277 kW Covered area - 396 m^2 Reduced annual diesel demand by 30 - 40 %	[3]
Fleischwaren Berger, Meat Products, Austria	Preheating of feed water for steam boiler Hot water for cleaning and drying	30 - 90	Flat plate collector Capacity 747 kW covering area of 1,067 m^2	[3]
Golden Hills Tea Factory in India	Preheating air for drying	110 - 150	Flat plate solar air collector system. Total area 264 m^2. Reduced lignite coal annual consumption by 71 tonnes	[34]

1.4. Potential of Sensible Thermal Energy Storage Technologies for Industrial Applications

Sensible thermal energy storage technology is the most matured and cheapest of all the heat storage technologies and this is evidenced by its dominance in the market [1]. Major characteristics of sensible thermal energy storage technology are summarised in Table 2.

Sensible heat is stored either in liquid or solid storage media where, the most used liquids are water, thermal oils, and molten salts [35]. Water tank thermal energy storage (WTTES) systems are most suitable for heat storage requirements at below 100 ˚C because beyond its boiling point, the design of storage tanks is costly to cater for leakage and high-pressure handling challenges [36].

Thermal oils and molten salts are usually preferred for high temperature applications, but they are more expensive as compared to hot water. Also, molten salts have high melting points which renders them unsuitable for low temperature applications below 200 ˚C [37].

On the other hand, several solid-state materials are being considered for sensible heat storage purposes which include, metals, natural rocks, and manufactured solids like, concrete, bricks, and ceramics [38]. However, majority of these solid materials are mainly under research and demonstration stages with minimum commercial applications [1]. A review by Seyitini et al., [39], recommended the use of solid state sensible thermal energy storage (SSSTES) systems that use natural rocks for low temperature industrial applications because they are harmlessness and cost effective.

Table 2. Characteristics of sensible heat storage technology and its projections [1].

Year	Cost (US$/kWh)	Efficiency (%)	Heat capacity (kWh/m^3.K)	Lifespan (cycles)	Temperature range (°C)
2018	0.1 – 35	50 – 90		1000 – 3000	
2030	0.1 – 25	60 – 90	0.4 – 0.9	3000 – 5000	-150 to 1000
2050	– 15	70 – 90		5000 – 7500	

2. Methodology

A survey intended to gather information on industrial process heat consumption by a wide range of industrial sectors was carried out. Seven different companies in the food and beverages production industry, chemical production, agro-processing, and mining sectors managed to participate. Data on daily demand of process heat, required temperature ranges and the current sources of heat was collected. Assessment of viability of using STES was done by simulating the proposed solar thermal technologies using TSOL Pro 5.5 and Systems advisor model (SAM version 2020.11.29) soft wares. TSOL is a professional computer program which is used for designing and simulating solar thermal systems that can supply hot water, process heat and space heating among others. It is a reliable tool which is based on comprehensive calculation and is being currently used by energy consultants, researchers, planners, and installers of solar thermal systems [40]. SAM is a popular software which applies thermal engineering concepts with other mathematical formulas to simulate performance of different solar thermal technologies [41]. Each of the software uses a similar approach where some input data is specified in the model, and it determines some performance parameters as illustrated in Fig 3.

Technical input data input including system power ccapacity, solar collector type, receiver type, heat transfer fluid type was entered to simulate the performance of proposed solar thermal systems. Also, some financial input parameters such as inflation rate, interest rate, value added tax, approximate cost of the system per kilowatt and estimated operational cost were specified to model the financial performance of solar thermal systems. Potential assessment of the proposed solar systems was done based on the performance parameters which include, annual energy yield, space requirements, capital investment cost, levelized cost of heat and pay back period.

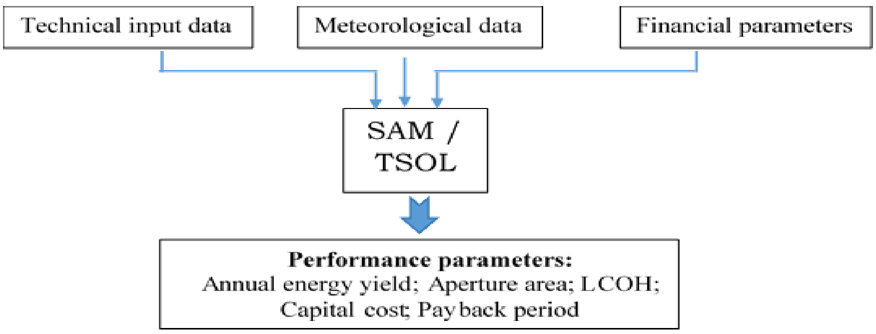

Fig. 3. Simulation flowchart for both SAM and TSOL.

Sensible thermal energy storage systems use liquids or solids as heat storing media. Literature data was used to guide the choice of suitable thermal energy storage technology between water tank thermal energy storage (WTTES) and solid state sensible thermal energy storage systems (SSSTES) depending on the range of required process temperature. Other potential storage media like molten salts and thermal oils were not considered mainly based on economic and environmental issues.

3. Results and Discussion

Most of the industries considered in this study use steam boilers to produce steam at high temperatures, which is used as the working heat transfer fluid. This steam will then provide the process heat at different required temperatures for various applications, through use of heat exchangers as illustrated in Fig. 4.

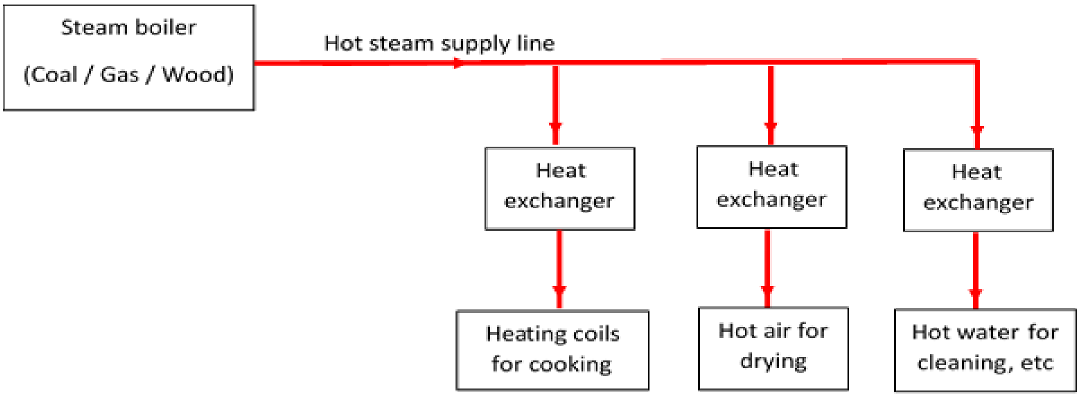

Fig. 4. Flow diagram for process heat supply in industries.

3.1. Sweets Manufacturing Company

3.1.1. Current State of Thermal Energy Requirements

Heat is needed mainly for cooking and production of hot water. A coal fired steam boiler produces superheated steam which is used to provide process heat for cooking via heating coils. Gas and firewood are also used for cooking. About 4000 litres of hot water is required daily and this is produced using electric geysers. Details of heat consumption and operating temperature ranges are summarized in Table 3. Evacuated tube solar water heater and linear Fresnel CSP systems were proposed and simulated as alternative sources of hot water and industrial process heat respectively. The proposed solar thermal systems are used are shown in Fig. 5a and 5b, respectively.

Fig.5a. Evacuated tube solar water heater [42]

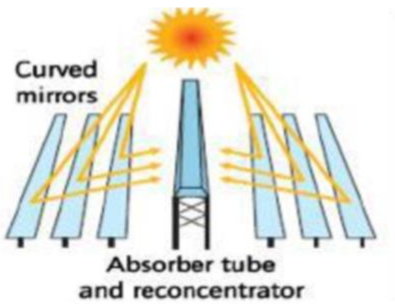

Fig.5b. Linear Fresnel solar thermal technology [43]

3.1.2. Feasibility of the Proposed STES

Simulation results showed that, the daily demand for hot water can be adequately supplied by the evaluated tube solar thermal system of capacity 31.3 kW_{th} and collector area of 48 m^2. This system can be installed at cost of about US$ 19 200.The solar collector system can be accommodated on the roof of the company factory and the system can be integrated with existing process heat source at process level. On the other hand, a linear Fresnel solar technology can perform well in generating process steam for cooking. This solar thermal steam generator can be integrated at supply level of the existing coal fired heating system and a plant of 1.25 MW_{th} can supply about 30 % of the needed process steam at a levelised cost of heat (LCOH) of 0.12 $/kWh. A space of about 1 760 m^2 will be required for the solar thermal collector aperture area. An initial capital of about $700 000 is required and the investment has an estimated payback period of 4 years. Another option is of using a solid-state sensible heat storage, which will be charged by the waste heat from the cooking process. The stored heat can then be used to produce hot water or at least preheat the water. This alternative will improve the efficiency of the heating system while limiting the use of electric geysers.

3.2. Brewery Company

3.2.1. Current Thermal Energy Situation

Process heat is consumed for cooking, pasteurisation, and production of hot water. A coal fired steam boiler is used to produce superheated steam which is used to provide heat for all the processes through use of heat exchangers. An average of 80 000 litres of hot water is required daily at about 70 °C while cooking and pasteurizing of beer is done using some heating coils. Details of heat consumption is summarized in Table 3. Two solar thermal systems can be considered separately, an evacuated tube solar water heater to supply of hot water and a linear Fresnel CSP system for direct steam generation for other applications

Table 3. Summary of findings and proposed solar thermal solutions and heat storage systems.

Current sources of process heat	**Mean daily heat demand (MWh_t)**	**Uses and required temperature ranges**	**Proposed solar thermal technologies**	**Suggested heat storage systems**
Sweets manufacturing company				
Coal (3900kg/day), Gas (7 kg/day), Wood fuel (15 kg/day), Electric geysers (7 x 2 kW)	30	Cooking – 150 °C Hot water – 70 °C	CSP Linear Fresnel - (SAM) Evacuated tube solar water heating system - (TSOL)	SSSTES WTTES
Brewery company				
Coal (6000 kg/day)	46	Cooking: 100 °C Hot water: 70 °C Pasteurization: 90 °C	CSP Linear Fresnel - (SAM) Evacuated tube solar water heating system- (TSOL)	SSSTES WTTES
Pharmaceutical company				
Coal (250 kg/day)	2	Cooking: 80 °C Hot water: 70 °C Drying: 70 °C	CSP Parabolic trough -(SAM) Evacuated tube solar water heating system- (TSOL)	SSSTES WTTES
Gold Mine				
Coal (1000 kg/day), Electric boiler	9	Hot air: 700 °C Steam: 120 °C	CSP Linear Fresnel - (SAM)	SSSTES
Beverages production company				
Gas (48 kg/day), Electric geysers (55 kW)	2	Cooking: 120-150 °C Hot water: 80-90 °C	CSP Linear Fresnel - (SAM) Evacuated tube solar water heating system- (TSOL)	SSSTES WTTES
Poultry farm				
Coal (600 kg/month), Wood fuel (400 kg/month)	0.2	Heating fowl run: 30 °C Hot water: 70 °C	Evacuated tube solar water heating system -(TSOL)	WTTES
Tea manufacturing company				
Wood fuel (250 kg/day)	1	Drying: 90 -140 °C	CSP Parabolic trough -(SAM)	SSSTES

3.2.2. Viability of Proposed STES

A large-scale solar water heating system of capacity 560 kW_{th} with a solar thermal collector area of 800 m^2 is required. This would cost approximately $313 842 with an estimated payback time of 4 years against a life span of up to 30 years.

A direct steam generator linear Fresnel CSP plant of capacity 1.6 MW_{th} will require a total reflective aperture area of about 2 280 m^2 to produce about 2 153.46 MWh_{th} annually and deliver about 30 % of the actual heat demand at a cost of $896 000. The levelised cost of heat is approximated to be 11 cents per kWh over the life span of the solar thermal system of about 30 years and the project has an internal rate of return of 25 %.

Also, solid state sensible heat storage systems can be considered for heat recovery purposes which can be used to preheat water, and this will reduce the consumption of coal for all the factory operations.

3.3. Chemical Production Company

3.3.1. Current Process Heat Requirements

Thermal energy daily demand is for cooking, drying, and coating and hot water production. A coal fired steam boiler is the primary source of all the required process heat, where steam is used to produce about 2000 litres of hot water and hot air for drying and coating, while steam pots are used for cooking. Details of heat consumption are summarised in Table 3. Evacuated tube solar water heater and a parabolic trough CSP system are proposed to supply hot water and industrial process heat respectively. A parabolic trough solar thermal collector is illustrated in Fig. 6.

3.3.2. Summary of Feasibility of the Proposed Stes

The daily demand of hot water would require a solar collector of area 20 m^2 that can be accommodated on the roof of the factory. Capital cost of approximately $8 000 is required for installation of the STES and this can be recovered in a period of 3.3 years. Also, an annual carbon emission reduction of 15.5 tCO_2 can be achieved. The solar thermal plant for industrial process heat will require a total reflective aperture area of about 235 m^2 at an estimated cost of $88 777. It will deliver energy equivalent to 22 % of the energy value of the coal being used currently for heating at a LCOH of 0.13 $/kWh.

Alternatively, utilisation of SSSTES in this factory, can enable recovery of waste heat from the cooking process and produce the required hot water. The thermal energy storage technology will reduce fuel consumption as well as enhancing the efficiency of the heating system.

Fig. 6. Parabolic trough solar thermal technology [11]

3.4. Mining Company

3.4.1. Current Scenario of Process Heat Demand

Heat is required mainly for production of hot air at high temperature (700 ℃) for gold mineral processing and production of steam. A coal fired furnace is used to produce hot air while an electric boiler is used produce steam at 120 ℃ which requires a daily feed of about 2000 litres of water. Details of heat consumption are tabled in Table 3. A solar thermal power plant using the Linear Fresnel technology is considered for the generation of steam and it was designed using SAM software.

3.4.2. Summary of Performance of the Proposed Thermal Energy Solutions

The proposed solar thermal plant of capacity 166.4 kW_{th} for process steam will require a total reflective aperture area of about 240 m^2 at an estimated cost of $93 184. It will deliver energy equivalent to 36 % of the energy value of the electrical energy being currently used for heating at a LCOH of 0.10 $/kWh. A solar thermal system operating in the high temperature range would be recommended for production of hot air at 700 °C. CSP using the Central tower type can be considered for such an application since it is being successfully used for production of heat for electricity generation in solar thermal power plants.

Another option to consider, is the use of a SSSTES to recover waste heat from the furnace and use it to preheat water being used for steam generation, this will significantly reduce the power consumption by the electric boiler.

3.5. Beverages Production Company

3.5.1. Current Thermal Energy Situation

Heat is needed mainly for cooking and production of hot water for sanitation. Electric heaters are used for steam generation which is used to produce about 4000 litres of hot water required per day, while gas is used for cooking. Details of heat consumption are given in Table 3. Two separate STES are proposed, a solar water heater to supply the required hot water, while a linear Fresnel CSP would generate steam for cooking.

3.5.2. Expected Performance of Suggested Stes

The solar water heater requires a solar collector area of 48 m^2 which can be installed on the roof of the factory. In case of prolonged periods of cloud cover, the already existing electric heater or gas fired boiler can be considered for backup heat. Capital cost of approximately $19 200 is required which can be recovered in a period which is less than half the life span of the solar thermal system. Also, an annual carbon emission reduction of 25.2 tCO_2 can be obtained.

Linear Fresnel solar thermal plant with a total reflective aperture area of about 180 m^2 is needed and the system will require an initial capital of about $70 560. The system will deliver thermal energy at a levelised cost of heat of 0.10 $/kWh, which is equivalent to 68 % of the energy value of the gas being currently used for cooking.

Waste heat recovery technique can reduce heat requirements for production of hot water. A heat storage system will be used to harness waste heat from the cooking process and use it to preheat water.

3.6. Poultry Farm

3.6.1. Current Thermal Energy Requirements

Heat is being used mainly for production of hot water and space heating in fowl runs. Firewood is the source of heat for generating hot water for de-feathering of about 1600 birds monthly while coal is used for heating the fowl runs especially during winter. For a monthly production of 1600 birds, a total of about 1280 litres of hot water is used for de-feathering. More data on heat consumption is summarised in Table 3. A solar water heater is proposed to supply hot water for de-feathering.

3.6.2. Summary of Proposed Alternative Thermal Energy Solutions

Demand for hot water for a day's de-feathering process requires 1 m^2 evacuated tube solar collector that can be easily accommodated on the roof of the fowl run at a cost of approximately US$400.

In this case, a different option from a STES can be considered for space heating in the fowl run. A bio-digester can be constructed on the farm since there is readily available chicken waste to feed the digester. A network of pipes can be designed to distribute heat in the fowl runs using hot water as the heat transfer fluid.

3.7. Tea Manufacturing Company

3.7.1. Current Thermal Energy Situation

Heat is needed mainly for drying processes. A steam boiler which is fired using wood fuel produces superheated steam which is used to produce hot air for drying in different drying chambers at different temperature ranges. More information on heat consumption is given in Table 3. A parabolic trough CSP plant is proposed to generate process heat for drying.

3.7.2. Feasibility of the Proposed Stes

The suggested solar thermal plant of capacity 160 kW_{th} requires a total reflective aperture area of about 235 m^2 and this requires a capital cost of about $89 600. Hot air for drying will be produced using heat exchangers where heated air will be pumped directly into drying chambers. The solar thermal system will deliver about 167.15 MWh_{th} annually at LCOH of 0.12 $/kWh, which is equivalent to 46 % of the energy value of the wood fuel that is currently being used for heating. Thermal energy storage systems can also be applied to recovery heat which can be used for the preliminary heating process which usually requires heat at about 35 °C.

4. Conclusion

Results for all the seven industrial processes considered in this assessment have shown that it is technically and financially feasible to adopt different solar thermal technologies for industrial applications in Zimbabwe. The space requirements for most of the solar thermal systems can be accommodated on the existing structures of the factories, and systems can be integrated with the current heating systems either at process level or at supply line level. Investing in the proposed STES is profitable since for all the systems assessed the total capital costs can be returned within a period which is less than half of the life span of the projects implying that clients will benefit free thermal energy for the greater portion of the life span of the solar thermal technologies. Also, sensible thermal energy storage systems are crucial in mitigating the intermittent nature of the solar resource to enable continuous supply of heat for industrial applications.

Most of the process heat is currently being supplied from boilers that are powered by fossil fuels to generate superheated steam at high temperatures even though, operating temperatures for most industrial processes do not exceed 150 °C. This highlights a possibility that a lot of heat may be wasted during operations. There is a huge potential for utilising cost effective sensible thermal energy storage systems for heat recovery in industries that require both process heat at temperatures higher than 100 ℃ and hot water at less than 100 ℃. Recovered waste heat from industrial processes at higher temperatures can be used to preheat or supply required hot water thereby cutting down the consumption of fuels as well as improving efficiency of the heating systems in some industrial sectors.

Acknowledgments

The authors would like to thank SOTRAIN and the Austrian Development Agency for funding this assessment project.

References

[1] IRENA, Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-279-6, 2020.

[2] J. Salgado-Beceiro, H. Kauko and V. B. Aasen, "Feasibility of Waste Materials from Metal Industry for Thermal Energy Storage Applications," 2024 9th International Conference on Smart and Sustainable Technologies (SpliTech), Bol and Split, Croatia, 2024, pp. 1-4, doi: 10.23919/SpliTech61897.2024.10612573

[3] Solar Payback Solar heat for industry brochure, 2017.Available from www.solar-payback.com/wp-content/uploads/2017/07/solar-heat-for-industry-solar-payback-april-2017.pdf (Last accessed 29 March 2023)

[4] S. Lee, S. Nengroo, Y. Jung, S. Kim, S. Kwon, Y, Shin, J. Lee, Y. Doh, T. Heo, Taewook and D. Har, "Factory energy management by steam energy cluster modeling in paper-making", 11th International Conference on SmartGrid (icSmartGrid), Paris, France, pp. 1-5, 4-7 June 2023. DOI: 10.1109/icSmartGrid58556.2023.10171060.

[5] U. Collier, Renewable Heat Policies Delivering Clean Heat Solutions for the Energy Transition, IEA, 2018.

[6] B. Boutaghriout, A. Bouakaz, C. Hamouda, H. Smadi and A. Malek, "Investigation on the use of solar thermal energy in the agro food industry in Algeria," 2013 International Renewable and Sustainable Energy Conference (IRSEC), Ouarzazate, Morocco, 2013, pp. 167-170, doi: 10.1109/IRSEC.2013.6529716.

[7] REN21, Renewable Energy Tenders and Community, Paris: September 2017. Available from http://www.ren21.net/wp-content/uploads/2017/09/LAC-Report.pdf (Last accessed 29 March 2023)

[8] B. Hangun, O. Eyecioglu and M. Beken, "Investigating the energy production trends of countries and its relationship between economic development", 11th International Conference on Renewable Energy Research and Application (ICRERA), Istanbul, Turkey, pp. 597-600, 18-21 September 2022, DOI: 10.1109/ICRERA55966.2022.9922684.

[9] M. Longo, M. Roscia, G. C. Lazaroiu and M. Pagano, "Analysis of sustainable and competitive energy system", International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, WI, USA, 014, pp. 80-86, 19-22 October 2014, DOI: 10.1109/ICRERA.2014.7016516.

[10] International Energy Agency - Solar Heating and Cooling, Solar Update, Newsletter of the IEA, Solar Heating and Cooling Programme, 2022. Available from https://www.iea-shc.org/Data/Sites/1/publications/2022-07-Solar-Update-Newsletter.pdf (Last accessed 20 March 2023)

[11] REN21. 2021. Renewables 2021 Global Status Report, Paris: REN21 Secretariat, 2021, ISBN 978-3-948393-03-8.

[12] R. Ramaiah and K.S. Shashi Shekar, "Solar thermal energy utilization for medium temperature industrial process heat applications - A review", IOP Conference Series: Materials Science and Engineering, DOI:10.1088/1757-899X/376/1/012035, vol. 376, 012035, 2018.

[13] P. Cederic. "Renewable Energy for Industry." Insights Series. Paris, France: International Energy Agency, 2017. Last accessed 17 April 2023, Available from https://www.iea.org/reports/renewable-energy-for-industry

[14] N. Cottret and E. Menichetti, Technical Study Report on Solar Heat for Industrial Processes, SSFA/2010/GFL 5070-4A54-2647-2101, 2010.

[15] IEA TASK 49, Process Heat Collectors: State of the Art and Available Medium Temperature Collectors, December 2015. Last accessed 4 April 2023, Available from www.task49.iea-shc.org

[16] Y. Haddad, I. Rahoma, F. Obeidat, M. Ali Amrani and M. Abdunnabi, "Modelling of a Solar Heating System for Industrial Processes using Linear Fresnel Reflectors," 2022 13th International Renewable Energy Congress (IREC), Hammamet, Tunisia, 2022, pp. 1-6, doi: 10.1109/IREC56325.2022.10001942.

[17] IEA-ETSAP and IRENA, Solar Heat for Industrial Processes, Technology Brief E21, 2015. Last accessed 18 March 2023, Available from www.irena.org/Publications

[18] T. Beikircher, P. Osgyan, M. Reuss, and G. Streib, "Flat plate collector for process heat with full surface aluminium absorber, vacuum super insulation and front foil," Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry, Energy Procedia, Elsevier, DOI: 10.1016/j.egypro.2014.02.003, vol. 48, p. 9-17, 2014.

[19] S. Föste, F. Giovannetti, N. Ehrmann, and G. Rockendorf, "Performance and reliability of a high efficiency flat plate collector – final results on prototypes," Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry, Energy Procedia, Elsevier, DOI: 10.1016/j.egypro.2014.02.007, vol. 48, pp. 48-57, 2014.

[20] A. Alarcón- Villamil, J. Hortúa and A. López, "Comparison of thermal solar collector technologies and their applications", TECCIENCIA, vol. 8, No. 15, pp. 27-35, 2013.

[21] Q. Chen and Y. Wang, "Research status and development trend of concentrating solar power", 2020 9th International Conference on Renewable Energy Research and Application (ICRERA), Glasgow, UK, 2020, pp. 390-393, 27-30 September 2020, DOI: 10.1109/ICRERA49962.2020.9242893.

[22] A. A. Ani and D. A. Anatolevich, "Hybrid Solar Thermal Power Plant Potential in Bangladesh," 2023 5th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Moscow, Russian Federation, 2023, pp. 1-7, doi: 10.1109/REEPE57272.2023.10086738.

[23] E. Bellos and C. Tzivanidis. "A review of concentrating solar thermal collectors with and without nanofluids". Journal of Thermal Analysis and Calorimetry, Springer, DOI:10.1007/s10973-018-7183-1, vol. 135, pp. 763–786, 2019.

[24] A. Hassouna, M. Hassan, M. Elnaggar, M. Alnahhal, B. Abd Al Gafoor and S. Kaware, "Novel Solar Parabolic Trough Collector System for Electrical Generation and Heating/Cooling Purposes," 2021 International Conference on Promising Electronic Technologies (ICPET), Deir El-Balah, Palestine, State of, 2021, pp. 24-27, doi: 10.1109/ICPET53277.2021.00011.

[25] A.C. Brent and M. Pretorius. "Industrial and commercial opportunities to utilize concentrating solar thermal systems in South Africa", Journal of Energy in Southern Africa, Academy of Science of South Africa, DOI:10.17159/2413-3051/2011/v22i4a3226, vol. 22, p. 15–30, 2011.

[26] C. Lauterbach,B. Schmitt, U. Jordan and K. Vajen. "The potential of solar heat for industrial processes in Germany", Renewable and Sustainable Energy Reviews, Elsevier, DOI: 10.1016/j.rser.2012.04.032, vol. 16, pp. 5121–30, 2012.

[27] R. Silva, F.J. Cabrera, and M. Pérez-García. "Process heat generation with parabolic trough collectors for a vegetables preservation industry in Southern Spain", Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry, Energy Procedia, Elsevier, DOI: 10.1016/j.egypro.2014.02.137, vol. 48, p.1210–1216, 2014.

[28] A.K. Sharma, C. Sharma, S.C. Mullick, and T.C. Kandpal."Carbon mitigation potential of solar industrial process heating: paper industry in India", Journal of Cleaner Production, Elsevier, DOI:10.1016/j.jclepro.2015.04.093, vol. 112, p. 1683-1691, 2016.

[29] M.B. Michael, E.T. Akinlabi and T. Jen. "A Review of Solar Thermal Systems Utilization for Industrial Process Heat Applications", Proceedings of the World Congress on Engineering and Computer Science, San Francisco, vol. 2, p. 859-863, 19-21 October, 2016.

[30] M. I. Ismail, N.A. Yunus, and H. Hashim "Integration of solar heating systems for low-temperature heat demand in food processing industry – A review", Renewable and Sustainable Energy Reviews, Elsevier, DOI: 10.1016/j.rser.2021.111192, vol. 147, 2021.

[31] S. H. Farjana, N. Huda, M.A. Parvez Mahmud, and R. Saidur, "Solar industrial process heating systems in operation – Current SHIP plants and future prospects in Australia", Renewable and Sustainable Energy Reviews, Elsevier, DOI: 10.1016/j.rser.2018.03.105, vol. 91, p. 409–419, 2018.

[32] B. Hassine, A. Helmke, S. Heß, P. Krummenacher, B. Muster, B. Schmitt, and H. Schnitzer. IEA SHC Task 49/IV - Deliverable B2 - Integration guideline. Solar Process Heat Production for Advanced Applications, 2015.

[33] Solar Heat for Industrial Processes, SHIP Database, Last accessed 15 March 2023, Available from http://ship-plants.info/solar-thermal-plants/57-daly-textile-china

[34] Sunbest, Industrial air heating, Last accessed 15 march 2023, Available from http://www.sunbest.solar/industrial-air-heating.php

[35] B. Zalba, J.M. Marin, L.F. Cabeza, and H. Mehling, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications", Applied Thermal Engineering, Elsevier, DOI: 10.1016/S1359-4311(02)00192-8, vol. 23, pp. 251–283, 2003.

[36] I. Sarbu, C. Sebarchievici, "A comprehensive review of thermal energy storage", Sustainability, MDPI, DOI:10.3390/su10010191, vol. 10, 2018.

[37] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, L.F. Cabeza, "State of the art on high temperature thermal energy storage for power generation. Part1—Concepts, materials and modellization", Renewable and Sustainable Energy Reviews, Elsevier, DOI: 10.1016/j.rser.2009.07.035, vol. 14, p.31–55, 2010.

[38] T. Bauer, S. Wolf-Dieter, D. Laing, and R. Tamme, "Thermal energy storage materials and systems", Annual Review of Heat Transfer, DOI:10.1615/Annual Rev. Heat Transfer.2012004651, vol. 15, 131-177, 2012.

[39] L. Seyitini, B. Belgasim, C. C. Enweremadu, "Solid state sensible heat storage technology for industrial applications –A review", Journal of Energy Storage, Elsevier, DOI:10.1016/j.est.2023.106919, vol. 62, 2023.

[40] SAM-help, Last accessed 2 September 2022, Available from www.nrel.sam/help

[41] Design and Simulation of thermal solar systems - User Manual, TSOL, Pro Version 5.5, 2013.

[42] SunMaxx Solar, Evacuated Tube Solar Collectors. Last accessed 2 August 2023, Available from https://www.sunmaxxsolar.com/product-info/evacuated-tube-solar-collectors/

[43] Chandra Y. P., Mohapatra S. K., Kesari J. P. "Concentrated Solar Thermal Energy: A sustainable and everlasting form of renewable Energy", International Conference on Breakthrough in Engineering, Science & Technology, INC-BEST'16, 2016.