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ASSESEMENT AND MODELLING OF INDUSTRIAL-SCALE SOLAR THERMAL SYSTEM APPLICATION IN HUNGARY

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Abstract: With approximately 1.2% growth annually, the industrial sector accounts for 54% of the total consumed energy globally. Most of those facilities use fossil fuels to generate their needs. Renewable energies, mainly solar energy, can play a major role in meeting the global policies of reducing carbon dioxide emissions. Presently, Hungarian researchers exploit more energy from renewable energies such as solar sources, wind, and biomass. Knowing that reducing the carbon emission level is a general tendency in Hungary. This article presents an extensive analysis of the solar thermal system in the central European climate, especially in Hungary. The scope of this study is the low-to-medium heat generation in industries such as pharmaceutical, pulp & paper textile, food processing and beverages. Through all the applications, the heat is consumed in hot water form. Integrating solar thermal technology in the industrial sector depends mainly on solar radiation, conventional fuel prices, available installation area, and the complexity level of integrating the solar system with the existing process. Furthermore, more challenges show up during the integration of economic difficulties. This article analyses the feasibility of providing industrial hot water for small-to-medium enterprises (SMEs) in different Hungarian counties. The analysis was performed using T*Sol 5.5 software, and metrological data were obtained by MeteoSyn built-in software. Results indicate that the most suitable region for integrating solar thermal energy was Szeged, Szolnok, and Kecskemet, which supplied 54.89%, 54.16%, and 54.03% of the total heat load for the studied case, respectively. This result accounts for 849.57, 840.25 and 839.27 kWh/m^2 of specific generated heat of the solar system. In addition, it results in points that the annual carbon dioxide saved amount is up to 4,442.3 kg and 2,100.7 m^3 annual amount of natural gas. In conclusion, Hungary has a potentially attractive market for solar thermal systems to provide industrial hot water for small and medium-sized factories.

Keywords: buffer tank, solar heat, flowrate, heat process, solar thermal system

1. Introduction

Using conventional energy generation technologies to cover the increase of the energy demand worldwide results in health, pollution, and environmental issues [1]. Also, it is reported that the availability of conventional fossil fuels is decreasing in the coming years [2]. Furthermore, process heat in industry accounts for 35% of the final consumed energy worldwide, and it reaches up to 48% in Malaysia, 70% in China, and 29% in Europe [3,4]. At the same time, 60% of this energy is consumed at a temperature between 30℃ to 250℃ [5]. And 71% of this demand is in a heat form [6]. Generally, the process heat temperature used in industry is below 400℃. It is also noted that 80% of the used energy in industry is powered by natural gas and fossil fuel products. More than 30% of the industrial demand is due to the petrochemical and food industries. However, the share of solar energy in these sectors is nearly zero [7]. Up to 2020, not less than 95 solar thermal plants have been installed worldwide in the food industry, with a total capacity of 41 MW_{th} [8].

The thermal conversion efficiency of solar radiation is much higher than the electrical conversion. This is due to the photon's low conversion efficiency and absorption. So, heat energy is preferred for various applications in the process industries. And thus, solar thermal technology is one of the most attractive solutions for producing heat process thermal energy. Hence, there is a massive opportunity to replace conventional sources with solar thermal systems. Important industrial applications where solar thermal energy can play a major role are serialisation, pasteurisation, washing, cooling, drying, dyeing, and distillation [9]. There were many efforts to analyse the potential of using solar thermal energy in industry. Jarimi et al. [10] explored the heat storage technologies and designs used for solar thermal energy storage. Also, they explored the heat recovery methods to restore industrial waste heat. Evangelisti et al [11]. conducted a comprehensive review study on solar thermal collectors and their potential use in industry. Schoeneberger et al. [12], summarised the policy recommendations and modelling approaches for solar heat for industrial processes. In conclusion, most of those researchers are restricted to a particular location and related to either applications of a certain solar energy system for a specific industrial process or performance analysis of a solar thermal system for a certain industrial process. Thus, there are gaps related to technological aspects and the understanding of the industrial energy requirements.

Hungary is a central European country in the middle of the Carpathian Basin, with a relatively flat surface surrounded by high mountains. Compared to other European countries, Hungary has favourable weather conditions for using solar energy. The average annual sunshine hours are between 1,900 – 2,200, while the average total incident radiation is 1,300 kWh/m^{2,} as in Figure 1. So, the southern and middle regions of the country are suitable areas to utilise solar energy for domestic hot water and process heat. The solar energy theoretical potential is 1838 PJ, and the actual potential is between 4-10 PJ.

Many paper and pulp mill factories in Hungary convert woods into paper form. And the global average consumption per capita is around 95 kg per year [13]. The maximum process temperature requirement in the pulp and papers industry is 200℃, while the average temperature range is between 127℃ and 175℃ [14], where 8 tons of steam are required for processing one ton of pulp. Usually, the recovery boiler alone produces the needed steam for this process. ETC collectors can be used for processes such as bleaching, drying, and washing as a solution for integrating solar thermal energy. And to overcome the natural fluctuation of solar energy, a buffer tank may be considered.

Also, the textile industry considering the production of new clothes and the subsequent manufacturer or design of all processes and EU countries alone accounts for 64% of the clothing consumption. The textile manufacturing process can be divided into spinning, weaving, and finishing. The required energy in terms of hot water or steam is used for weaving, yarning, bleaching, curing and drying. The required temperature in textile industry varies between 40℃ to 120℃ [15]. Generally, all processes require heat temperature below 100℃ except for yarn conditioning. As a solution for integrating solar energy, the ETC collector can generate the required temperature up to 120℃ and be mounted on the roof of the building. Therefore, ETC solar system is the best option to meet the textile heat demand. Similar to the pulp and paper industry, using auxiliary heaters or buffer tanks will minimise the effect of solar fluctuation.

Most notably in Hungary, the food processing and beverage industry are highly fragmented and comprises of many sub-segments like milk, meat fruit, grains products, packaged food and drinks [16]. Most of that food and drinks have cooking, sterilisation, washing vessels, drying, and chilling processes. The heat required for this industry can be harvested from solar thermal systems. All food and beverage processes have a process temperature between 60℃ and 120℃ except for drying, which can reach up to 180℃ [17]. Two main processes are involved in the dairy industry: i. heat treatment ensures the milk's safety, and ii. derivatives products like butter, cheese, and milk powder. Dairy processes like pasteurisation, sterilisation, drying and cleaning require heat energy. This industry consumes substantial heat energy and electricity for heat processes and storage [18], and in addition to utilizing solar energy, the use of heat pumps also has significant savings potential [19].

Nevertheless, all processes can be done using heat temperature below 120℃. ETC solar system is the best option for dairy industry applications. While in the case of enormous heat demand and available land, a linear Fresnel reflector (LFR) solar system is a better solution. Also, an auxiliary heat source and buffer tank can help avoid fluctuation during the rising season or prolonged cloudy weather. It is also important to mention that the temperature range and the load profile are the most critical factor. For example, dairy factories sometimes shut down during the cold season due to the low market demand and raw material availability [20]. It gives the advantage to shift the load profile towards sunny seasons and thus, increase the solar fraction.

The pharmaceutical industry includes many processes that consume both electrical and thermal energy. Usually, the thermal energy is produced gas-fired boilers for meeting the requirements of the steam and hot water, which range between 55°C and 120°C. Most thermal processes require low heat demand, which can be achieved easily by non-concentrating solar thermal systems like FPC, ETC. Generally, ETC collectors are considered the most suitable solar system to provide the required heat up to 120°C. Finally, the automotive industry is the fastest-growing globally [21]. Most of the processes are mechanical and uses electricity for operating.

In contrast, few processes consume a significant amount of thermal energy like painting, metal casting, and pre-treatment. Generally, it is produced using conventional methods to produce hot water [22]. At the painting process, hot air is needed at a temperature between 80°C to 100°C, while hot water is needed at only 40°C [23]. As an integrating solution, ETC solar system is the most suitable solution for providing hot water at around 100°C.

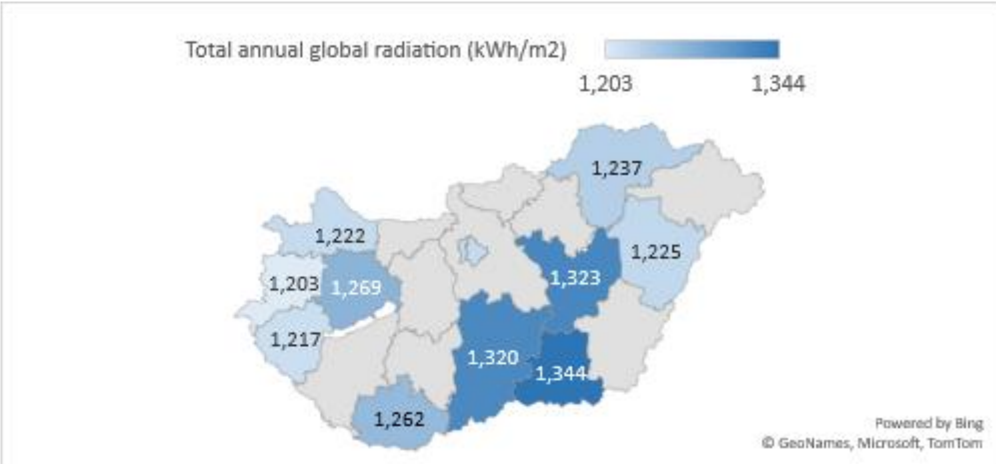

Figure 1. Annual global radiation in Hungary.

While the currently installed systems are about 0.1 PJ with around 70,000 m^2 surface area, Hungary has no database available on the actual installed solar capacity; therefore, all efforts made are only estimates [24]. In 2021, the adequate potential of solar energy had been identified by more than 2,000 MW. On the contrary, solar thermal energy is far beyond the electrical one and the most common collector in Hungary is the flat-plate collector (FPC). However, the demand for other types like evacuated tube collectors (ETC) has recently increased. In Hungary, industrial solar production began with small steps, and the installed capacities are hard to measure economically. Using solar energy has the highest positive effects of creating new jobs among all other types of renewable energies. According to the Hungarian solar energy association, installing 449 MW results in 1,500-1,600 new jobs all around the country. This capacity would provide around 1.1% of the total electricity demand in 2020. Another advantage is that installed solar systems are decentralised, reducing power distribution losses. Energy generation of renewable energy sources in Hungary has increased by approximately 30% over the last two decades. At the same time, the solar heat for industrial processes (SHIP) continued to its steady growth during 2020, with at least 74 new plants primarily in Germany, Mexico, and China.

Hungary has around 1980 hours of annual sunshine while July is the sunniest month with 279 hours and December is the lowest with only 51 hours. The average annual sunshine is quite close to Austrian data, with about 1925 hours per year. But Austria is among the best countries in Europe to utilise solar energy (fifth place in 2019) while Hungary stands at the bottom of the list (21st place over 27). It is also noted that all neighbour countries have a higher share of renewable energies in their gross final energy consumption, e.g., Croatia 28.5%, Romania 24.3%, Slovenia 21.7%, Bulgaria 21.6%, and Slovakia 16.9% while Hungary is only 12.6%. This data motivates researchers to search for a genuine reason and show decision-makers potential, especially since Hungary is a solid industrial country and a well-known destination for multinational companies.

The most recent reported efficiency of the production of low-temperature solar systems for the flat-plate collector (FPC) and the evacuated tube collector (ETC) is in the range of 15-40% while for medium temperature generation in the range of 50-60% [25]. The nominal achieved temperature by the FPC, and the ETC is 85℃ and 125℃, while the average cost per square meter is 180 $/m^2 for both collector types [13].

The present article aims to map researchers' generated knowledge in solar thermal technologies and the actual industrial applications. It also proposes a general help to investors and decision-makers to find the generated solar energy corresponding to each location in Hungary. The procedures developed in this article assume that the solar system's integration is a design modification or a retrofit dilemma. Therefore, an existing industrial process is assumed to integrate the solar thermal system.

2. Methodology

The SHIP system comprises ETCs, an integrated heat exchanger in the buffer tank, and the heat process section as in Figure 2. In the primary loop, the water flows in the pipes using an active circulation pump in a closed loop. The flow rate of the primary loop is 50 litres per hour, and the fluid is a mixture of glycol and water of 30% volumetric percentage to avoid freezing and bursting during low-temperature conditions. The demand at the factory is constant from 6:00 AM – 5:00 PM at assumed constant load on weekdays except for Saturday and Sunday. The average daily consumption for all cases is 115 kWh, and the resulting annual energy requirement is 29.89 MWh. The assumed maximum hourly requirements are not more than 10 kWh, which means a small factory like food processing or packaging. The process heat needed at 75℃ nominal supply temperature and 60℃ minimum outlet temperature. The collector field consists of 16 ETC with 34.24 m^2 gross area. The manufacturer is B. Schweizer Energie AG, and the type is Swisspipe 2 with an 87.8% conversion factor as in Table 1. The collector field faces the south at 0º azimuth angle and 72º inclination angle lengthwise. The buffer tank has 1,900 litres, and it has stratified return with a redirection valve and buffer tank bypass. Finally, the boiler is a gas-fired Riello Unit SL 48 S ECO with a 53.1 kW nominal output. All data were analysed using T*Sol software, a thermal solution program developed by Valentine software GmbH, Germany. This software is used for optimising and designing solar thermal systems dynamically. The results can be calculated over an annual cycle for several systems like domestic hot water, heating support, and process heating system. The studied Hungarian locations were chosen all around the country to have a full-scale assessment as in Table 2.

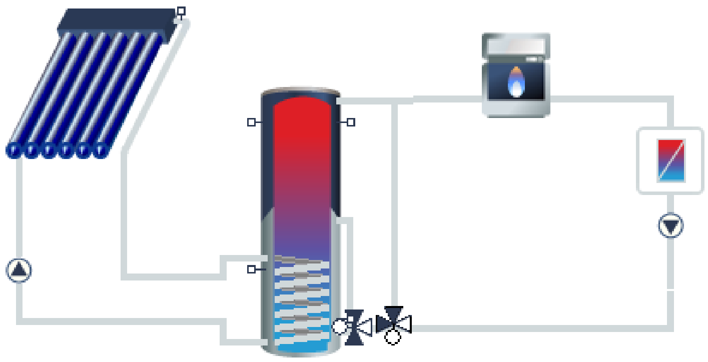

Figure 2. Process heating system with a buffer tank and continuous flow heater.

Table 1. ETC collector specifications.

Collector	Characteristics	Value
Evacuated-tube collector (ETC)	Absorber area	1.31 m^2
	Optical efficiency (a_0)	87.8 %
	Heat loss coefficient (a_1)	1.43 W/m^2 k
	Heat loss coefficient (a_2)	0.0038 W/m^2 k^2

Table 2. The studied Hungarian stations.

Station	Latitude	Longitude	Total annual global radiation (kWh/m^2)	Mean outside temperature °C	Diffuse radiation percentage (%)
Budapest	47.5°	19.0°	1,222.4	11.4	53.6
Miskolc	48.1°	20.8°	1,236.7	10.4	52.1
Veszprém	47.1°	17.9°	1,268.8	10.6	52.1
Debrecen	47.5°	21.6°	1,225.3	10.9	52.9
Szeged	46.3°	20.1°	1,344.4	11.5	49.5
Pécs	46.0°	18.2°	1,261.8	11.6	52.9
Zalaegerszeg	46.9°	16.8°	1,217.1	10.7	53.8
Szombathely	47.3°	16.6°	1,202.8	10.5	53.7
Sopron	47.7°	16.6°	1,228.9	10.9	52.4
Győr	47.7°	17.7°	1,222.0	11.1	52.5
Kecskemét	46.9°	19.7°	1,320.0	11.4	50.3
Szolnok	47.2°	20.2°	1,323.0	11.6	49.6

3. Results and Discussion

The analysis results in 12 studied stations are as in Table 3. According to the results, it is noted that Szeged, Szolnok, and Kecskemet have the highest solar fraction with 54.89%, 54.16%, and 54.03%, respectively. All power stations produce good yields per annum by supplying between 745-850 kWh/m^2/year. It is also noted that the system efficiency is around 60% for all stations.

Table 3. The analysis results.

Station	Specific irradiation collector active surface area	Specific energy delivered by collector loop	The energy delivered by the collector	Solar contribution	Energy from auxiliary heating	Total solar fraction of process heat	System efficiency
	kWh/m^2	**kWh/m^2**	**kWh**	**kWh**	**kWh**	**%**	**%**
Zalaegerszeg	1,160.31	745.48	15,625	14,392	15,492	48.16	59.18
Debrecen	1,176.50	757.24	15,872	14,640	15,255	48.97	59.37
Budapest	1,187.09	761.89	15,969	14,719	15,184	49.22	59.15
Szombathely	1,187.51	757.36	15,874	14,592	15,315	48.79	58.62
Győr	1,222.01	765.98	16,055	14,788	15,103	49.47	59.31
Sopron	1,190.69	757.81	15,884	14,592	15,305	48.81	58.47
Pécs	1,194.00	762.11	15,974	14,701	15,185	49.19	58.74
Miskolc	1,204.64	773.18	16,206	14,925	14,988	49.89	59.11
Veszprém	1,227.54	790.65	16,572	15,270	14,614	51.1	59.35
Szolnok	1,299.60	840.25	17,612	16,196	13,707	54.16	59.46
Kecskemét	1,301.20	839.27	17,591	16,169	13,758	54.03	59.29
Szeged	1,302.02	849.57	17,807	16,417	13,493	54.89	60.16

A robust negative correlation is found by plotting the correlation between the total annual global radiation and the diffusive radiation. It means that as high is the diffusive radiation, low is the total annual global radiation, as shown in Figure 3a. Also, the diffusive radiation is negatively correlated with the solar fraction. It means as high is the diffusive radiation as low is the solar fraction as in Figure 3b. It is a logical result since the solar fraction is strongly correlated with the annual global radiation in Figure 3c.

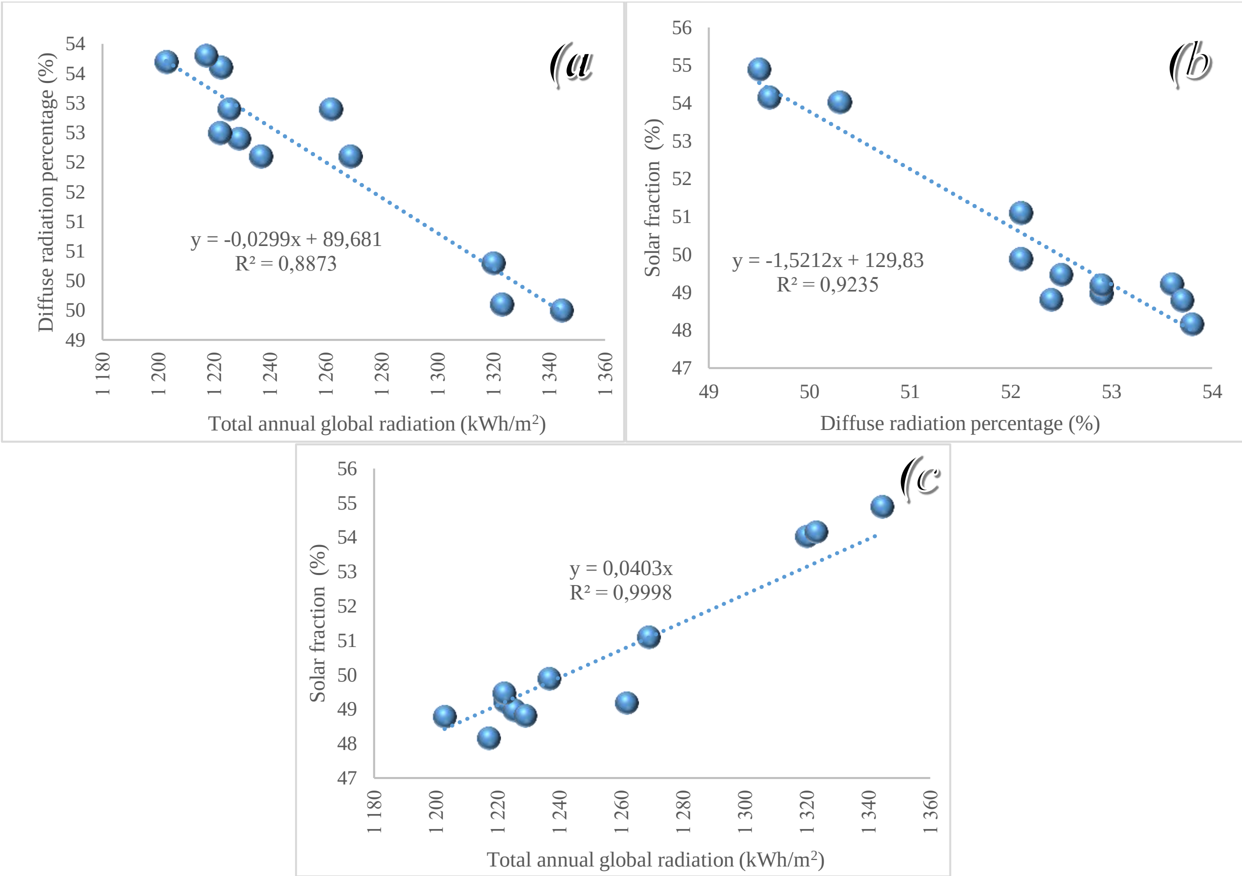

Figure 3. a) Correlation between annual global radiation with diffusive radiation percentage. b) Correlation between diffusive radiation and solar fraction. c) Correlation between annual global radiation and solar fraction.

The solar fraction map shows that Szeged, Szolnok, and Kecskemet, which accounts for the lowest diffuse radiation with 49.5%, 49.6%, and 50.3%, have the highest solar fraction with the highest 54.89%, 54.16% and 54.03%, respectively. To understand the potential, each square meter of the collector field can generate a certain amount of energy per year. Suppose we consider the average Hungarian annual radiation on a horizontal surface as around 1280 kWh/m^2. In that case, the plotted map in Figure 4 shows us the highest potential regions for utilising the solar thermal system. The specific highest potential is around 840 kWh/m^2/year for Szeged, Szolnok and Kecskemet.

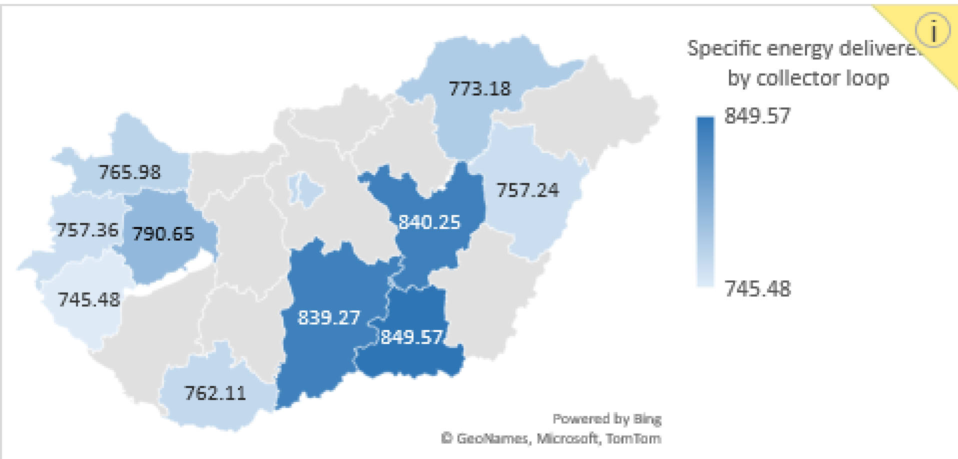

Figure 4. The specific solar generation per square meter collector area.

Comparing the specific energy delivered by the collector loop between pioneer European countries at approximately the same latitude as Budapest, Hungary is proper to compare it with Vienna, Austria and München, Germany. Vienna and München have global solar radiation of 1212.048 kWh/m^2 and 1156.022 kWh/m^2, respectively. It results in 751.59 kWh/m^2 and 698.467 kWh/m^2 specific energy delivered by the collector loop. By comparing those values with the specific collector energy in Budapest 757.24 kWh/m^2, it is found that Budapest has a higher potential than Vienna and München. Nevertheless, Austria and Germany are far better than Hungary utilising solar energy. It happens due to main reasons, like the late joining of Hungary to the EU compared to Austria and Germany, national renewable energy strategies, incentive subsidiary projects, and national decision-makers [26]. Without a subsidy, it was reported that no payback would be reached during the lifetime of the solar system, which shows the importance of the governmental subsidy [27].

4. Conclusions

Important factors decide the solar augmentation for a specific industrial heat process within the existing process. Food & beverage, textile, rice mill, leather, automotive, and pharmaceutical industries offer low-temperature solar utilisation and are available widely in Hungary. To improve the process efficiency and reduce the installation costs, an extensive technical assessment analysis should be done before integrating the solar collectors within the industrial heat process. This assessment should study the potential solar thermal system and its applications to various heat processes. According to the literature, no comprehensive work has been conducted to find the optimal location in Hungary for SHIP use.

Further, the simulation supply of heat is required for the heat process in industrial factories, which is another innovation of this article. The results show that each studied location can supply a partial amount of the required solar heat. Therefore, this article uses T*Sol 5.5 software to investigate the potential of using the solar thermal system in Hungary. Assessment analysis of 12 different locations under the Hungarian meteorological conditions was conducted for presumed industrial processes with daily and annual hot water demand. For low temperature below 120°C applications, evacuated-tube collectors ETC showed good yields with not less than 745 kWh/m^2 per year and around 840 kWh/m^2/year at three locations Szeged, Szolnok, and Kecskemét. Those results were higher than pioneer users of solar thermal energy in the EU, such as Germany and Austria. The results presented in this study can be beneficial for industrial manufacturers and decision-makers who look for clean energy sources to minimise greenhouse gases and reduce their operating costs.

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